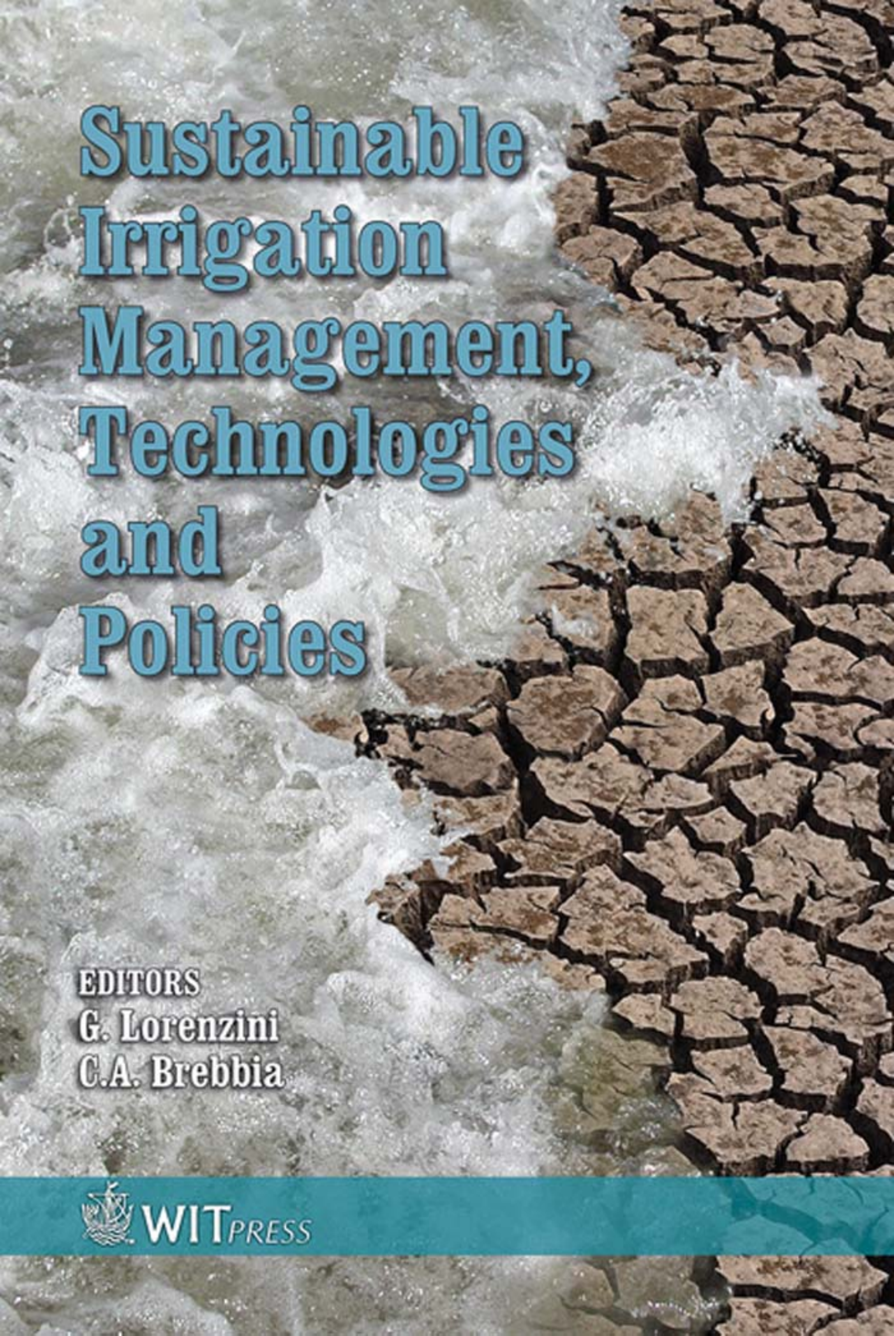

Sustainable Irrigation Management, Technologies and Policies

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Sustainable Irrigation Management, Technologies and Policies

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Preface

This book contains most of the papers presented at the First International Conference on Sustainable Irrigation, Management, Technologies and Policies, held in Bologna in 2006 and organised by the Wessex Institute of Technology. The objective of the Meeting was to bring together engineers, scientists and managers from laboratories, industry, government and academia to exchange knowledge in the field of irrigation in its broadest sense. The conference aimed to cover technical as well as policy related topics in order to find innovative solutions for the many problems to be resolved in order to reach sustainable irrigation solutions.

The emphasis of the Conference on inter-disciplinary activities explored new areas for collaboration among different professionals involved in irrigation studies and applications. This made the First International Conference unique.

Irrigation is of great relevance in many fields, such as agriculture, landscaping, water management, water policies and economics, amongst others. Improving our understanding of technical as well as economic issues can lead not only to a better understanding of the topic and all aspects of the problem, but also to find more effective solutions.

This book contains the following sections: Irrigation controls; Irrigation systems and planning; Irrigation modelling; Irrigation management.

The organisers are grateful to the members of the International Scientific Advisory Committee who have helped with the selection of the papers included in the book, as well as to all contributors. The quality of the material makes this Volume a most valuable tool for scientists and researchers to appreciate the state-of-the-art in this important field.

The Editors
Bologna, 2006

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Section 1
Irrigation controls

Surface irrigation with a variable inflow hydrograph

B. Mostafazadeh-Fard & Y. Osroosh
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Isfahan University of Technology, Isfahan, Iran

Abstract

Surface irrigation is one of the most common methods of irrigation in which its hydraulic behaviour is influenced by the inflow hydrograph. The use of electronic devices in surface irrigation to manage water delivery to the field is important because the water losses can be decreased which results in higher application efficiency. Previous studies have shown that the efficiency of surface irrigation is influenced by the inflow hydrograph shape. In this study, an electronic device has being designed and constructed that is able to regulate the irrigation pump outflow to produce different furrow or border inflow hydrographs including constant inflow, cut-back inflow, gradual reducing inflow, modified cut-back inflow, modified gradual reducing inflow and surge inflow for actual field conditions. The device is controlled by computer and can be programmed for actual field conditions data for any desired inflow rate, inflow variations and irrigation time in order to increase water application efficiency. Based on information given, the device can control deep percolation along the field and runoff at the lower end. The system can also be programmed to account for infiltration characteristics changes along the irrigation season to reduce losses.

Keywords: surface irrigation, inflow hydrograph, automation.

1 Introduction

Surface irrigation is one of the oldest methods of irrigation in which soil surface is used to convey and infiltrate water [8]. This method of irrigation as compared with sprinkler or trickle methods is inexpensive. Therefore, more attention is being paid to improve the efficiency of surface irrigation. For instance runoff

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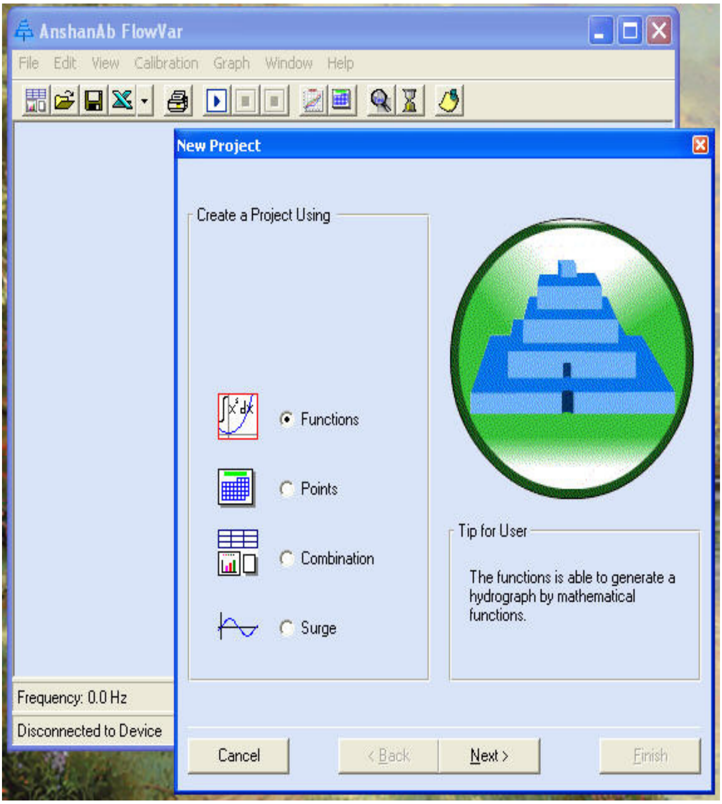
recovery, cutback technology, variable inflow hydrograph and surge flow irrigation have been studied to reduce losses [2, 9, 3, 6]. Previous studies have shown that the proper selection of inflow hydrograph shape for surface irrigation can reduce runoff and deep percolation which the result is higher application efficiency [1, 2, 5]. The use of non-constant inflow rate (surge flow) for automatic furrow irrigation was first suggested by Stringham and Keller [4] as an improved method of automating cutback furrow irrigation. Since most simple automatic irrigation valves can only turn water on and off, they concluded that it would be simpler to cycle valves to reduce the flow rate on a time basis than to partially close the valves to achieve the cutback stream. The efficient application and distribution of water by surface irrigation is highly dependent on parameters such as inflow rate and shape, advance time, soil texture, soil infiltration, plant coverage, roughness coefficient, field shape, irrigation management and ect. A number of mathematical models of surface irrigation have been developed to simulate irrigation phases such as advance, recession, infiltration, runoff and deep percolation. For instance the Sirmod model can be used to evaluate, simulate and design surface irrigation for constant inflow hydrograph and for limited variable inflow hydrographs such as cut-back inflow hydrograph or surge inflow hydrograph for furrow or border irrigation [7].

To use water and energy most efficiently, and to save labour, it is important to use automatic devices for surface irrigation. However, to date little or no research has being done to design and construct an electronic device controlled by computer which can regulates the pump outflow to provide different or desired furrow or border inflow hydrographs for actual field conditions. This operation is much simpler as compared to the control and automation of individual valve to regulate water delivery to each furrow or border.

The objective of this study is to design and construct a computer control system which can regulates the irrigation pump outflow to produce any desired inflow hydrograph for border or furrow irrigation for actual field conditions.

2 Materials and methods

In this study attempts have being made to design and manufacture a device to achieve the indicated objectives. The device that can be controlled automatically has two mechanical and electronically sections and can be programmed by user based on constant or variable inflow rate for different time periods from beginning to the end of irrigation. The written software for the device which has the graphical capability can be used in windows 98/2000/XP. The menu to create inflow hydrograph is new project from file menu (Figure 1). The new project includes points, functions, combination of points and functions and surge option. Using function it allows the user to develop inflow hydrograph according to a function or combination of different functions provided by the software. The software also has the capability to develop and use other functions based on information given by user. Using points it allows the user to use points to develop inflow hydrograph. Each point has the scale of time and discharge. Using combination it allows the user to use the combination of points and function to develop inflow hydrograph. Using surge it allows the user to simulate surge inflow hydrograph. The user can select surge option to produce surge inflow hydrograph for any desired cycle time or cycle ratio during irrigation time. In this way the automatic operation are simple and the need for surge valve to regulate inflow to the furrows or borders will be eliminated which the results are simplicity and lower operational cost. So, any desired inflow hydrograph including constant inflow, cut-back inflow, gradual reducing inflow, modified cut-back inflow, modified gradual reducing inflow and surge inflow can be obtained with high accuracy for actual field conditions. The obtained hydrograph can be observed using trace window. The inflow rate can starts from a maximum value, remain constant, change gradually, reach zero, remain zero or change according to user demand during irrigation time. The soil infiltration characteristics changes along the irrigation season can also be accounted for by changing the form of inflow hydrograph from irrigation to irrigation. In other word the management of inflow water delivery to the furrows or borders can be achieved easily to reduce losses.



● Functions

○ Points

○ Combination

○ Surge

The functions is able to generate a hydrograph by mathematical functions.

Frequency: 0.0 Hz

Disconnected to Device

Figure 1: New project from the file menu.

Most electro pumps used for irrigation are operated by motors which have constant rotation. However, using the Squirrel-cage induction motors including rotation control device (variable frequency drive, VFD, Fig. 2), the rotation of the motors can be controlled which the result is the variable pump outflow. Based on this fact the hardware section of the proposed system was designed.

The electronic section of the device receives information (frequency) from computer and sends appropriate signal to the variable frequency drive to adjust the output frequency (voltage) of the VFD connected to the electro motor to regulate the rotation of the pump. Therefore, the rotation of the electro motor controls the pump outflow to the water delivery system to furrows or borders based on desired inflow hydrograph selected by user. The selected irrigation pump for the field depends on the required flow rate.

The electronics has an on board LCD monitor to see the operation and a keypad to input the basic parameters. The device is relatively inexpensive and its energy is supplied by one or three phase power electrical lines depending on the motor or VFD type.

3 Results and discussion

Figure 3 shows an example of a developed constant inflow hydrograph. The flow rate is 2 lps and irrigation time is 160 minutes. Under this condition, to have complete irrigation at lower end of the field, the tail water runoff will be unavoidable. Figure 4 shows an example of a linear gradual reducing inflow hydrograph. As compared to Figure 3 the flow rate and irrigation time are the same but the tail water runoff can be reduced. Figure 5 shows an example of a modified gradual reducing inflow hydrograph. This form of inflow hydrograph can be used to avoid deficit irrigation at the lower end. Figure 6 shows an example of another form of a modified gradual reducing inflow hydrograph. Depends on field conditions, this form of inflow hydrograph can be used to have better distribution of water along the field. Figure 7 shows an example of input data to develop a surge inflow hydrograph for different cycle times of 20 and 40 minutes and cycle ratio of one half. Figure 8 shows the developed surge inflow hydrograph for the data given in Figure 7. Figure 9 shows an example of non-linear gradual reducing inflow hydrograph. Depends on field conditions, this form of inflow hydrograph can be used to reduce losses. All the above inflow hydrographs have the same initial inflow rate of 2 lps and irrigation time of 160 minutes. Based on field conditions, the right inflow hydrograph can be selected to reduce deep percolation at upper end of the field and to reduce runoff at the lower end of the field which the result is better distribution of water along the field and consequently higher application efficiency.

The proposed system as compared to other automatic water delivery systems to the field is simple to use, the irrigation management can easily be done and the need for using the complicated water delivery devices to control and change the inflow rate will be eliminated.

The system can be used as a management tool to apply the desired inflow hydrograph to surface irrigation field in order to reduce losses and have better distribution of water along the field.

Figure 2: Variable frequency drive.

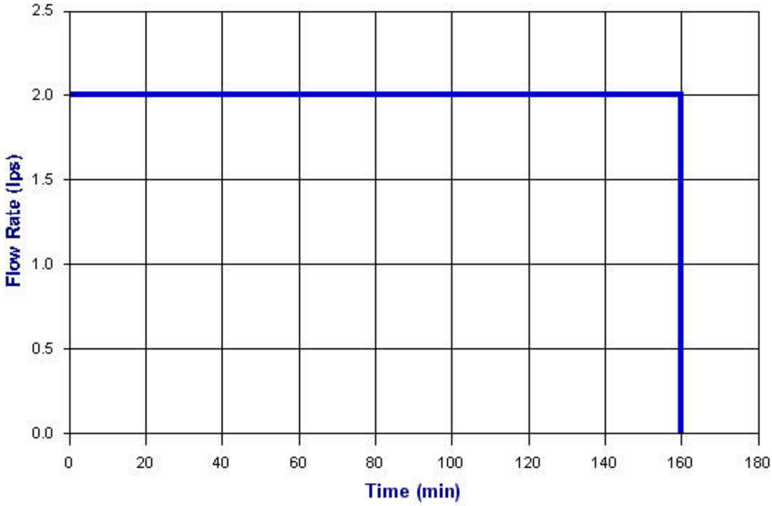


Figure 3: Example of constant inflow hydrograph.

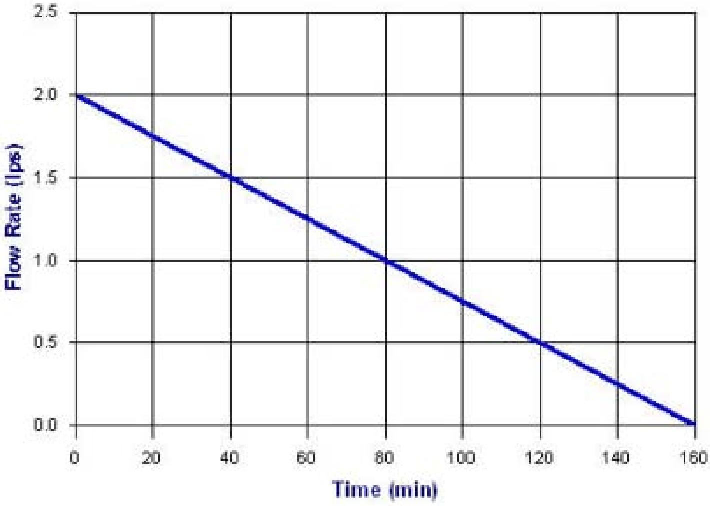


Figure 4: Example of linear gradual reducing inflow hydrograph.

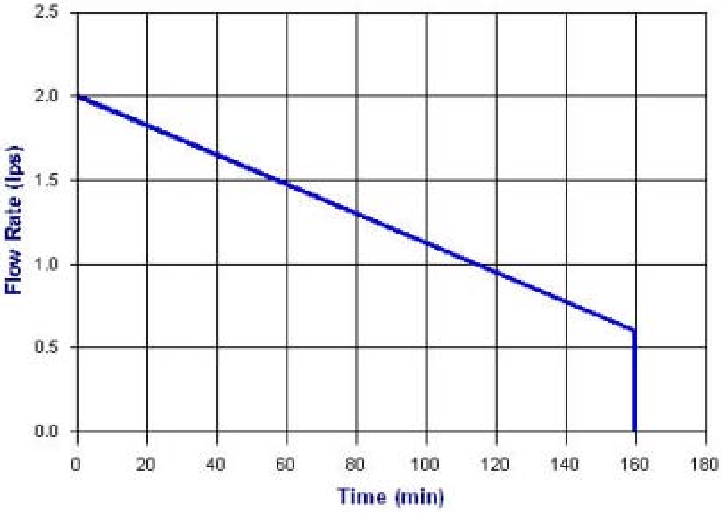


Figure 5: Example of modified gradual reducing inflow hydrograph.

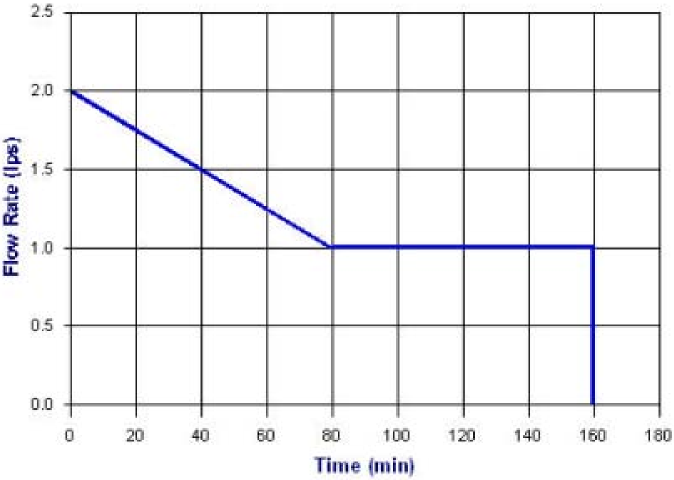
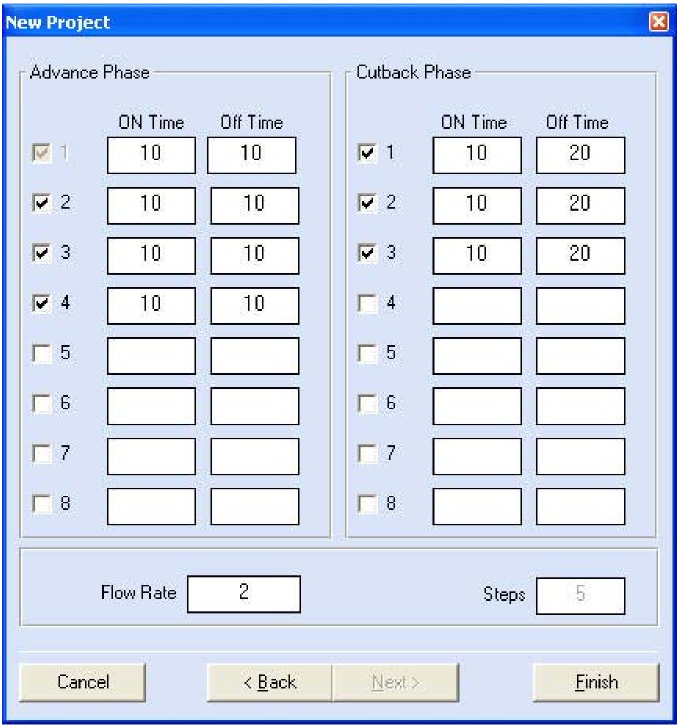


Figure 6: Example of modified gradual reducing inflow hydrograph.



Advance Phase

	ON Time	Off Time
☑ 1	10	10
☑ 2	10	10
☑ 3	10	10
☑ 4	10	10
☐ 5		
☐ 6		
☐ 7		
☐ 8		

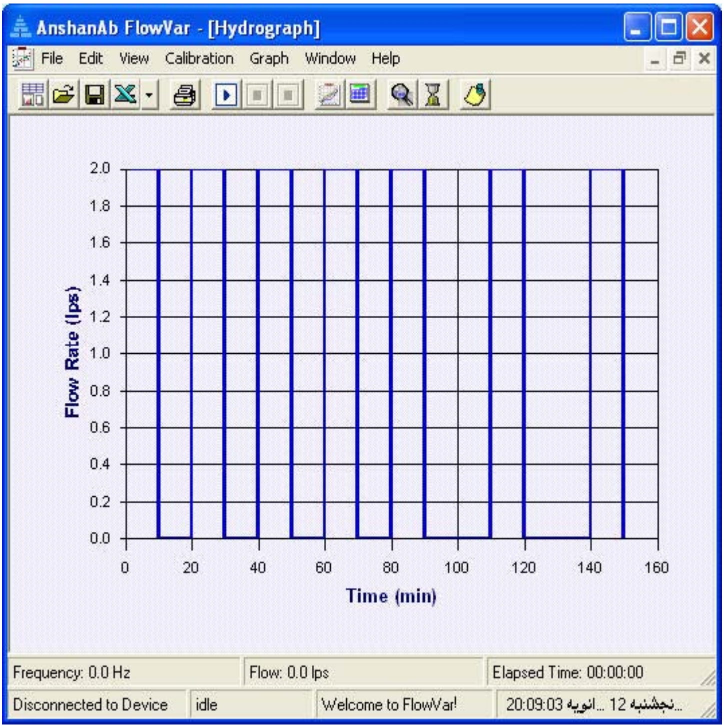
Cutback Phase

	ON Time	Off Time
☑ 1	10	20
☑ 2	10	20
☑ 3	10	20
☐ 4		
☐ 5		
☐ 6		
☐ 7		
☐ 8		

Flow Rate 2

Steps 5

Figure 7: Input data for surge inflow hydrograph.



Frequency: 0.0 Hz

Flow: 0.0 lps

Elapsed Time: 00:00:00

Disconnected to Device

idle

Welcome to FlowVar!

20:09:03 انويه... 12 نجشنبه...

Figure 8: Example of surge inflow hydrograph.

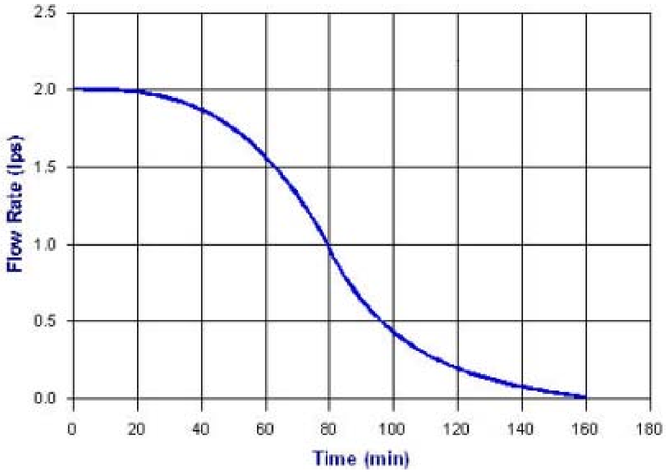


Figure 9: Example of non-linear gradual reducing inflow hydrograph.

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Simulation of performance for a simple real time control system of furrow irrigation

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Abstract

A simple real-time control system for furrow irrigation is proposed that predicts the infiltration characteristic of the soil in real time using data measured during an irrigation event, simulates the irrigation and determines the optimum time to cut-off for that irrigation. The basis of the system is a new method for estimating the soil infiltration characteristic under furrow irrigation, developed previously by the authors, that uses a model infiltration curve, and a scaling process to predict the infiltration characteristic for each furrow and each irrigation event. Using this method, infiltration parameters were calculated for two different fields. The SIRMOD simulation model was then used to simulate irrigation performance under different model strategies, framed to assess the feasibility of the real time control strategy. The simulation results showed that the system is feasible and that the scaled infiltration is suitable for use in real-time control. The results further indicated that under simple real time control the irrigation performance for the two fields could be improved greatly with substantial reductions in the total volume of water applied.

Keywords: surface irrigation, real-time control, simulation, optimisation, application efficiency, infiltration scaling.

1 Introduction

The performance of surface irrigation is a function of the field design, infiltration characteristic of the soil, and the irrigation management practice. However, the complexity of the interactions makes it difficult for irrigators to identify optimal design or management practices. The infiltration characteristic of the soil is the

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most crucial factor affecting the performance of surface irrigation (Khatri and Smith [3]) and both spatial and temporal variations in the infiltration characteristic are a major constraint to achieving higher irrigation application efficiencies.

A real-time control system has the potential to overcome these spatial and temporal variations and highly significant improvements in performance are achievable with real-time optimization of individual irrigation events. A study undertaken by Raine et al. [8] showed that when the flow rate and application time were optimized for each irrigation throughout the season to simulate perfect real-time control of individual irrigations, the average application efficiency increased to 93% with a storage efficiency of 90%, without any significant difference in the distribution uniformity.

Extracting the maximum information on soil infiltration from a minimum possible quantity of field advance data is of enormous importance for the automation of surface irrigation using real time control. The greatest limitation of the most of the infiltration estimation methods is that they are data intensive and hence not suitable for use in real-time control (Khatri and Smith [4]).

To over-come this problem a new approach to prediction of infiltration in real-time (REIP) that uses a model infiltration curve and a scaling technique was developed by Khatri and Smith [5]. The method requires minimum field data, inflow and only one advance point measured around the mid length of the furrow. Testing of the method using data from the two fields having very different infiltration characteristics has shown reliable results for prediction of infiltration characteristics. The method has potential for use in real time control.

The work reported in this paper is the second part of a study directed at the development of a simple and practical real-time control system for surface irrigation. The feasibility of the proposed system is assessed through simulation of the irrigation performance, using the scaled infiltration parameters given by the proposed method and those estimated from full advance data. The gains in irrigation performance possible from adoption of the real time control strategy are demonstrated.

2 Description of the proposed system

The proposed real-time control system involves: (i) measurement or estimation of the inflow to each furrow or group of furrows, (ii) measurement of the advance at one point approximately mid way down the furrow, (iii) estimation of the infiltration characteristic for the furrow or group of furrows using the technique of Khatri and Smith [5], and (iv) simulation of the irrigation and optimization to determine the time to cut off the inflow. The actual measurement, simulation and control would preferably be automated but could be undertaken manually with very little capital investment on the part of the farmer.

A necessary precursor to application of the system is the determination of the shape of the infiltration characteristic (model infiltration curve) for the particular field or soil type. This is best done from a comprehensive evaluation of one or more furrows from the field, involving measurements of the inflow, advance and where possible runoff, with the infiltration curve determined using a model such as INFILT (McClymont and Smith [6]). The preferred (constant) furrow inflow rate is also determined at this stage although it may be altered over time as experience with operation of the system is accumulated.

The underlying hypothesis for the method is that the shape of the infiltration characteristic for a particular field or soil is relatively constant despite variations in the magnitudes of the infiltration rate or depth of infiltration. These spatial and temporal variations are accommodated by scaling the infiltration curve, where the scaling is determined from the measured advance point and the volume balance equation. The method of scaling is as described by Khatri and Smith [5] and is summarized below. Any infiltration equation can be used however for consistency with available simulation models the present study employs the Kostiakov–Lewis equation.

In this method a scaling factor (F_s) is determined for each furrow or event from a re-arrangement of the volume balance model (as used by Elliot and Walker [2]):

$$F_s = \frac{Q_o t - \sigma_y A_o x}{\sigma_z k t^a x + \dfrac{f_o t x}{1+r}} \tag{1}$$

where Q_o is the inflow rate for the corresponding furrow (m^3/min), A_o is the cross-sectional area of the flow at U/S end of furrow (m^2) (determined by any appropriate method), a, k, f_o are the modified Kostiakov infiltration parameters for the model furrow, σ_y is a surface shape factor taken to be a constant (0.77), σ_z is the sub-surface shape factor for the model furrow, defined as:

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+a)(1+r)} \tag{2}$$

r is the exponent from power curve advance function for the model curve, and t (min) is the time for the advance to reach the distance x (m) for the corresponding furrow.

This scaling factor (F_s) is then applied in conjunction with the Kostiakov–Lewis infiltration model to scale the infiltration parameters for each furrow:

$$a_s = a_m \qquad k_s = F_s k_m \qquad f_{os} = F_s f_{om} \tag{3}$$

where a_s, k_s, f_{os} are the scaled infiltration parameters for a furrow, F_s is the scaling factor for the corresponding furrow, and a_m, k_m, f_{om} are the infiltration parameters for the model furrow.

For the proposed real time control the infiltration estimates are required in sufficient time to allow selection and application of optimum times to cut-off while the irrigation event is under way. To achieve this, the advance times ($t_{0.5}$) taken at or near the mid-point down the furrow/field ($x_{0.5}$) are used in equation (1).

3 Analysis

3.1 Irrigation performance and infiltration data

Two very different fields with a total of 44 furrow irrigation events conducted by growers using their usual practices were selected for analysis, 27 furrow irrigation events for field T and 17 furrow irrigation events for field C. These fields were selected from the different farms across the cotton growing areas of southern Queensland for which irrigation water balance and irrigation advance data have been collected. The basis for selection was the relatively large number of events for each field.

Data collected for each event included: (i) furrow inflow and outflow rates; (ii) irrigation advance (advance times for various points along the furrow including the time for the advance to reach the end of the furrow); and (iii) physical characteristics of the furrow (length, slope, cross section shape).

The flow rate and irrigation advance were measured using the IRRIMATETM suite of tools developed by the National Centre for Irrigation in Agriculture (NCEA), as described by Dalton et al. [1]. The data sets are summarized in Khatri and Smith [5].

The actual infiltration parameters and the scaled parameters for each furrow/event from the two fields, given by the INFILT software (McClymont and Smith [6]) and the method of Khatri and Smith [5]), respectively, have been taken from the previous paper (Khatri and Smith [5]).

3.2 Simulation methodology (using surface irrigation model SIRMOD)

To test the proposed real-time control system, simulations were performed for the two fields using the actual (INFILT) and the scaled infiltration parameters in the simulation model SIRMOD (Walker [9]). These SIRMOD simulations were used to compare the irrigation performance (application efficiency E_a, requirement or storage efficiency E_r, and distribution uniformity DU) of the actual irrigations, recipe approaches to irrigation performance improvement, and the simple real time control strategy.

SIRMOD is a software package designed to simulate the hydraulics of surface irrigation at the furrow scale, and to optimize the irrigation system parameters to maximize application efficiency. The ability of the SIRMOD to evaluate the irrigation performance of furrows and borders has been well documented (for example, McClymont et al. [7]).

3.3 Model strategies

To perform the simulations, six (6) irrigation strategies were framed to test the proposed system and to demonstrate the achievable gains in irrigation performance. The model strategies adopted are:

Strategy 1. Is the actual irrigation simulated using the actual infiltration parameters (INFILT a, k, f_o), actual inflow (Q_o) and actual cut-off time (t_{co}) as recorded under usual farm practices.

Strategy 2. Prediction of the actual irrigation simulated using the scaled infiltration parameters, actual inflow and actual cut-off time.

Strategy 3. Optimisation of the actual irrigation. In this case each irrigation event was optimized by using the INFILT parameters and varying the inflow and cut-off time to obtain maximum application efficiency (E_a). This strategy also indicates the best over all flow rate.

Strategy 4a. A simple recipe for performance improvement, simulated using the INFILT parameters, actual inflow but with the cut-off time fixed equal to 90% of the advance time.

Strategy 4b. An alternative recipe, simulated using the INFILT parameters, a fixed inflow as selected from strategy 3 and cut-off time equal to 90% of the advance time.

Strategy 5. A simple practical real time control strategy in which the scaled infiltration parameters were used with a fixed inflow while varying/optimizing only the cut-off time to achieve the best irrigation.

Strategy 6. Simulation of the actual result of the real time control strategy (5), using the INFILT parameters and the same inflow and cut-off time as used in strategy 5.

4 Results and discussion

4.1 Advance trajectories

The previous paper (Khatri and Smith [5]) showed that the scaled infiltration was able to reproduce the measured advance curves when applied in the same volume balance model that was used to generate the infiltration parameters. This ability was confirmed by the SIRMOD simulations which showed that the scaled infiltration was able to reproduce the measured advance trajectories (Figure 1). As expected, the advance trajectories pass through the advance point selected for the infiltration scaling, for example, in the case of data sets T1 and T22 as shown in Figure 2, but exhibit some small divergence by the end of the field.

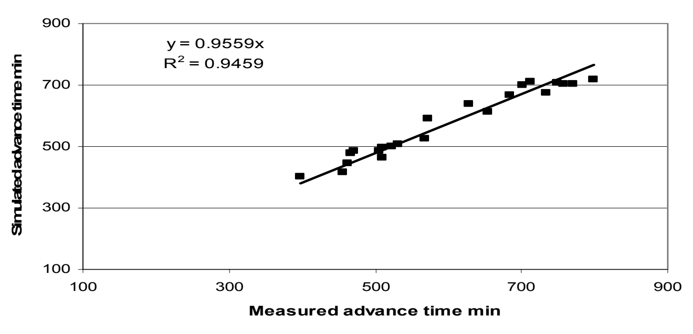


Figure 1: Final advance times for measured and simulated advance trajectories.

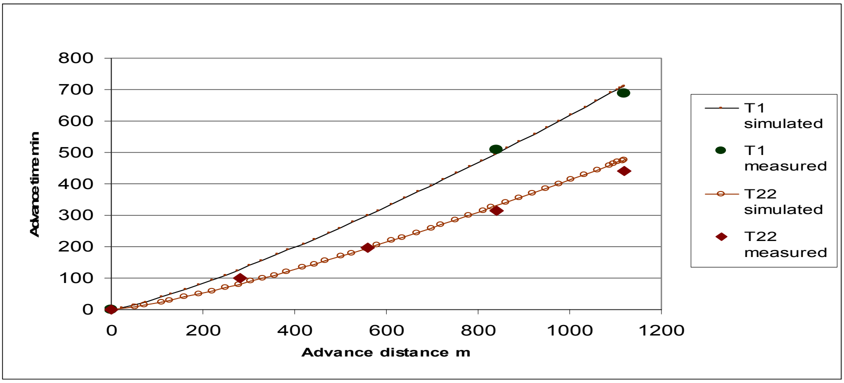


Figure 2: Measured and simulated advance trajectories for selected furrows.

4.2 Irrigation performance

The summary of simulated irrigation performance results obtained for the model strategies are shown in Tables 1 and 2 for fields T and C respectively. The results obtained under each of the model strategies are discussed below.

4.2.1 Strategies 1 and 2 (Actual irrigation - usual farm management)

From the summary of simulation results for field T (Table 1) it is evident that the over all mean irrigation performance (application efficiency and storage efficiency) of the actual irrigations (Strategies 1 and 2) was reasonable, with a mean application efficiency E_a of 77% and storage efficiency E_r 91%. However, application efficiencies were shown to be highly variable from 50 to 95%.

Table 1: Summary of irrigation performance for field T.

Management/Model strategies	E_a (%)	E_r (%)	DU (%)
Strategy 1 Actual irrigation	77.6	91.3	93.4
Strategy 2 Scaled infiltration	77.3	90.6	91.7
Strategy 3 Perfect management	90.2	90.1	94.0
Strategy 4a Simple recipe management **	81.3	86.6	82.2
Strategy 4b Simple recipe management **	80.5	88.6	84.5
Strategy 5 Real-time control (scaled infiltration)	82.1	90.2	92.2
Strategy 5 Real-time control (actual infiltration)	82.7	90.2	92.5

Table 2: Summary of irrigation performance for field C.

Management/Model strategies	E_a (%)	E_r (%)	DU (%)
Strategy 1 Actual irrigation	38.0	97.9	80.2
Strategy 2 Scaled infiltration	38.2	96.9	83.9
Strategy 3 Perfect management	72.1	95.9	92.5
Strategy 4a Simple recipe management **	68.5	79.5	72.2
Strategy 4b Simple recipe management	34.4	88.6	86.6
Strategy 5 Real-time control (scaled infiltration)	70.3	82.7	88.5
Strategy 5 Real-time control (actual infiltration)	70.2	82.2	90.7

**Denotes advance failed to reach the end of the field.

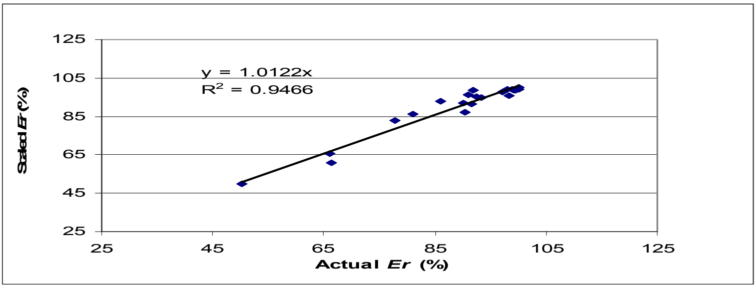
Similarly in case of field C the application efficiencies showed considerable variation from 16 to 57%, but this field showed a poorer performance (Table 2) with an over all mean application efficiency of 38% and storage efficiency of 97%.

For all of the irrigation events, the simulated performance using the scaled infiltration (Strategy 2) was similar statistically to the actual performance (Strategy 1) for each field as shown for field T in Figures 3 a and b, respectively. The results summarized in Tables 1 and 2 also confirm that the overall mean performance obtained for each field under strategies 1 and 2 is almost identical, reflecting the ability of the scaled infiltration parameters to reproduce the actual irrigations.

4.2.2 Strategy 3 (perfect control and management)

In this case the INFILT parameters were used and each irrigation event was optimized by varying inflow (Q_o) and cut-off time (t_{co}) to suit individual soil conditions and furrow characteristics. As expected an excellent performance was obtained for most events. The mean over all irrigation performance (E_a and E_r) obtained for all of the irrigation events for field T was above 90% and for field C the E_a was above 72% and E_r 95% as shown in Tables 1 and 2. This strategy involves the application of advanced irrigation management practices that may not be possible to practically implement in field. The overall best flow rate of 6.5 l/s as observed under this strategy was selected for use in strategies 4, 5 and 6.

(a) Application efficiency



(b) Requirement efficiency

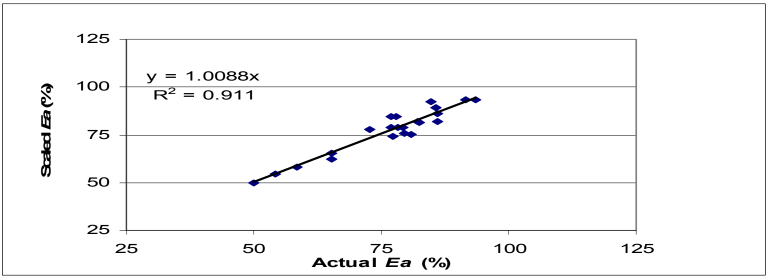


Figure 3: Irrigation performance results for model strategies 1 and 2 for field T.

4.2.3 Strategy 4 a and b (simple recipe management)

Under Strategy 4a a simple recipe management was applied where the cut-off time was fixed equal to 90% of the advance time. The performance was improved but in many events the advance did not reach the end of the field. To overcome this, strategy 4b was applied, using all the same parameters as in Strategy 4a except that the inflow rate was increased to 6.5 l/s.

The simulation results (Table 1) revealed that performance was raised for field T, the application efficiency was improved in most events but showed great variation from 50% to 100% with a mean of 80%. Some furrows still faced an incomplete advance. The simple recipe management showed poorer results in case of field C, under both strategies 4a and 4b. The advance was unable reach the end of the field for many of the furrows and yet the field was shown to have low application efficiencies, varying from 15% to 47% with an overall mean of 34% (Table 2). Field C poses substantial problems for the irrigation manager because of the extreme variation in the infiltration characteristic across the field, hence its poor response to recipe management.

4.2.4 Strategies 5 and 6 (real-time control)

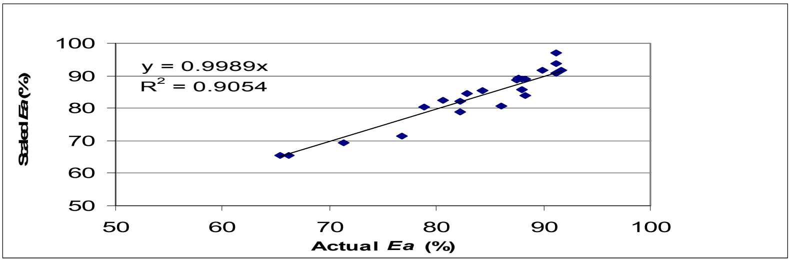
From Tables 1 and 2 it is evident that the simple real time control strategy (5) predicts improved performance (E_a and E_r) for both fields. For field T the means of the performance measures are E_a 82.1% and E_r 90.2%, with mean E_a of 70.3% and E_r 82.7% for field C.

The actual outcomes from the real time control strategy predicted using the actual infiltration parameters (strategy 6) are comparable to those above, with mean E_a 82.7%, E_r 90.2% and E_a 70.2, E_r 82.2% for fields T and C, respectively. This indicates that the mean performance predicted by the real time control system based on the scaled infiltration is very close to the actual outcomes. The predictions obtained under both strategies for the 44 individual irrigation events are also almost identical to each other, providing further evidence of the equivalence between the scaled and actual infiltration parameters. This is illustrated in the comparison of the requirement and application efficiencies predicted under both strategies for individual irrigation events as shown for field T in Figure 4. The volume of water infiltrated under both strategies is also similar. The results for these strategies show that real-time control using the scaled infiltration parameters is feasible and that significant gains in irrigation performance are possible from this system.

4.3 Water savings from real-time control

The performance simulation results (Tables 1 and 2) show there is considerable opportunity to improve the irrigation performance obtained under usual farm practices (Strategy 1). The recipe management strategies (4a & b) were shown to raise the performance for field T but for some furrows the advance failed to reach the end of the field. However, the recipe management could not bring a simultaneous improvement in the three irrigation performance measures for field C.

(a) Application efficiency



(b) Requirement efficiency

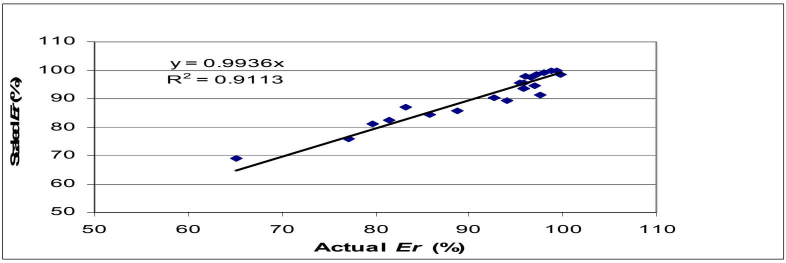


Figure 4: Irrigation performance results for model strategies 5 and 6 for field T.

When the real time control (strategy 5) was applied the overall mean irrigation performance was improved for both fields. A highly significant improvement in irrigation performance was noted in case of field C, with application efficiency increasing from 38% to 70% as shown in Table 2, along with acceptable uniformity and storage efficiency. It is evident from these results that the simple real-time control system does have potential to bring significant gains in irrigation performance, with the additional benefit of reducing the volume of water applied per irrigation and deep drainage volumes, thus reducing the potential for environmental harm.

The volume of water applied to the 44 furrows at fields T and C was reduced from 7341 m^3 under usual farm management to 5071 m^3 under real-time control. This indicates the substantial potential savings of 2270 m^3 (2.270 Ml) of volume of water per irrigation, which is a significant loss of water to the grower. For Queensland cotton growers applying 4 to 6 irrigations annually this represents an annual water saving of 1.283 to 1.924 Ml/ha that can be used beneficially to grow more crop, indicating the substantial benefits that are achievable in the industry by implementing simple real time control.

5 Conclusions

A simple practical system for real-time control of furrow irrigation that varies only the time to cut-off is proposed. To evaluate the method, the SIRMOD model was used to simulate the irrigation performance for two fields, for a range of irrigation strategies using both the scaled and the actual infiltration parameters. One of the strategies included in the simulations was the proposed real-time control strategy.

It is concluded that the measured advance curves and measured irrigation performance were able to be reproduced with sufficient accuracy using the scaled infiltration parameters. Consequently, the simple real-time control strategy is feasible and has the potential to bring significant improvements in irrigation performance over that achieved under simple recipe management or current farmer management. Substantial reductions in the total volume of water applied per irrigation are achievable, that could be used beneficially to grow a greater area of crop.

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Section 2

Irrigation systems and planning

Sustainable irrigation in South China: a case study of the Chengyang valley

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Abstract

In South China, in the rural Chengyang area, large rice fields crossed by the Linxi River are still irrigated by the river water raised by bamboo water-wheels. These water-wheels represent a viable and elegant example of a sustainable irrigation system, whose functional aspects are successfully combined with their aesthetic characteristics. The advantages provided by the material, which is easily available in the area, and the morphological characteristics of the land, have allowed the construction of numerous examples of this system of irrigation. It has a simple assembly, is efficient and has low operational and maintenance costs and enables irrigation requiring no petrol or oil.

This paper analyses the device focusing on its architectural and constructive aspects, on the important role played by the material, and on its advantages and disadvantages.

Keywords: bamboo construction, irrigation, eco-architecture, China.

1 Introduction

Bamboo has a long and well-established tradition as a building material throughout the world's tropical and sub-tropical regions. Bamboo is a renewable and versatile resource, characterized by straightness, lightness, hardness, high fibre content and easy workability. These particular qualities of bamboo make it ideal for different technological purposes.

Located in South East China, in the sub-tropical humid monsoon climate region, Guangxi has a good climate for bamboo plantations and, at the same time, people there have experience in selected seed cultivation and planting techniques.

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In the area of the Linxi River, near the village of Chengyang, irrigation of large fields is guaranteed by numerous bamboo water-wheels, which, moved by the river current, raise water from the river itself to the banks. The fields are between 3-4 metres to 7-8 metres above normal river level.

2 Structure characteristics

The construction methods of the water-wheels on the Linxi river are representative of the numerous bamboo machines which are still in use for irrigation in other regions of China and several countries of Southeast Asia, like Cambodia, Burma, Thailand, Vietnam and Indonesia. The origin of these bamboo water-wheels is unknown, but existing records show that it was already in use in China in the 14th century.

Apart from the horizontal axis which is made of a timber trunk, all the components of the machines are made of bamboo canes with different dimensions and diameters which range between a few centimetres and about 15 centimetres. The bamboo canes are not shaped, but retain their natural appearance. For spokes and rims, canes with a diameter of 3-5 centimetres are used, while buckets and aqueduct channels are made of bamboo timbers which can have a diameter of more than 10 centimetres.

The wheel consists of two parallel external rims, and two internal rims close to each other. They are connected by bamboo paddles on which the river current pushes causing the rotation of the wheel. The paddles consist of a sequence of half bamboo canes or wooden plates.

Containers made of segments of bamboo canes with a diameter of about 10 centimetres are tied to the two external rims. During the rotation they fill with water as they become submerged when the wheel turns round. They are subsequently discharged at the top of the wheel into a wooden or bamboo channel from which water is transported into the irrigation network.

Figure 1: Rice fields on the Linxi River.

Figure 2: A water-wheel for irrigation.

Figure 3: Water pouring in the channel.

The network of channels is made of bamboo canes with a diameter of about 10-15 centimetres. In order to evacuate the redundant quantity of water, the irrigation channels are opened on the upper part at regular intervals.

The strength of the wheel is guaranteed by numerous pairs of radial spokes. Each pair of spokes connects one of the ends of the horizontal axis supporting the wheel to a paddle on the opposite rim. The two spokes cross each other creating a brace to the structure. The internal rims sit either side of where the spokes cross and thus give more strength to the structure.

The diameter of the wheels depends on the height of the banks. It can reach about 8 metres.

The central axis of the wheel is supported by wooden poles which lie on the bed and on the banks of the river. Because of its lightness and flexibility, the structure can be moved to wherever needed along the river banks.

These water-wheels are easily replaced and repaired due to their extremely simple assembly and the lightness and availability of the bamboo used in their construction. Untreated bamboo, like that used to build these structures, has an average life of only few years when it is directly exposed to soil and the atmosphere and so frequent replacement and reconstruction are necessary.

In order to raise more water it is possible to find groups of consecutive water-wheels whose close disposition is allowed by a river current which is not particularly strong and where there is no risk of turbulence which could interfere with the smooth running of the wheels.

Bamboo pots, during the circular motion, gradually change position depending on the volume of water carried in the pot. In fact, at the river level, when they fill, due to the weight of water, they are in a vertical position, with the base at the bottom. Going up, between the river level and the top of the wheel, they are in an oblique position, which becomes horizontal at the top. Here, during the transfer of water to the channel, they are parallel to each other. Going down, between the top of the wheel and the river level, they are again oblique, but with the base at the top. At the river level they return to a vertical position due to gravity.

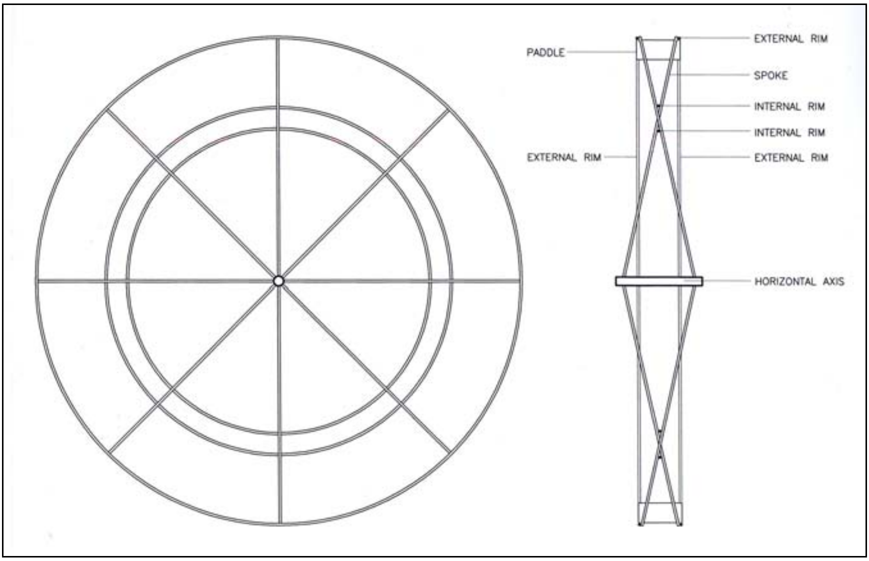

Figure 4: Schematic elevation and section of the wheel.

Figure 5: Detail of the wheel.

Figure 6: An irrigation channel.

3 Continuity of sustainable irrigation

These structures represent a clean technology for the environment, allowing irrigation fully exploiting the power of the river, without the use of petrol or oil. They do not present a risk of provoking environmental damage. In the eventuality of small floods, these are not dangerous to the wheel. In fact the embankments where these structures are located, always considerably exceed the river level in height. The easy availability of the material in the area, the simple assembly and re-assembly of the components of the structures, together with the favourable morphological characteristics of the river, continue to guarantee the use of this ancient irrigation method which is strictly integrated into the ecological system of the area and, because of the lightness of the structure of the wheels, often makes them appear part of the natural landscape.

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Evapotranspiration, yield, crop coefficients, and water use efficiency of drip and furrow irrigated processing tomatoes

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Abstract

A key component of sustainable agriculture is maintaining profitable yields, which involves applying sufficient water to meet a crop's evapotranspiration (ET_c) requirements. This requires knowledge of the current ET_c requirement. Yield of processing tomatoes has increased by 53% over the past 35 years in California. Thus, concern exists about the current ETc and crop coefficients of processing tomatoes. Past irrigation practices were furrow and sprinkle irrigation, whereas drip irrigation is now commonly used in some parts of the state. Thus, the Bowen Ratio energy balance method was used in eight commercial fields to determine current seasonal ET_c, crop coefficients, and water use efficiency for furrow and drip irrigated fields. Results showed seasonal crop evapotranspiration to range from 528 mm to 752 mm with an average of 648 mm. Commercial yields ranged from 78.6 Mg ha^{-1} to 146.7 Mg ha^{-1}. Water use efficiency ranged between 0.114 Mg ha^{-1} mm^{-1} to 0.235 Mg ha^{-1} mm^{-1}. No statistical differences in seasonal ET_c, yield, and water use efficiency were found between furrow and drip irrigation. Mid-season crop coefficients varied from 0.96 to 1.09 depending on year with statistically similar values between furrow and drip irrigation for a given year. Current ET_c rates were similar to those of the 1970s. Thus, average water use efficiency of processing tomatoes increased from 0.082 Mg ha^{-1} mm^{-1} to 0.12 Mg ha^{-1} mm^{-1} over the 35 year period.

Keywords: evapotranspiration, processing tomatoes, drip irrigation, furrow irrigation, water, irrigation, tomato, water use, water use efficiency, crop coefficients.

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1 Introduction

A key component of sustainable agriculture is maintaining profitable crop yields. It is well established that crop yield is strongly dependent on seasonal crop evapotranspiration (ET_c). A profitable yield of processing tomatoes requires supplying sufficient irrigation water to satisfy ET_c. Thus, it is critical to know the current seasonal ET_c of processing tomatoes for sustainability.

The average state-wide yield of processing tomato per unit area increased from 53.0 Mg ha^{-1} during 1970 - 1974 to 81.3 Mg ha^{-1} during 2000 - 2004, a 53 percent yield increase [1]. During the 1970s, calculated seasonal ET_c ranged from 637 mm to 714 mm with an average seasonal value of 645 mm [2].

ET_c is commonly estimated by multiplying a crop coefficient by a reference crop evapotranspiration (ET_o). Measured mid-season crop coefficients, developed 20 to 35 years ago from experimental data, ranged from 1.05 under subsurface drip irrigation [3] to 1.25 under sprinkler irrigation [4].

The long term yield increase coupled with the variability in crop coefficients determined from experimental data 20 to 35 years old raises questions about current ET_c requirements. This study evaluated ET_c, yield, crop coefficients, and water use efficiency of processing tomato on the west side of the San Joaquin Valley of California for furrow-and drip-irrigated commercial fields under a wide range of cultural practices experienced by growers.

2 Materials and methods

ET_c of processing tomato was determined from 2001 to 2004 for three furrow-irrigated and five drip-irrigated commercial fields located on the west side of the San Joaquin Valley near Five Points, CA. ET_c was determined with the Bowen Ratio Energy Balance Method (BREB). Other data collected were soil water potential (Watermark electrical resistance blocks), canopy coverage (infrared digital camera), yield and soluble solids (commercial grading station), and applied water.

Fields were selected to obtain a wide range of cultural practices. Planting times ranged from 1 March to 25 May. Transplants in some fields, while others were direct-seeded. Sprinkle irrigation was used for stand establishment in six fields, while subsurface drip irrigation was used in two fields. Crop season ranged from 109 days to 147 days. Soil type was clay loam for all fields. Subsurface drip irrigation was used with drip lines buried 0.2 m to 0.36 m deep.

Crop coefficients were calculated as the ratio of ET_c to $ET_{o.}$ ET_o was obtained from the California Irrigation Management Information System (CIMIS) station located at the University of California Westside Research and Extension Center, about 5 to 8 km from the eight fields. Water use efficiency was calculated as the ratio of yield to ET_c.

3 Results and discussion

Seasonal crop ET_c ranged from 528 mm to 752 mm with an average of 648 mm (Table 1). Average ET_c was 620 mm and 696 mm for drip and furrow irrigation, respectively. The difference in the average seasonal ET_c between irrigation methods was not statistically significant (t-test, level of significance of 0.05). Applied water ranged from 582 mm to 1018 mm (Table 1). The furrow irrigation amounts included surface runoff that was recovered and reused elsewhere on the farms.

Crop yield ranged from 78.6 Mg ha^{-1} to 146.7 Mg ha^{-1} (Table 1). The difference in average yields between irrigation methods was not statistically significant. No correlation occurred between crop yield and ETc, mainly due to the different varieties and site conditions of this study.

Water use efficiency (WUE) ranged from 0.11 Mg ha^{-1} mm^{-1} to 0.23 Mg ha^{-1} mm^{-1} (Table 1). The average WUE was 0.13 Mg ha^{-1} mm^{-1} and 0.16 Mg ha^{-1} mm^{-1} for furrow and drip irrigation, respectively, but these values were not statistically different based on the t-test (level of significance = 0.05).

Table 1: Seasonal ET_c, applied water, crop yield, and water use efficiency (WUE).

	Seasonal ET_c (mm)	Applied Water (mm)	Yield (Mg ha^{-1})	WUE (Mg ha^{-1} mm^{-1})
2001				
Furrow	648	836	86.2	0.129
Drip	571	582	93.6	0.159
2002				
Furrow	688	660	78.6	0.110
Drip	742	764	87.8	0.115
2003				
H2003 (drip)	622	803	146.7	0.228
D2003 (drip)	528	894	91.2	0.167
2004				
Furrow	752	1018	116.4	0.150
Drip	630	625	82.1	0.124

During the sprinkle irrigation for stand establishment, maximum crop coefficients ranged from 0.91 to 1.21 with an average maximum coefficient of 1.03. The average crop coefficient between sprinkle irrigation and 10% canopy coverage was 0.19. Crop coefficients at the start of the crop season were smaller than 0.3 for sites where subsurface drip irrigation was used for stand establishment. Average mid-season crop coefficients varied from year to year with values ranging from 0.96 to 1.09 (Table 2). No statistical differences were found between the mid-season crop coefficients of the two irrigation methods for a given year; however, differences were significant between years.

Crop coefficients (K_c) were related to canopy coverage (C) by a second-order polynomial equation (Fig. 1; Eq. 1). The regression was highly significant with a coefficient of determination of 0.96.

$$K_c = 0.126 + (0.0172)(C) - (0.0000776)(C^2) \qquad (1)$$

Table 2: Average daily mid-season crop coefficients for each year. (SD = standard deviation.) Values with the same letter were statistically similar at a level of significance of 0.05, based on the t-test.

	2001		2002		2003		2004	
	Furrow	Drip	Furrow	Drip	Drip	Drip	Furrow	Drip
Ave.	1.02ab	0.96b	1.06c	1.05ac	1.05c	0.99ab	1.09d	1.08d
SD	0.04	0.05	0.04	0.06	0.04	0.11	0.04	0.02
Min.	0.92	0.84	0.96	0.92	0.96	0.72	0.93	1.02
Max.	1.11	1.07	1.13	1.30	1.15	1.19	1.16	1.14

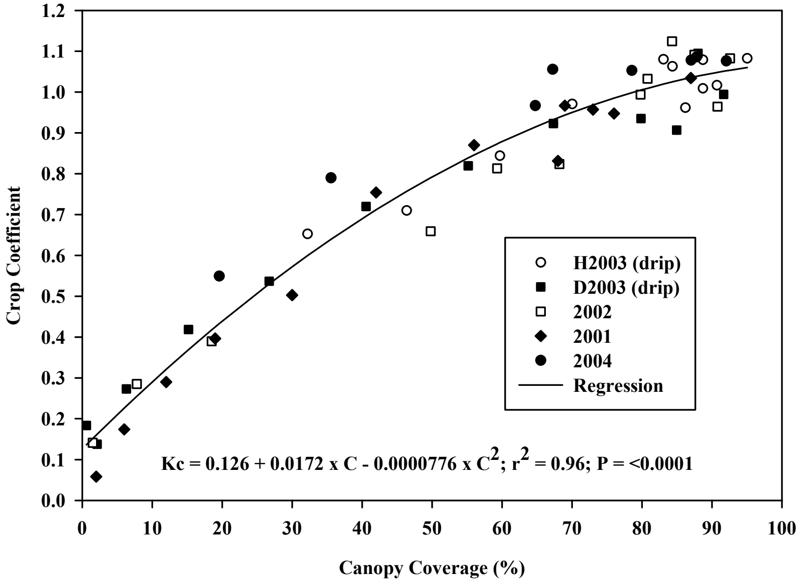

Figure 1: Crop coefficient as a function of canopy coverage.

It has been hypothesized that the seasonal ET_c of subsurface drip irrigation is smaller than that of furrow irrigation due to reduced evaporation from the soil. The only study found on this matter showed little difference in seasonal ET_c – measured with lysimeters – between surface drip and furrow irrigation of processing tomatoes [5].

The only conclusion that can be drawn from our current study is that evaporation under subsurface drip irrigation may be smaller during the early growth stages compared to furrow irrigation, as occurred in 2001 (data not shown). For the 2001 furrow system, relatively high evaporation occurred during both the stand-establishment sprinkle irrigation and the furrow irrigations of the canopy development stage, as evidenced by crop coefficients nearly equal to one during these irrigations (data not shown). During those irrigations, wetting of the soil surface across the bed width occurred due to excessive irrigation times. In contrast, little surface wetting occurred with the subsurface drip system. Cumulative ET_c at the end of the canopy development stage was 117 mm higher for the furrow system as compared to the subsurface drip system. The behaviour of the 2001 furrow system, however, was not found during the canopy development stages of the 2002 and 2004 furrow systems because these systems were managed to minimize soil-surface wetting.

4 Conclusions

No difference in average seasonal ET_c was found between irrigation methods. These seasonal ET_c's are similar to those reported by Fereres and Puech [2]. The 53% increase in yield between 1970 to 1974 and 2000 to 2004 has not increased the seasonal ET_c, but instead increased the average water use efficiency of processing tomato from 0.079 Mg ha^{-1} mm^{-1} to 0.11 Mg ha^{-1} mm^{-1} over the 35 year period. Mid-season crop coefficients varied between years, but similar values were found between irrigation methods for a given year.

It is unlikely that converting from furrow to drip irrigation in processing tomatoes will reduce seasonal ET_c. While some reduction in water use may occur during the early growth stages, as shown by the 2001 data, the 2002 and 2004 showed that evaporation under furrow irrigation can be reduced by improved water management. Stand establishment with subsurface drip irrigation may reduce ET_c during the initial growth stage compared to sprinkler irrigation, but this approach is feasible only for transplanted fields. There is little or no opportunity for reduced drip ET_c during the midseason growth stage because for a given year, similar midseason crop coefficients occurred with both irrigation methods.

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Problems of the irrigation system in the Turpan Basin of China

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Abstract

The water resources of Turphan are composed of snow and glaciers from the Tian Shang Mountains. People in Turphan have continued with a consolidated agriculture method since old times, depending on traditional channels and Kareez (underground conduits). In recent years, arable land has increased with the population and the demands of the irrigated water have increased abruptly for the assurance of productivity. Traditional systems of irrigation could not supply the essential water to the extended arable land, so dams and wells have been constructed for irrigation. The construction of large scale reservoirs, canals and wells enabled the enlargement of the irrigated area and an increase in the production of agricultural products. But, the excessive irrigation caused an increase in the evapotranspiration and salinization. In conditions like this, the extensive arable land has progressed to desertification and abandonment. The more traditional systems of irrigation have been largely ignored because of the interference problems caused by various facilities that have decreased the use of traditional Kareez irrigation systems. The potentiality of water resources development is comparatively small, judging from the present condition of water use in Turphan, because the developed water resources must be utilized effectively and strong measures must be taken to save irrigation. The management of irrigation systems must be intensified, the new technology of irrigation must be popularized and the efforts of saving water must be made for the irrigation system
Keywords: Kareez, irrigation, Turpan basin, arid area.

1 Introduction

In an arid area, stable agricultural production depends heavily on irrigation. Irrigation systems consist of intakes, irrigation/discharge canals and the irrigated

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farmland, and their efficient operation requires specialized management. Most of the water used in Turpan, a city in the Xinjiang Uygur Autonomous Region of northwestern China, is underground water recharged by ice and snowmelt in the Tian Shan Mountains. The people here have long engaged in intensive farming, relying on traditional irrigation canals and underground conduits called Kareez.

The area under cultivation here has expanded with population increases, which has caused a rapid increase in demand for irrigation water. Because traditional irrigation systems did not provide sufficient water for the greater area under cultivation, irrigation dams and wells were constructed. Although large-scale reservoirs, canals and wells have helped to increase the irrigated area and the agricultural output, the expansion of the irrigation system has promoted evapotranspiration and has accelerated salt accumulation. In light of this, many farm plots have been devastated and abandoned. Furthermore, interference between the various irritation facilities has decreased the use of traditional Kareez irrigation.

This paper examines the relationship between water resources and irrigation farming in an arid area and confirms the necessity of local irrigation management in achieving sustainable development.

2 Study area and method

Turpan, a city with the administrative status of a prefecture, is in the eastern part of the Xinjiang Uygur Autonomous Region, between the north latitudes of 42°15’10” and 43°35’00” and the east longitudes of 88°29’28” and 89°54’33”. The city lies in a basin that is bordered to the north by the Tian Shan Mountains (approx. 4,000 m elev.) and to the south by the Qollok Mountains (approx. 1,500 m elev.). The Huoyan Shan Mountains run east-west through the center of the basin.

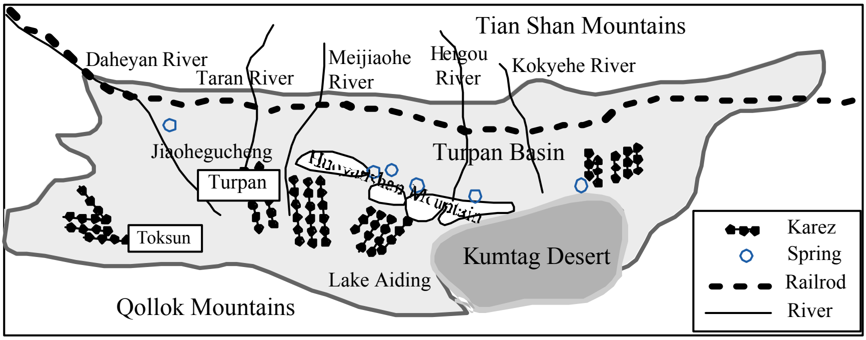

Figure 1: Outline of investigation area.

Mountains and plains respectively account for 21.8% and 78.2% of Turpan’s area (3,275 km^2 and 11,758 km^2 out of 15,033 km^2). The topography is characterized by an incline from the northern Tian Shan Mountains (4,000 m) to the southern Aiding Lake (−154 m) (Figure 2).

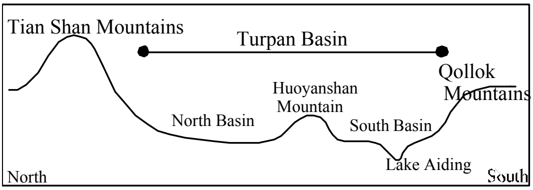

Figure 2: Cross section of Turpan Basin.

Twelve municipalities comprise Turpan. Between 1949 and 2003, the population grew from 67.3 thousand to 243.8 thousand and the cultivated area grew from 13.3 thousand ha to 19.3 thousand ha.

According to 2002 statistics for Xinjiang, 70.3% of Turpan City's population was engaged in farming (171.5 thousand out of a population of 243.8 thousand), indicating that agriculture is the key industry. The main products are wheat, cotton, grapes and gourds (Table 1) [2].

Vineyards in Turpan City account for 45.2% of the cultivated area, and grapes account for more than half of a farming household's income. Since the climate favors long-staple cotton, cotton is produced on 4,900 ha of land, or 17.7% of the total area under cultivation. Gourds are one of the local specialties and their fields were drastically expanded from 386.7 ha in 1995 to 1,146 ha in 2002.

This study was conducted by interviews with officials at the Turpan Water Management Bureau, fieldwork, and a review of the literature.

Table 1: Crop types and irrigation water supply.

crop type	grain crops	grape	cotton	vegetables	melon	others	total
area (ha)	6380	12486	4900	1393	1146	1353	27658
ratio (%)	23.1	45.2	17.7	5.0	4.1	4.9	100.0
duty of Irrigation water ($mm \cdot y^{-1}$)	720	1200	825	1395	1095	600	
total irrigation water (million $m^3 \cdot y^{-1}$)	0.46	1.50	0.41	0.19	0.13	0.08	2.77
ratio (%)	16.6	54.2	14.8	6.9	4.6	2.9	100.0

3 Results

3.1 Hydrology

The highest and lowest temperatures ever recorded at Turpan City are 47.6 °C and –28 °C. The average temperature in July is 33 °C, with a large daily temperature range, and the average temperature in January is –10 °C. The annual average temperature is fairly high, exceeding 14 °C. The region is arid, with annual average rainfall of only 16.2 mm and a far greater annual evaporation potential of 2,838 mm.

Although Turpan City receives little rain, the Tian Shan Mountains receive 500 - 800 mm per year, and high peaks in the mountains are covered with glaciers. Rainfall in the Tian Shan Mountains and glacial meltwater are the major water sources of rivers.

The rivers in Turpan City are grouped into either the Tian Shan river system or the Huoyan Shan river system, depending on their origins. The Tian Shan river system includes five rivers that originate in rainfall, ice and snowmelt, and springs in the Tian Shan Mountains. These five rivers have a catchment area of 1,949 km^2, an annual average discharge of 336 million m^3 and an annual average flow rate of $9.38m^3/s$.

The Huoyan Shan river system originates in underground water that is recharged from the Tian Shan Mountains and blocked by the Huoyan Shan Mountains at the center of the basin (Figure 2). Such blocked underground water surfaces as springs that form rivers. Soon after they flow into the southern part of the basin, they subside to become underground water. The annual discharge of the Huoyanshan river system is 166.4 million m^3, which is equivalent to nearly half the annual total discharge of the Tian Shan river system.

Surface water in Turpan City averages only 19,690 m^3/km^2. This is considerably less than the average for China, which is 270,800 m^3/km^2. Thus, Turpan has one of the highest demands for water in China.

3.2 Irrigated agriculture

The irrigation system in the Turpan Basin integrates the traditional Kareez and spring irrigation that draws from the Huoyan Shan river system with canals and reservoirs that draw from the Tian Shan Mountains and new wells.

3.2.1 Spring irrigation

Irrigation agriculture in Turpan City has been operated by using springs of the Huoyan Shan Mountain as water sources. Oases that were created by spring irrigation include Lukqun, Huoyan Shan and Lake Aiding.

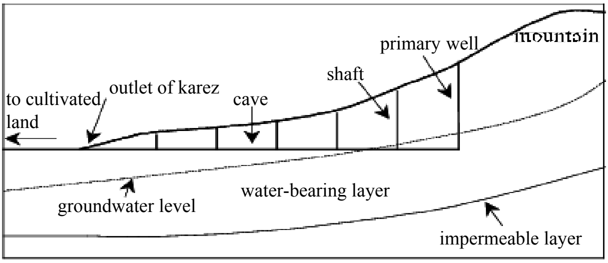

Figure 3: Structure of Kareez.

3.2.2 Kareez irrigation

A Kareez is an underground aqueduct laid from mountain foothills to oases in areas to be irrigated. It is constructed by digging vertical holes at intervals of 20 to 30 meters and then connecting the bottoms of the holes by horizontal tunneling (Figure 3). A Kareez is the last part of a quanta.

3.2.3 Irrigation using canals and wells

With population growth and the accompanying expansion of cultivated area, the Kareez irrigation system failed to satisfy the agricultural demand. Meanwhile, the social system in Turpan changed drastically after China's Cultural Revolution and agriculture was collectivized. From around 1955, the construction of leak-proof main irrigation canals and dams started on the rivers of the Tian Shan river system. This leak prevention enabled canals to be laid in the Gobi Desert. The combined length of all canals as of 2002 was 1,971 km, of which 748.4 km was leak-proof. The volume of irrigation water conducted through the canals became 203 million m3/year in 2002, accounting for 60% of the total river discharge. Moreover, seven reservoirs with a combined storage capacity of 4.90 million m3 were constructed. Consequently, the area irrigated by the Tian Shan river system expanded rapidly. Yet, there are great seasonal differences in the volume of available irrigation water. Usually surface water is provided from mid-May, water shortages in the seeding period of early spring created serious problems. To improve the situation, well-digging started in 1965 and wells number 1,468 today. Wells play an important role in mitigating water shortages in early spring, providing 40 - 50% of all irrigation water in that season.

Table 2: Irrigation reality in Turpan in 2002.

water resources	water reserve (million m^3)	Amount of intake (million m^3)	Amount of irrigation water (million m^3)	propotion of each water reserve to total water reserve %	irrigation efficiency %	Using rate of water reserve %
River	3.365	2.031	0.914	34	45	27
Spring	1.664	1.137	0.692	26	61	42
Well	0.992	0.801	0.641	24	80	64
Kareez	0.818	0.556	0.429	16	77	52
Total	6.839	4.525	2.676	100		

4 Discussion

4.1 Water resources

Irrigation water in Turpan City today can be broken down by source into 34% from rivers, 26% from springs, 24% from wells and 16% from Kareez. Before 1949, Turpan City relied heavily on Kareez and springs. But after the social system underwent complete change and the People's Commune program was established with the aim of collectivizing agricultural production, the water and land resources underwent intensive development. Rezoning, reclamation, canalization, and reservoir construction were particularly active. By 1976, seven reservoirs had been completed in Turpan City, increasing the irrigated agricultural land area from 13.3 thousand ha to 27.7 thousand ha and the volume of irrigation water to 267 million m^3. Table 3 outlines Turpan's current irrigation system.

Population growth directly leads to increased demand for agricultural products. To boost the agricultural output, the irrigated area needed to be expanded. Also, population growth brings water shortages and environmental degradation to oases. Canals and reservoirs constructed by the People's Commune after 1958 were unable to supply enough irrigation water to the expanded farmland. To supply more water, wells were dug intensively near canals. The increased uptake from these wells lowered the groundwater level and caused drying up of Kareez.

4.2 Problems of the irrigation system

4.2.1 Some main problems of water resource utilization in Turpan City [4]

4.2.1.1 Shortage of absolute quantity of water resources The annual water supply per capita in Turpan is 1.57 ton, much less than the 6.46 ton for the Xinjiang Uygur Autonomous Region as a whole and 2.63 ton for China. Water supply per hectare of cultivated land per year in Turpan is 1.38 ton. This is half the amount for other areas.

4.2.1.2 Seasonal variations in discharge of surface water resources The outflow of surface water predominates in summer. The average summer discharge between May and August accounts for 70% of the annual discharge, or for 78% of the annual discharge in the highest year. Irrigation water is in particularly short supply in early spring.

4.2.1.3 Water leakage from irrigation canals under construction and from those that are old Because there are too few distribution facilities such as water gates, the use efficiency remains only 27% for river water, 42% for spring water, 64% for well water and 52% for Kareez water.

4.2.1.4 Less use of Kareez caused by increase of intake water from wells and rivers. The number of wells has increased markedly since the 1970s, with 1,468 wells operating today. In 1949, Kareez in Turpan City numbered 592 and the irrigation water they discharged was 210 million m3, or 56% of the total irrigation discharge. Today, the number of Kareez has dropped to 291 and their annual irrigation discharge has fallen to 43 million m3, only 16% of the total annual irrigation discharge.

The collective agricultural management conducted under the People's Commune after 1949 promoted the development of farmland and water resources. Yet, Turpan's traditional Kareez irrigation system failed to support collective agriculture. The expansion of water demand led to the construction of irrigation canals and wells instead of Kareez. The rapid increase in well intake lowered the groundwater level, reducing the available volume of Kareez water.

4.2.2 Specific causes of decline in Kareez

The Kareez system in Turpan has a long history. Until 1960, Turpan relied heavily on Kareez for water for agricultural production and household use. But, as the development of water supply facilities and wells increased the intake from rivers and wells, the supply for underground water was reduced and the groundwater level fell. As a result, the water volume of the Kareez declined.

4.2.2.1 Unplanned placement of wells An increase in the volume of irrigation water was triggered by the expansion of farmland. From 1965, well water was used for irrigation. Kareez were also used, but their intake was insufficient to meet the irrigation demand because rainfall is scarce in early spring. For this reason, the role of wells in agriculture production gradually increased. Because the cost for a shallow well was small, many shallow wells were constructed haphazardly. As a consequence, underground water in near-surface aquifers was pumped up in large amounts, causing the gradual reduction of groundwater level in many wells and Kareez, which eventually invited the reduction and depletion of Kareez water.

4.2.2.2 Unplanned development of water resources Since dams and irrigation canals were developed in the ground surface river system and surface water was conducted to irrigation areas by applying concrete ducts in canals, water supply to Kareez has been reduced and the groundwater level has fallen.

4.2.2.3 Unreasonable water levies As water facilities were developed with great government subsidies, water rates became very cheap. Kareez construction and maintenance are cost- and labor-intensive. As a result, the rates for Kareez water became five times those for surface water, and more than twice those for well water. For this reason, people started using the cheaper surface water and lost the motivation to build and manage Kareez.

4.2.2.4 Kareez mismanagement As various water supply facilities were constructed after 1960, the water management authorities came to delegate the management of Kareez to villages. But the villages lacked funds to maintain them.

5 Conclusion

Kareez have long supported agricultural and dairy production as well as household life in the Turpan basin, and thus they are referred to in this region as "givers of life." It is evident that they will continue to play an important role in Turpan. Judging from the state of water resources in Turpan, there is little likelihood of successfully developing additional water resources. Effective use of the water resources that have already been developed should be given high priority and measures to economize water consumption should be reinforced.

In 1981, when the People's Commune system was discontinued, the farmland in Turpan was allocated to farming households according to the number of family members. Larger families received more farmland. Land ownership today averages 1,613.4 m^2 (2.42 Chinese acres) per person. The change in management system prompted more farming households to cultivate grapes, which brought a considerably higher profit per unit area (more than three times that for wheat), instantly producing problems in water demand. To deal with such problems, the local government restricted grape cultivation per farming household to 666.7 m^2 (1 Chinese acre). Yet, as grape cultivation still accounts for more than half of the irrigation water supplied (Table 1), measures to economize water consumption are a major task.

In addition to such measures, there is a need to introduce methods for irrigation water conservation, such as appropriate maintenance procedures for leakage prevention, proper and voluntary water management by farmers, and development and dissemination of efficient irrigation techniques.

The Kareez is a water supply system that is designed to achieve efficiency in a harsh natural environment. Its merits include energy saving owing to natural inflow, stable water volume, rotational use, and easy water management. How to maintain such an efficient water supply system, one that is part of the local culture, is an important issue to be addressed in terms of tangibles and intangibles.

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Allocation of flow to plots in pressurized irrigation distribution networks

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Abstract

The method of allocating flow to plots proposed by Clément and Galand (1979) has been revised. Mention is made of its drawbacks owing to the lack of consideration of the specific technical-economic factors of current pressurised irrigation systems (drip or sprinkler) in the plot. A method for fixed irrigation systems is proposed which, based on economic considerations, determines an optimum block area. Bearing in mind the method of irrigation in the plot, an allocation of constant flow is proposed up to a value of maximum surface area, and, from there on, a linear increase related to the plot area. A formula is also presented for calculating the maximum number of blocks from variables easily obtainable in the project phase.

Keywords: irrigation network, pressurized irrigation, allocation of flow.

1 Introduction

In the current context of high competition for water, there is a need for systems to allow an adequate control of this resource combined with easy management. A good solution is the use of pressurised irrigation distribution systems.

When engineers face the design of a distribution network, they start with different size plots that have to be supplied. The design problem consists of responding to the question of which flow to supply depending on the area of the plot. Once this question is solved, in the case of networks organised by demand, the probability of opening is calculated, and hence, the maximum flows in the network sections, for a specific frequency can be obtained through Clément's first formula [1,3]. The following step is the calculation of the diameters of the sections.

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Thus, the problem that concerns us is the allocation of flows to the plots. Being at the early phase of the process this has important repercussions on the final solution. Moreover, this allocation has a direct influence on the degree of satisfaction among the users.

This article is a revision of the Clément and Galand method [2], which is still used in some projects today, and a proposal for a new methodology for allocating supply discharges to the plots. The underlying idea of the method presented is to consider users' requirements, thus planning the network from the bottom up.

The basic equation that has to be fulfilled in an irrigation system is that the volume applied per unit of area, also called irrigation depth or irrigation dose (term on the left of eqn. 1), must be equal to the needs between irrigations (term on the right). The variables in this equation are not homogeneous, but, as they have the same units on both sides, the conversion factor is the same and thus is annulled.

$$q_{rg}\, t_{rg} = q_{fb}\, I_r\, 24 \tag{1}$$

where:

q_{rg} : Irrigation specific discharge, is the flow applied by the planned irrigation system per unit of area, in the case of sprinkler irrigation, it is equivalent to the average rainfall (l s^{-1} ha^{-1}).

t_{rg} : Application time, is the irrigation time to apply the depth (h).

q_{fb} : Continuous gross specific discharge. It expresses the needs plus the losses in form of flow per unit of area (l s^{-1} ha^{-1})

I_r : Irrigation interval, that is, the time between two irrigation (days).

The maximum discharge that could be supplied to a plot of a total area A_p is:

$$d_{max} = q_{rg}\, A_p \tag{2}$$

That is the flow that could be applied by the irrigation system.

The minimum discharge that could be supplied to a plot of a total area A_p is:

$$d_{min} = q_{fb}\, A_p \tag{3}$$

That is the flow to provide the needs.

Any supply discharge between these two could be assigned. Thus the allocation of the supply discharge in the plot is a problem that has no single solution but rather admits multiple proposals. However, as shown below, if various determining factors are taken into account, the optimum solution is fairly limited.

2 Clément and Galand's method

Clément and Galand [2] proposed the calculation of a supply specific discharge (q_p, l s^{-1} ha^{-1}) which is obtained by dividing the volume required during the irrigation interval by the available operating time of the hydrant in the plot (t_p) in the irrigation interval.

Another characteristic of the method is to set standard values for the discharges in the hydrant (2.78, 5.56 l/s…) conditioned by commercial availability on the market. Minimum and maximum plot areas are obtained for each standardised discharge by dividing the discharge by 1.2 q_p and 0.8 q_p respectively. That means leaving a range of variation of ±20 % for q_p. The result of this methodology is shown in figure 1.

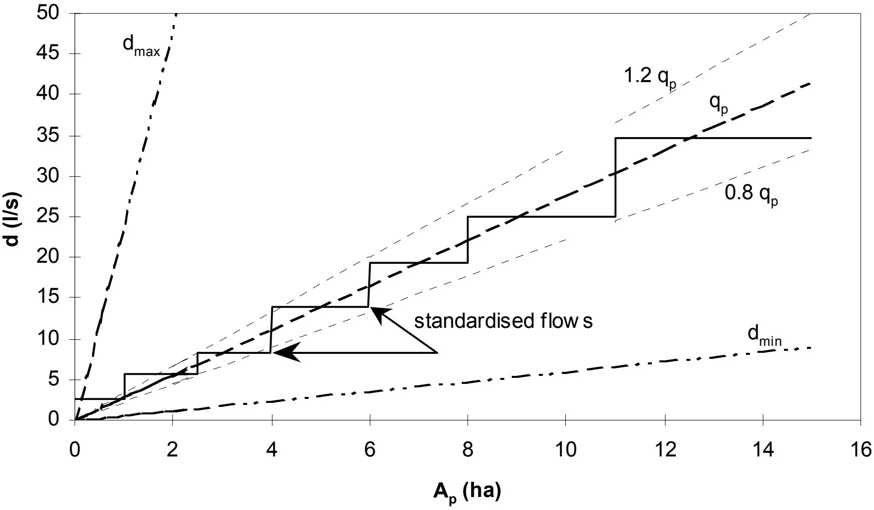

Figure 1: Allocation of discharge depending on plot area proposed by Clément and Galand.

Discussion of this methodology is presented below. The area that each farmer can irrigate simultaneously (Area of the block, S_b) is the quotient between the supply discharge (d) and the discharge consumed by the irrigation method per unit of area (q_{rg}). Thus, given that q_{rg} is constant, the area of the block S_b grows when d grows. This could be seen comparing figures 5 and 6, in which the steps in the Clement line are wider for larger plots (fig 6) than for smaller plots (fig 5). The increase in the size of the block with the area of the plot is not logical given that, as shown below, the size of the block relies more on economic factors than the size of the plot.

Another fact to emphasise is the high number of blocks that forces small plots to be made. For example in a plot of 1 ha (Fig. 5), 11 blocks must be made, which is not practical. A possible explanation for these results is that when this method was proposed, the systems were lateral hand-moved sprinkler irrigation and in this case the term block is equivalent to a lateral position, and thus an increase in the number of blocks meant that there were more changes of position but as there was time available between irrigations this was feasible. Nowadays, this technique has been abandoned in many countries owing to its high labour requirements and there is a tendency towards buried fixed systems. In this case, a valve is needed for each block, which means a very high cost. Moreover, nowadays the tendency is to irrigate at shorter intervals to increase the hydric comfort of the plant, which is not possible with moveable piping systems. For all these reasons, Clément and Galand's method does not seem recommendable for fixed systems.

We also believe that Clément and Galand's proposal to set standard flows (2.78, 5.56 l/s) was justified by the technology then available (calibrated orifices). However, current hydrant technology based on flow limit and pressure reducing hydraulic valves need not be conditioned by any specific flow as the limiters can be preset to any specified discharge.

3 Proposed method

The proposed method could be applied to fixed irrigation systems for both sprinkler and drip irrigation.

As mentioned above, when allocating the discharge to a plot, it is possible to provide the d_{max} (fig. 1) in such a way that the whole plot can be irrigated simultaneously. Given that this solution maximises the costs of the piping, it is not advisable, whether analysed at a network or plot level.

It is worth asking whether it is necessary to irrigate a plot simultaneously, or whether it can be divided into blocks (block is understood as the area of land irrigated at one time). When the block is very big could be divided into subunits, each of them with a pressure control valve), as a reduction in the simultaneous irrigated area means a reduction in discharge and thus of the diameters of the system.

A first question that arises when subdividing a plot into blocks is the optimum size of the block ($A_{b\ opt}$). Given that the division into blocks responds to economic criteria, the variation in the unit cost of the block (€/ha) depending on its size can be analysed. Figure 2 shows the variation of the relative unit costs of the block (over one) in relation to its size. To calculate these costs, the cost of the materials has been taken into account including the three main components of a block: laterals, manifold and control valve costs. The results presented correspond to a sprinkler irrigation set with laterals of 180 m fed from an intermediate point separated by 18 m, and 1550 l/h sprinklers every 18 m. Likewise, the cost of the manifold pipe has been counted with a variable diameter according to the size of the block, and the head valve. The contribution of each of the components (lateral, manifold and valve) has been broken down for each block area.

Figure 2 clearly shows that, in the case analysed, there is an optimum block area of 0.65 ha at which the unit cost is minimised, thus achieving a 30 % reduction of cost in comparison with the most expensive solution. Analysing the contribution of each item shows that the contribution of the laterals is constant, as the increase in cost grows linearly with area. The valve has a decreasing weight as its relative value decreases as the area increases. However, from 0.81 ha upwards, an increase is observed owing to the increase in the size of the valve and thus, its price. The contribution of the manifold rises as, when the area increases, so does the manifold diameter and thus its unit cost. The conclusion is that the decisive factor for establishing the optimum block area is the valve, as when a larger size has to be chosen, this means an important increase in unit cost. These conclusions can be extrapolated for any type of pressurised irrigation system.

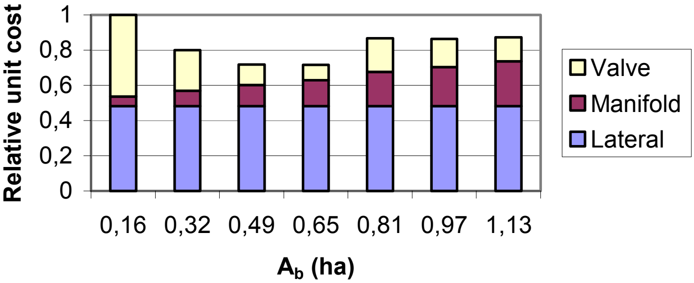

Figure 2: Variation of the relative unit cost of a block depending on its size for a sprinkler irrigation set.

The value of the optimum area will vary depending on the characteristics of the planned irrigation set. Thus it is advisable to calculate this for each specific case.

There are other costs not considered in this analysis, these include labour and trench excavation etc., which vary linearly with the area, thus their effect on the unit cost is constant. Another factor is the cost of the main and submain pipelines and control station, which will be higher the bigger the block is, which also supports the conclusion that there is an optimum block area with an intermediate value.

From the above, the number of blocks of a plot (n_b) can be calculated by rounding up the quotient $A_p/A_{b\,opt}$, and then,

$$A_b = A_p/n_b \tag{4}$$

The subdivision of a plot into blocks has a limit that derives from the availability of time between two consecutive irrigations (irrigation interval). Thus, it is important to calculate the maximum number of blocks ($n_{b\,max}$), which can be calculated as:

$$n_{b\,max} = \left[\frac{J_r}{t_{rg}}\right]_w \quad \left[I_r\, r_p\right]_w \tag{5}$$

where:

J_r, operating time, number of hours of irrigation per day.

r_p, operating ratio, quotient between operating days and the irrigation interval.

If in eqn (1), we find t_{rg} and substitute it in (5) then:

$$n_{b\ max} = \left[\frac{q_{rg} J_r\, r_p}{q_{fb}\, 24} \right]_w \tag{6}$$

Equation (6) is easier to apply than equation (5) as two variables, t_{rg} and $I_{r,}$ whose estimation involves a certain difficulty, have been eliminated. Moreover, the result must still be a whole number. Equation 6 shows the factors that allow $n_{b\ max}$ to be increased and those that make it decrease.

Considering the definition of q_{rg} (eqn (1)) and the partition on blocks (eqn (4), the supply flow in the plot will be:

$$d = q_{rg}\ A_b \tag{7}$$

The value resulting from equation (7) is significantly lower than the value of d_{max} mentioned above (eqn 2).

For very large plots, it may be that $n_b > n_{b\ max}$, which is not possible owing to the limitations on the time available between irrigations mentioned above. Thus, if we adopt $n_b = n_{b\ max}$, we will obtain values of $A_b > A_{b\ opt\ which}$ is possible hydraulically although it is not economically optimum. There is also the possibility of dividing a block into subunits (a subunit is understood as the lateral and manifold set fed by a pressure reduction valve), which may reduce the costs.

The results of the application of eqn (7) shows that the discharge allocation varies linearly with the area of the plot. There is a step when the number of blocks is increased, until the maximum number of blocks is reached. Then a constant slope is maintained. A drawback of this result is the wide variety of discharges obtained in depending on the area of the plot.

An alternative is that the plots between $A_{b\ opt}$ and $n_{b\ max}\ A_{b\ opt}$ have the possibility of making $A_{b\ opt}$ blocks. Applying these criteria would give figure 3, a much simpler application in work, but which supposes a certain oversizing of the network capacity. Continuing this idea of simplifying, the plots between 0 and $A_{b\ opt}$, could also be assigned $q_{rg}\ A_{b\ opt}$.

The above methodology is applied below to the case developed by Clément and Galand [2]. The starting data is: $q_{fb} = 0.6$ l s^{-1} ha^{-1}, irrigation operating time 16 h, 8 days of irrigation every 10, $r_p = 0.8$, irrigation specific discharge = 24.1 l s^{-1} ha^{-1}, optimum block area 0.5 ha.

Substituting in equation 6, $n_{b\ max} = 21$.

Figure 4 shows that the “proposed” assigned discharges for small plots are higher than those envisaged by Clément and Galand and, in contrast, for large plots the “proposed” assigned discharges are lower.

The reason for these differences can be observed in figures 5 and 6. As mentioned above, Clément and Galand’s method for small plots (fig 5) requires small blocks and thus a high number of blocks, which in principal, is not suitable for plots with fixed irrigation sets as it complicates the system.

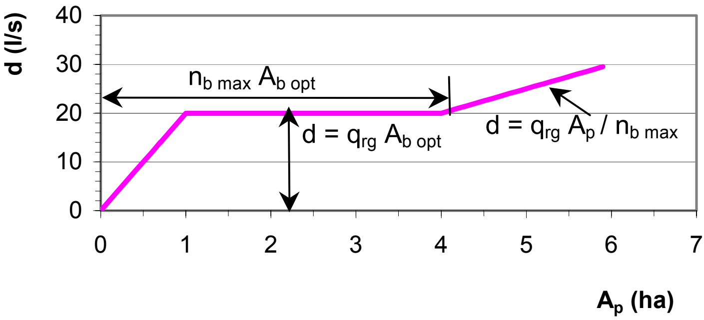

Figure 3: Allocation of discharge by plot area (q_{rg} = 20 l s^{-1} ha^{-1}, $A_{b\ opt}$ = 1 ha, $n_{b\ max}$ = 4).

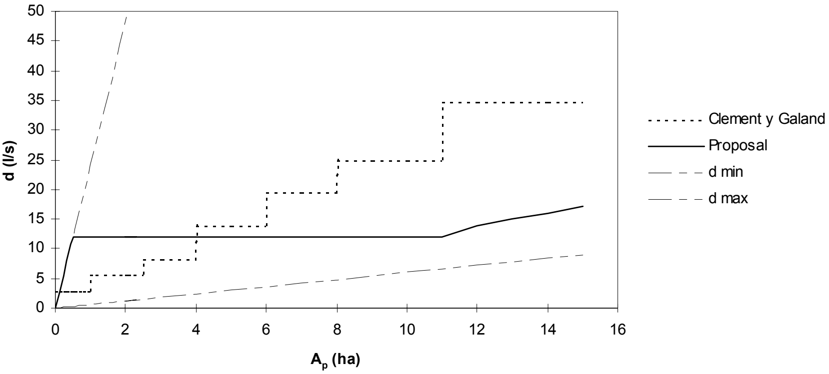

Figure 4: Comparison of the methodology proposed with that of Clément and Galand.

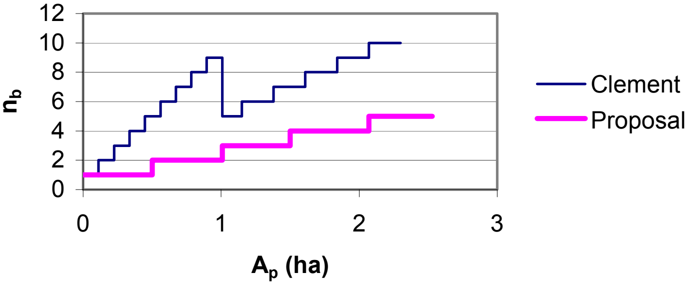

Figure 5: Number of blocks depending on plot size, for plots between 0 and 3 ha.

In contrast, for large plots (fig 6) Clément and Galand's method forces blocks to be created that are much larger than the economic size. This is illogical bearing in mind that the number of blocks can be increased up to 21 for the case studied.

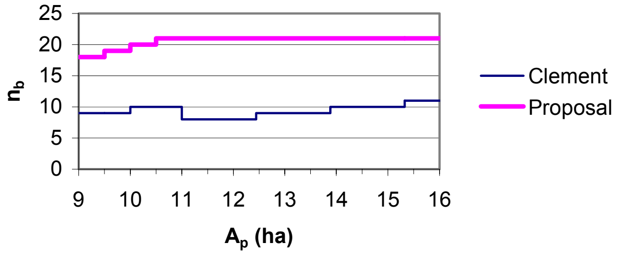

Figure 6: Number of blocks depending on plot size, for plots between 9 and 16 ha.

4 Conclusions

Clément and Galand's method for allocating flow to plots has the drawback of not being adjusted to the determining factors of fixed pressurised irrigation systems. For example, with this method, the block size depends on the area of the plot, while, as shown in this study, the economically optimum area of the block for a determined type of irrigation system has a specific fixed value. Another illogical result of this method is that the number of blocks for small plots is higher than for large plots.

Another fact is that nowadays, hydraulic valve technology with a flow limiter allows hydrants to be adjusted for any flow thus it is no longer necessary to establish standardised flows for hydrants as in Clément and Galand's method.

In the proposed method, the existence of a minimum cost block size is shown and which must be calculated for the main type of system that is envisaged. Thus, the flow to be supplied is that necessary for the planned irrigation method and the optimum area of the block. This results in the flow remaining constant independently of the size of the plot, as this is divided into blocks. When the maximum number of blocks is exceeded, the flow varies linearly with the area of the plot.

5 Notation

A_b = Area of the block (ha)
$A_{b\ opt}$ = economic optimum size of the block (ha)
A_p = Area of the plot, (ha)
d_{min} = minimum supply flow (l s^{-1})
d_{max} = maximum supply flow (l s^{-1})
I_r = irrigation interval (days)

J_r = operating time per day (h)
n_b = number of blocks
$n_{b\,max}$ = maximum number of blocks
q_{fb} = continuous gross specific discharge (l s^{-1} ha^{-1})
q_p = supply specific discharge (l s^{-1} ha^{-1})
q_{rg} = irrigation specific discharge (l s^{-1} ha^{-1})
r_p = operating ratio
t_{rg} = application time (h)
t_p = irrigation time in the plot (h)

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Assessing canal seepage and soil salinity using the electromagnetic remote sensing technology

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Abstract

Canal seepage and soil salinity are two major problems in irrigated areas of California's Central Valley, USA. Seepage is very common throughout the vast network of irrigation canals found in California. Most of these canals are earthen structures, where seepage contributes to the loss of millions of litres of water annually. Salinity problems are attributed to saline parent material, clayey soils, intensive irrigation, shallow water tables, and inadequate drainage that prevents the leaching of soluble salts. Several irrigation management practices, including sequential reuse of drainage waters within farm boundaries, are currently being tested in the region. Such practices are expected to reduce drainage volume, conserve irrigation water, and contribute to soil reclamation. Canal seepage and soil salinity can be assessed very accurately using the electromagnetic (EM) remote sensing technique. When coupled with a GPS and data logging capabilities, a mobilized EM system can provide automated and geo-referenced measurements over large areas. The study objectives were to locate seepage along irrigation canals and assess soil salinity in agricultural fields using the EM approach. Calibration of the EM data was performed following soil sampling. Samples were analyzed for electrical conductivity, texture, and moisture. Surface maps describing spatial distribution of these parameters were generated using GIS. The study suggested that the location of seepage could be detected rapidly and cost-effectively with the EM meter. The salinity assessment survey indicated that soil salinity levels ranged from 1 to 39 dS/m, with high spatial variability observed in most areas. Elevated salinity values were associated with poor drainage management. Growers and water agencies can utilize information from this study to develop water management and conservation strategies.

Keywords: canal seepage, soil salinity, electromagnetic induction, drainage.

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1 Introduction

Seepage from irrigation canals is a serious water management problem in California's San Joaquin Valley, USA. It is estimated that more than 600 million cubic meters of water are being lost every year. Seepage reduces irrigation efficiency and its water may contain toxic substances harmful to soils and ground waters. Additionally, water shortage is becoming a very important problem for California agriculture. Is it is forecasted that, by 2030, California's population will increase to 48 million people and the state will experience water shortages of 1.2 billion m^3 in average years and 4.8 billion m^3 in drought years [2]. These shortages will inevitably result in water reallocation to urban and industrial sectors, thereby posing a significant threat to the agriculture industry. Thus, it is important to identify tools that can help detect potential seepage along canals, thereby conserving irrigation water and sustaining crop productivity in the region.

High salinity is also a major water quality concern in many irrigated agricultural lands of California. Such salinity condition is attributed to a combination of factors including sedimentary parent material weathering, shallow saline water table (< 3 m), high agricultural water demand, inadequate drainage, and increased canal seepage. Excessive soil salinity can affect crop productivity, soil structure, and water quality. These salinity-related impacts eventually result in soil erosion and land degradation. Approximately 2 million hectares of the state irrigated farmlands are affected by saline soils or saline irrigation water [9]. Salinisation is particularly a threat in the San Joaquin Valley, where the daily net salt inflow into the region during the irrigation season is approximately 1.3 million tons [15]. Managing salinity and improving management of water resources therefore appears essential to sustain land quality and crop production.

Soil salinity is difficult to quantify because of rapid changes over space and time. Traditional measurement methods, such as four-electrode probes and soil sampling, require extensive data collection and laboratory analyses that are very slow, labour-intensive, and expensive [10]. The electromagnetic (EM) induction technique has become a very useful and cost-effective tool to monitor and diagnose soil salinity over large areas, because it allows for rapid and aboveground non-invasive measurements [7]. Additionally, EM sensors generally provide better and faster estimates of soil salinity than direct methods [16]. The EM instrument's transmitter coil induces an electromagnetic field in the ground, which in turn creates a secondary magnetic field that is measured by the receiver coil. The ratio of the primary and secondary electromagnetic fields provides a measure of the depth-weighted apparent electrical conductivity (EC) in a volume of soil below both coils [17]. Along with Global Positioning System data, the EM technique can provide geo-referenced distribution of soil EC (salinity) conditions in vast irrigated areas. Details on electromagnetic induction principles and soil conductivity measurements can be found in McNeill [11, 12]. Since EC of a soil is a function of its water content, salt content, and texture, the EM technique can also be very valuable for canal seepage assessment.

Researchers in Australia found the technology was effective for such detections [1]. Therefore, the objectives of this study was to assess seepage along irrigation canals and soil salinity in agricultural fields of Central California using remote sensing approaches, including electromagnetic induction (EM) technique and Global Positioning System (GPS).

2 Materials and methods

A Mobile Conductivity Assessment (MCA) system was developed at California State University, Fresno, to conduct extended canal and salinity surveys. The MCA system comprised four basic components mounted on a vehicle: (1) an EM induction sensor, (2) a global positioning system (GPS) receiver, (3) a computer, and (4) a hydraulic soil sampler. The EM sensor was placed in a plastic carrier-sled attached to the rear of the vehicle. The EM and GPS instruments were connected via digital interfaces to an on-board computer that simultaneously recorded the EM readings along with their geographical locations. Since EM measurements are relative, calibration of the data through soil sampling was necessary to obtain absolute soil moisture and salinity values. Optimal sampling plans were generated using the statistical package ESAP, specially developed to analyze the EM data [8].

2.1 Canal seepage assessment

The canal seepage survey was conducted at the Lost Hills Water District in the southern San Joaquin Valley. An unlined section of a canal, about 1200 m long, was selected for the study. The survey was performed when the canal was open and susceptible to seepage. The soil along the canal was a clay loam with increasing clay content with depth.

The EM and GPS data were recorded from four traverses parallel to water flow on each side of the canal. The survey was conducted at a speed of about 6 km/h, with readings taken every 2.5 s. The sensor used in this survey was an EM-31 meter (Geonics Limited, Ontario, Canada) that measured soil EC and indirectly moisture down to a depth of 3 m. The EM-31 operates at a frequency of 9.8 kHz and has a fixed inter-coil spacing of 3.7 m.

Optimal sampling plan consisted of six locations characterizing the spatial distribution of EM readings along the canal. At these sites, soil samples were collected in 0.3 m increments to a depth of 2.7 m using the hydraulic sampler. Soil water content was determined on these samples, following standard analytical methods [6, 14]. Estimates of soil water content were then obtained for the entire survey area using ESAP. Contour maps showing the soil water distribution down to 2.7 m were generated with the ArcGIS software [3].

2.2 Soil salinity assessment

The soil salinity surveys were conducted in 2004 on a farmland located south of Fresno in the Central San Joaquin Valley. The site was chosen because it served as a leading demonstration project on sequential drainage water reuse for the

Westside San Joaquin Valley. The soil in the study area is classified as an oxalic silty clay loam with a well-developed salinity profile. The entire farmland is drained with subsurface plastic tiles installed at 2.5 to 3 m depth and spaced every 80 to 90 m. In this reclamation project, drainage water (DW) is reused three times to irrigate crops of increasing salinity tolerance. Good quality canal water is first used to irrigate high value crops (Area A), fig.1. Then, drainage water collected from A is applied to salt tolerant crops (Area B) and drainage from B is applied to salt tolerant forages (Area C). Area D receives the highly saline drainage water collected from C. Overall benefits of drainage reuse practices are detailed in Grattan and Oster [4], Kaffka et al. [5], and Oster and Grattan [13].

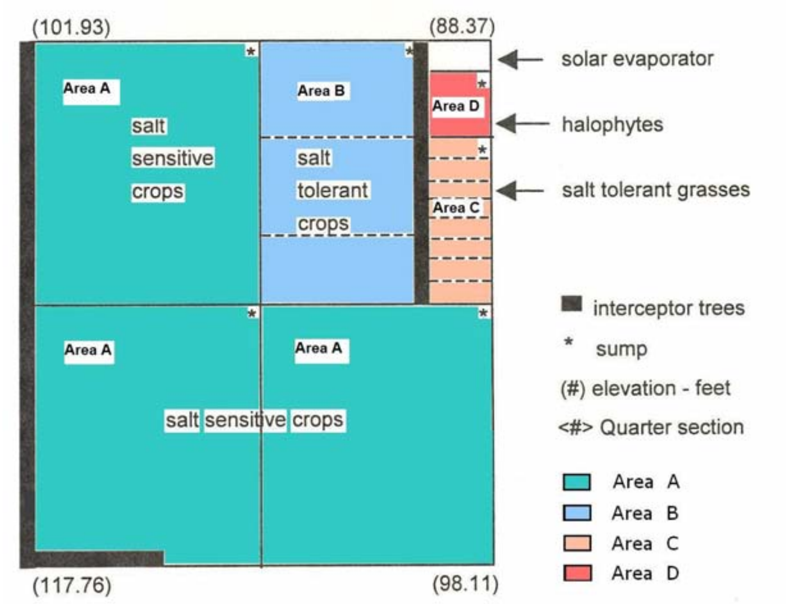

Figure 1: Schematic of drainage reuse system implemented at study site.

The EM measurements were taken in the four areas (A: tomato-wheat, B: grass- wildrye, C: salt tolerant forages- wheatgrass, D: halophytes- saltgrass, salicornia), which successively received reused DW. In each field, the EM and GPS data were collected along transects spaced 24 m apart; measurements were taken every 12 m along transects. The EM instrument used in this study was the EM-38 dual dipole. The device was operated in both horizontal and vertical positions at the soil surface to obtain effective measurement depths of 0.9 m and 1.8 m, respectively. The instrument operates at a frequency of 14.6 kHz and has a fixed inter-coil spacing of 1 m.

Depending on the field size, six or twelve sites characterizing the spatial distribution of EC across each field were selected for calibration. At these sites, soil samples were collected in 0.30 m increments to a depth of 1.5 m. Electrical conductivity (1:1 soil:water extracts), moisture, and saturation percentage were determined on these samples, following standard analytical methods [14]. Soil salinity for the entire survey area was then estimated using ESAP. Contour maps showing the salinity distribution on all fields were generated with ArcGIS [3] using kriging interpolation.

3 Results and discussion

3.1 Canal seepage assessment

Contour maps showing the soil moisture distribution along the canal at different profile depths are presented in fig. 2.

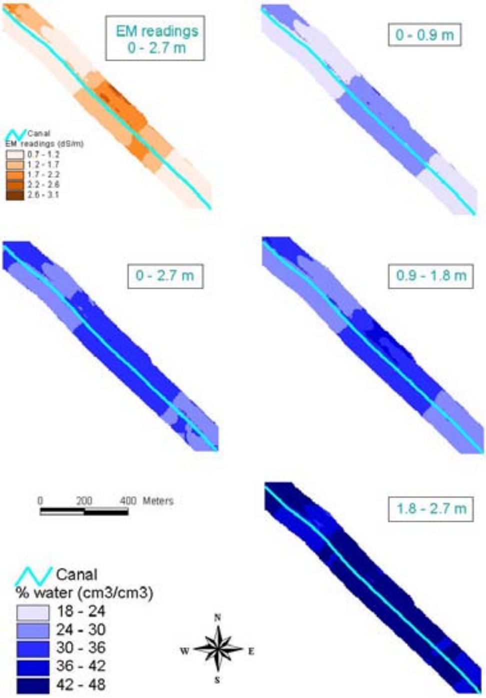

Figure 2: Soil moisture distribution along canal.

The results from the canal seepage survey indicated that soil water content was lowest near the surface (0–0.9 m) with values ranging from 20 to 30%. The maps also showed that water content increased with depth. The 1.8–2.7 m profile had the highest moisture levels (up to 48 cm^3/cm^3) due to the presence of water table at those depths. In the upper soil profile (0–1.8 m), water content was greater in the mid-section and north-east segment of the canal. Higher soil water content was indicative of potential seepage. Water loss in that section of the canal was also observed by the Irrigation District. The overall results of such study and the contour maps can be useful in determining the exact location of seepage as well as improving water management and conservation strategies along irrigation canals.

3.2 Soil salinity assessment

The results indicated that the vertical to horizontal EM signal correlations were very high ($r > 0.97$) in fields covering areas A, B, and C. Correlations in area D ($r = 0.75$) were lower due to the important variability in salinity observed across the profile depths. In each area, the correlations between measured EC and estimated salinity data were above 0.85, suggesting a high degree of survey reliability for salinity estimation. Basics statistics on the salinity levels predicted by ESAP across the farmland are presented in Table 1.

Table 1: Statistics of soil salinity data (dS/m) estimated in all areas of farmland.

Area	Depth (m)	Mean	Standard deviation	Minimum	Maximum	n
A	0–0.3	1.77	1.00	0.38	14.0	6780
	0.3–0.6	3.34	2.25	0.09	17.5	
	0.6–0.9	4.56	2.19	0.27	15.3	
	0.9–1.2	4.70	1.90	0.42	17.4	
	1.2–1.5	4.96	1.69	0.67	14.1	
B	0–0.3	6.34	1.17	0.34	17.8	1896
	0.3–0.6	8.63	1.06	1.30	19.9	
	0.6–0.9	9.62	1.46	2.29	20.2	
	0.9–1.2	9.47	1.33	4.06	14.4	
	1.2–1.5	8.71	1.20	4.27	20.2	
C	0–0.3	10.4	4.23	7.52	33.8	207
	0.3–0.6	9.42	3.01	7.28	24.8	
	0.6–0.9	9.70	5.62	6.14	38.6	
	0.9–1.2	9.14	4.46	6.32	31.8	
	1.2–1.5	8.12	2.63	6.29	19.6	
D	0–0.3	15.7	0.04	15.6	15.9	130
	0.3–0.6	16.9	0.21	16.1	17.4	
	0.6–0.9	15.7	0.26	15.1	16.7	
	0.9–1.2	14.6	0.39	13.2	15.6	
	1.2–1.5	10.5	0.96	7.22	13.0	

The mean soil salinity levels in area A ranged from 2 to 5 dS/m and increased with depth, which is indicative of good drainage management and leaching of salts through the profile. In area B, higher mean salinity was observed (6–10 dS/m), although maximum values were similar to those found in areas A. Mean salinity levels in area C ranged from 8 to 10 dS/m; however very high values were detected in part of the field. Mean soil salinity was highest in area D, ranging from 11 to 17 dS/m, and decreasing with depth. This inverted soil profile was explained by the very high salt concentration in the drainage water applied to that area.

The contour maps representing the average salinity levels in the 0–1.5 m profile are shown in fig. 3 for the entire surveyed farmland. These maps illustrate the drainage management practices performed on the farm. The lowest salt amounts (< 10 dS/m) were observed in areas A where fresh canal water was applied to the fields, whereas area D which received the third reuse drainage water, exhibited the highest salinity levels (12–18 dS/m). Salinity levels increased from south to north in area B, indicating that the northern portion is suffering from a more pronounced salinity problem and that the southern part is slowly being reclaimed. Area C showed high variability in soil salinity (8–18 dS/m). When compared with maps generated in previous years, soil salinity levels decreased in areas A and B, suggesting the benefits of the sequential drainage reuse practices.

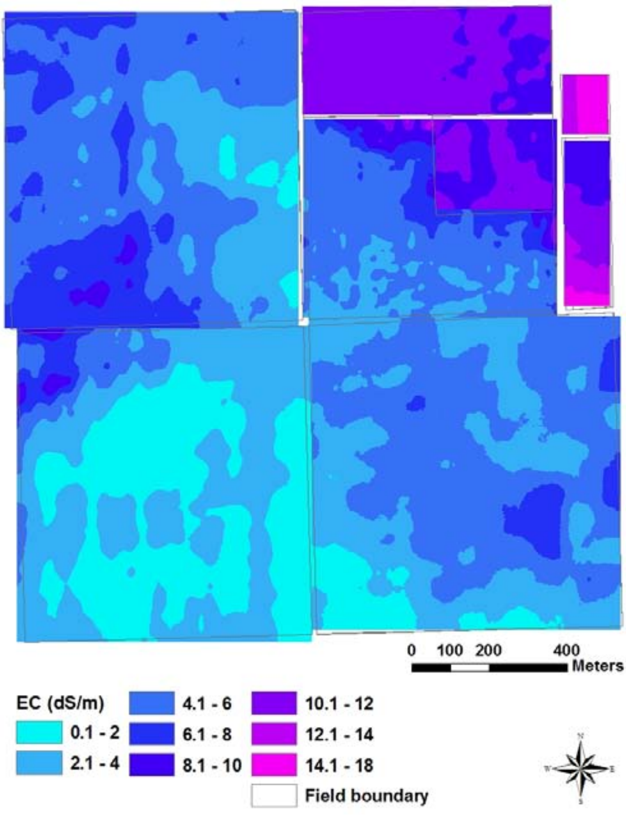

Figure 3: Average salinity distribution (0–1.5 m) on the surveyed farmland.

4 Conclusions

The purpose of the study was to characterize the distribution and variability of EM induction measurements for canal seepage detection and salinity assessment on irrigated lands. The surveys demonstrated that the EM technique had great potential for quick evaluation of soil properties over large areas and was a cost-effective alternative to extensive sampling. Data obtained from the canal surveys can aid in financial decision making by providing information on the extent of canal seepage and need of canal lining. Soil salinity surveys can help in giving recommendations for suitable cropping systems and application of precision farming practices. Overall, this research shows that canal seepage and salinity assessment studies are very valuable tools for improving water management and conservation strategies in salt-affected lands and along canal banks of Central California.

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Is drip irrigation sustainable in the salt affected soil of the San Joaquin Valley of California?

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Abstract

Many areas along the west side of the San Joaquin Valley of California are affected by saline soil due to shallow, saline ground water conditions. Artificial subsurface drainage is not an option for addressing the salinity problem because of the lack of drainage water disposal facilities. Thus, the salinity/drainage problem of the valley must be addressed through improved irrigation practices such as converting to drip irrigation. The effect of drip irrigation on processing tomato yield and quality, soil salinity, soil water content, and water table depth was evaluated in four commercial fields located in the San Joaquin Valley of California, USA. Results showed drip irrigation of processing tomatoes to be highly profitable under these conditions compared to sprinkle irrigation. No trend in tomato yield was found with soil salinity levels. While a water balance showed little or no field-wide leaching, soil salinity data clearly showed localized leaching around the drip lines.

Keywords: drip irrigation, processing tomatoes, soil salinity, water table, subsurface drip irrigation, leaching, saline, ground water, tomato, salinity.

1 Introduction

About 1 million ha of irrigated land are affected by saline, shallow ground water conditions along the west side of the San Joaquin Valley. Upward flow of the shallow groundwater has resulted in excessive levels of root-zone soil salinity. The traditional approach to dealing with shallow ground water problems is to install subsurface drainage systems for water table control and improved leaching, but the proper operation of these drainage systems requires disposal of the subsurface drainage water. No economically, technically, and

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environmentally feasible drain water disposal method exists for the San Joaquin Valley, and thus, the drainage problem must be addressed through options such as better management of irrigation water to reduce drainage below the root zone, increasing crop water use of the shallow groundwater without any yield reductions, and drainage water reuse for irrigation [1]. One option for improving irrigation water management is to convert from furrow or sprinkler irrigation to drip irrigation.

Drip irrigation can apply water both precisely and uniformly compared with furrow and sprinkler irrigation resulting in the potential to reduce subsurface drainage, control soil salinity, and increase yield. The main disadvantage of drip irrigation is its cost, which based on grower experience can be as much as \$2,470/ha. For drip irrigation to be at least as profitable as the other irrigation methods, more revenue from higher yields and reduced irrigation and cultural costs must occur. Yet, several large-scale comparisons of furrow and drip irrigation of cotton revealed uncertainty in the economic benefits of drip irrigation [2,3]. Thus, growers converting to drip irrigation face uncertainty about the economic risks involved.

Subsurface drip irrigation of processing tomatoes was evaluated to determine its effect on crop yield and quality, soil salinity, water table depth, and profitability in salt-affected, fine-textured soil underlain by saline, shallow groundwater. Because tomatoes are a high cash value crop, a better potential for increased profitability with drip irrigation exists compared to cotton. However, tomatoes are much more sensitive to soil salinity, which could result in reduced crop yields in salt-affected soil.

2 Methods and materials

Experiments in three commercial fields involved comparing subsurface drip irrigation of processing tomatoes with sprinkle irrigation under saline, shallow ground water conditions [4]. Drip irrigation systems ranged from 16 ha to 32 ha in size. Field length was 400 m. Drip lines were buried 0.2 to 0.305 m deep, depending on the field. Drip irrigations occurred every two to three days. At one field, water table depths were about 2 m, while at the other two fields, water table depths generally ranged between 0.5 m and 1 m. The electrical conductivity (EC) of the irrigation water was about 0.30 to 0.35 dS m^{-1} at two fields, and was 1.06 to 1.2 dS m^{-1} at the third field. The EC of the shallow ground water ranged from 4.7 dS m^{-1} to 16.4 dS m^{-1}, depending on the particular field and time of year. Soil type was clay loam at the three sites. In addition, a small-plot randomized replicated experiment was superimposed on each drip system with irrigation treatments consisting of different amounts of irrigation water to determine the minimum amount of water that can be applied under saline, shallow ground water conditions without reducing crop yield.

At the fourth commercial field, a small-scale randomized replicated experiment was conducted under conditions of very shallow ground water, with water table depths between 0.45 m and 0.61 m. Treatments consisted of different amounts of applied irrigation water. Drip irrigations occurred daily. The electrical conductivity of the irrigation water was 0.52 dS m^{-1}. The electrical conductivity of the shallow ground water ranged from 8 to 11 dS m^{-1}.

3 Results and discussion

Over a three-year period, the yields of the three large-scale subsurface drip systems were 12.1 Mg ha^{-1} to 22.6 Mg ha^{-1} higher than those of sprinkle irrigation [4]. The average yield of three drip-irrigated fields was 93.7 Mg ha^{-1} compared to 74.8 Mg ha^{-1} under sprinkle irrigation. The average yield difference between the irrigation methods was statistically significant (t-test, $\alpha = 0.05$). The small plot experiment showed tomato yield to decrease as applied water decreased. Tomato yield was unaffected by the range of soil salinity in these fields, which in one field, exceeded the threshold soil salinity of tomatoes of 2.5 dS m^{-1}. (The threshold soil salinity, expressed as the electrical conductivity of the saturated extract, is the maximum root zone soil salinity at which no yield reductions occur.) The average difference in soluble solids between the two irrigation methods was not statistically significant. However, the small plot experiment showed soluble solids to increase as applied water decreased. Based on a crop price of \$55 Mg^{-1}, drip irrigation increased profits by \$1284 Mg^{-1} compared to sprinkle irrigation.

At the fourth site, the small-scale randomized replicated experiment showed tomato yield to range from 77.5 Mg ha^{-1} for 396 mm of applied water to 95.9 Mg ha^{-1} for 589 mm of water. The regression between yield and applied water was highly significant at a level of significance of 0.05 ($P = 0.0008$). Soil salinity at this field exceeded the threshold soil salinity.

Soil salinity around drip lines was found to depend on the depth to the ground water, salinity of the shallow ground water, salinity of the irrigation water, and amount of applied water. For water table depths of 2 m, soil salinity (expressed as the EC of a saturated extract) was smaller than the threshold salinity and was distributed relatively uniformly around the drip line (Fig. 1A). For water table depths of less than 1 m, soil salinity varied considerably around drip lines with the smallest levels near the drip line and high values near the periphery of the wetted volume (Fig. 1B). Higher values of soil salinity occurred near the drip line for the field using the higher EC irrigation water (Fig. 1C).

The key to the profitability and sustainability of drip irrigation of tomatoes in the valley's salt affected soils is salinity control. Salinity control requires leaching or flushing of salts from the root zone by applying irrigation water in excess of the soil moisture depletion. The leaching fraction, defined as the percent of applied water that percolates below the root zone, is used to quantify the amount of leaching. For sprinkle and furrow irrigation, the field-wide leaching fraction historically has been calculated as the difference between the seasonal amount of applied water and the seasonal crop evapotranspiration.

It was concluded that because of salinization issues, sustainable agriculture may not be possible in these salt affected soils of the valley, based on a regional salt balance assessment which showed salt imports into the valley to exceed salt exports [5]. Data from these experiments showed that based on the historical approach to calculating leaching fractions, little or no field-wide leaching occurred, which appears to support this conclusion. Yet, considerable localized leaching occurred around the drip lines, as seen in Fig. 1. The higher the amount of applied water, the higher the localized leaching around the drip line, as evidenced by the larger zone of low salt soil for 589 mm of applied water compared to 397 mm of water (Fig. 2). This localized leaching appears to be the main contributor to the high yields previously mentioned. Thus, the historical approach to estimating leaching fractions may be inappropriate for drip irrigation. However, it is difficult to estimate the localized leaching fraction under drip irrigation because leaching fraction, soil salinity, soil moisture content, and root density all vary with distance and depth around drip lines.

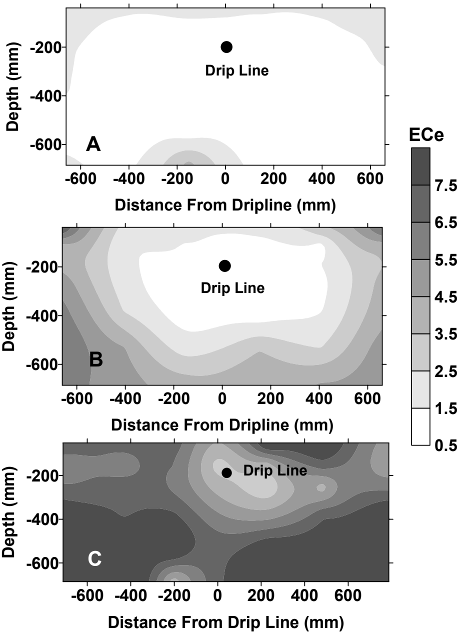

Figure 1: Patterns of soil salinity around drip lines for (A) an average water table depth of 2 m and an EC of the irrigation water equal to 0.3 dS m^{-1}; (B) a water table depth between 0.61 and 1 m and an EC of the irrigation water equal to 0.3 dS m^{-1}, and (C) a water table depth between 0.61 and 1 m and an EC of the irrigation water equal to 1.1 dS m^{-1}.

4 Conclusions

From a macroscopic viewpoint based on a field-wide or regional basis, a sustainable agriculture may not be possible in the valley's saline soils because of an apparent lack of leaching. However, from a microscopic viewpoint (root zone around drip lines), substantial localized leaching occurred, even under severe saline conditions, and thus, a sustainable agriculture may be possible with drip irrigation. Based on these experiments, the following are recommended for successful drip irrigation of processing tomatoes under saline shallow ground water conditions:

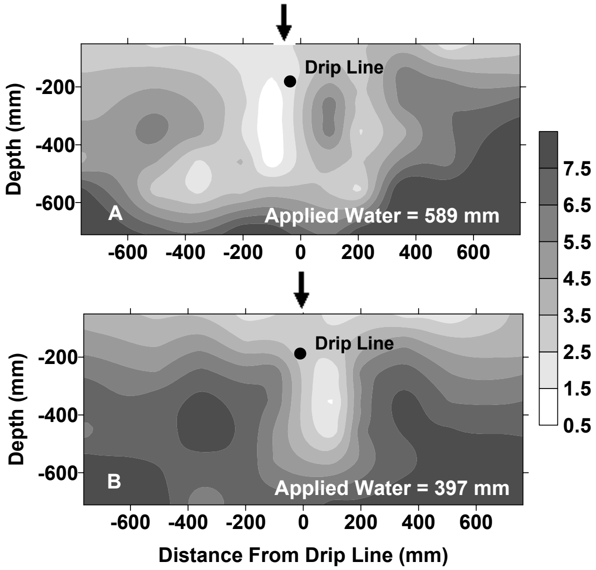

Figure 2: Effect of amount of applied irrigation water on the patterns of soil salinity around the drip line.

- Sufficient leaching must occur near drip lines to maintain profitable yields.

- Salinity of the irrigation water should be less than 1.1 dS m^{-1}.

- Seasonal water applications should be about equal to the seasonal crop water use. This water application appears to provide sufficient localized leaching. Higher applications could raise the water table; smaller applications could decrease tomato yield due to reduced leaching and possibly, decreased soil moisture content.

- Drip irrigation systems must be designed for high field-wide uniformity of applied water.

- Periodic leaching of salt accumulated above the buried drip lines will be necessary with sprinklers for stand establishment if winter and spring rainfall is insufficient to leach the salts.

- Periodic system maintenance must be performed to prevent clogging of drip lines. Clogging will not only reduce the applied water needed for crop ET, but also reduce the leaching.

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Managing salinity in degraded soils by mandatory tree planting: on dynamics and economic modeling of a common pool resource

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Abstract

Many farming areas in the semi-arid tropics and sub-tropics are characterized by increasing salinity. Due to (1) the common property problem of the media, water, (2) high transaction costs in soil protection and (3) non-point-pollution problems, salinity is a common feature of poorly managed irrigation schemes. Environmental regulations, governing water use, and farm practices such as (1) limitations in water dosage, (2) specific plants mixes, etc., but also (3) regeneration of soils, by methods such as (4) fallowing, (5) tree planting, (6) applying gypsum, etc., are normally not in the direct interest of small-holder farmers. Such measures reduce current income and future benefits have to be shared. In contrast as a new idea, tree planting to extract salt and minimize shocks from droughts have gained the interest of salinity management, notably as a low cost and appropriate technology solution. This paper presents an innovative model that accounts for salinity in the short and long run; introduces mandatory tree planting to farmers for salinity reduction; and reckons current income waivers from reduced cropping for trees. A dynamic concept is used to control farm activities and cater for a reduction of salinity in communities. It models water tables, tree cover and salt content.

Keywords: tree planting, salinity, dynamic optimization.

1 Introduction

In irrigation projects the salinity of soils is a serious and complex problem for resource economics [1]. Salinity threatens agricultural production in many areas of the tropics and subtropics. Though gypsum application and leaching are possible treatments [2] they are mostly too expensive for farmers. However, salinity may change through soil improvements associated with fallowing and

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tree planting. Salinity is a non-point pollution problem, specifically in communities that share the soil as a common-pool property. A common property management problem therefore emerges. Tree planting seem to be not only a technical thing [3], rather it needs cooperation of farmers. Common property and tree planting management, together, should be viewed as interwoven tools for salinity control. The task is to extract salt from saline soils so that improvement occurs and costs of desalinization are minimized. The management and cleaning of a saline area, as to be understood in this paper, is a co-management consisting of long run benefits from reduced salt inflows and short run costs from restrictions in land use, detected as strips planted with trees [4]. Costs include planting and costs of cutting trees, and water evaporated by trees. Benefits include firewood and fruits.

The questions [5] are, (1) how soils improve, if a public will exists and optimizes actions; (2) how to implement public management; and how (3) to minimize free-riding as strategy. Also, what are ecological prerequisites, economic incentives and institutional needs to achieve improvements? For this and the purposes of the paper, a few assumptions are in order, (1) that an irrigation scheme, given a certain tree cover, has a potential to reduce salt, though only to a certain extent and a long run perspective is needed; (2) farmers have an interest in soil quality; (3) an institutional setting is agreed upon which solves problems of non-point pollution and common property; (4) in principle, we will hand over the task of improving soils to a common-pool property manager, whose task is to reduce the negative externality of salinity; and (5) the manager will be given the right to allocate trees. Then s/he maximizes social welfare, i.e. being a benevolent dictator.

It is the prime objective of the paper to show how tree planting can be an alternative to unsustainable practices. The method suggested is a dynamic economy model which depicts several small-scale farmers. The paper is organized in four sections. In Section 2 we will look at the dynamics of salinity. In section 3 we will state farmers' objective functions concerning waivers on land use. Section 4 will use this information to explore the dynamic behavior of tree growth, and in section 5 a control theory model shows how a particular soil improvement can occur.

2 Dynamics of soil and land set-aside in smallholder agriculture

The quality of the soil in a watershed or irrigation system shall be described by an index that measures the negative impact of salinity on the productivity of soils. As discussed elsewhere [1], a decline in soil quality associated with salinity has several implications for soils and farm productivity. Fundamentally soils are a public good and salinity is shared by farmers. The concentration of sodium can be used as a measurable variable for salinity; in principle sodium is accepted as major quantitative contributor to soil quality decline [2]. Sodium contents can change, and are subject to accumulation. This accumulation is stimulated by three components, (1) irrigation water use, (2) rise of water table, and (3) fertilization of the watershed. Farmers do not see salinity as non-point-pollution; for them it is only a by-product of irrigation. To present the dynamics of salinity in conjunction with farm activities and deduction of salty nutrients, we, as scientists, can use a first order differential equation (1) for the change of soil quality. We explicitly recognize land allocation for trees; i.e. tree planting is on land set-aside by farms.

$$\dot{S}(t) = -\kappa_0 S(t) + \kappa_1 W(t) + \kappa_2 [\sum_j (A^t - A_j)] + \kappa_3 [O^0 - O(t)] - \kappa_4 l^l(t) \quad (1)$$

Broadly, equation (1) recognises the dynamics of salinity S(t) as dependent on the water table “W”, land allocation "A" and organic matter "0". Land allocation, as one part, describes farming activity by area under crops (A-ΣA_j) and area set-aside (A, as second part). An explanation for the water table will follow later. Organics are given by area times stand of trees which changes equation (1) to (1’)

$$\Leftrightarrow \dot{S}(t) = -\kappa_0 S(t) + \kappa_1 W(t) + \kappa_2 \sum_j [A^t - A_j] + \kappa_3 [F^0 \cdot A^0 - F(t) \cdot A(t)] - \kappa_4 l^l(t) \quad (1')$$

where S(t): soil quality index (sodium) at time t (can be sodium content: natural decrease)

W(t): water table at time t (increase)

A^t-A_j(t): polluting acreage of farmers at given technology, i.e. irrigation use (increase)

O(t): organic matter by growth in matter per hectare on communal fallow (decrease)

A(t): area under fallow of each farmer (decrease)

l^l(t): deliberate used water for leaching of water to combat salinity (decrease)

F(t): organic matter per hectare

A^0: steady state fallow stand to offset salinity

Equation (1’) describes a natural system, whereby salinity diminishes by natural leaching of soils due to rainfall, low water tables, etc. Vegetation is an amplifying measure for salt reduction. Upper and lower boundaries are specified for S. Presuming that decreasing salinity is associated with increasing prevalence of trees in the area, a first order differential equation with a coefficient of "κ" below 1 implies that the soil is still capable of improving itself. Land set-aside plays a major role. For instance, presuming an approachable constant level of salinity at a certain size of natural vegetation, the value of "A^0" can specify the steady state situation. Lowest salinity, from a modeling point of view is the steady state under the condition "$\kappa_2(A^0-A(T))/\kappa_0$", apparently, without agricultural use. Natural tree cover "A^0" can be used for calibration of the lower bound of lowest salinity (upper end of soil quality). Special cases can be distinguished beside the natural situation. In the case of no land set-aside, "A=0", farmland is maximized. This means apparently the model would move to an upper point of salinity ($\kappa_1[\Sigma A^*_j-A^0]+\kappa_2 A^0)/\kappa_0$".

Equation (1’) is connected with the water table. By water infiltration, soils show, depending on local conditions, changes (rise) in water tables (after years of use).

$$\dot{W}(t)=\zeta_0+\zeta_1 W(t)+\zeta_2[\sum_i(1-z)l_j]+\zeta_3[F^0\cdot A^0-F(t)\cdot A(t)]$$
$$-\zeta_4 F(t)\cdot A(t)+l_m^l(t)-l_m^p(t) \tag{2}$$

where additionally: l(t): water not used in plant production, retained in soils at farm j in time t
Z: technical factor on leaching
$l^l(t)$: leaching water to clean surface soils from salt on a hectare basis
$l^p(t)$: water pumped out of the system with special technical devices
ζ_0: threshold of water table

In equation (2) inflows from leaching, evaporation by trees, and additionally a policy variable such as pumping groundwater change the table. We also assume a natural outflow given as an autonomous change of the system, and consider the possibility of making the function linear to distinguish water and land allocation:

$$\dot{W}(t)=\zeta_0+\zeta_1 W(t)+\zeta_2(1-z)\sum_i[l^0[A^t-A_j]+[A^t-A_j^0]l_j]$$
$$+\zeta_3[F^0\cdot A(t)-A^0\cdot F(t)]-\zeta_4 F(t)\cdot A(t)+l_m^l(t)-l_m^p(t) \tag{2'}$$

Next, organic matter content that perhaps does absorb salt and improves soil fertility is seen as a dynamic process. Organic matter, as quantity standing ready for extraction, supports desalinization of soils by filtering salt out of water. The filter potential is determined by the size of the biomass. Biomass enters our dynamic function (1'), and it is influenced by the water table. Loss or enrichment (change) of bio-mass "O" is due to cutting of trees by farmer j on set-aside land $a_j(t)$. Finally building up organic matter (1) is described by a differential equation (3):

$$\dot{O}(t)=-\varphi_0 O(t)+\varphi_1\sum_j a_j(t)-\varphi_2\sum_j u_j(t)+\varphi_3 W(t) \tag{3}$$

As stated above, organics O are qualified as land set-aside multiplied by stands of trees per hectare "F" and area measured as hectare "A": That is, O=F·A. It follows:

$$[\mathrm{F}(\mathrm{t})\cdot\dot{\mathrm{A}}(\mathrm{t})]=\varphi_0[\mathrm{F}(\mathrm{t})\cdot\mathrm{A}(\mathrm{t})]-\varphi_1\sum\mathrm{a}_\mathrm{j}(\mathrm{t})+\varphi_2\sum\mathrm{u}_\mathrm{j}(\mathrm{t})+\varphi_3\mathrm{W}(\mathrm{t}) \tag{3'}$$

where additionally a_j (t): individual cutting of bush and tree land set-aside: optimized
u_j (t): individual new set aside of small-holders to bush: mandatory regulated

After a calculus intended to reduce complexity and to focus on area in land set-aside, and in particular assuming a constant growth of the existing trees, we get;

$$F(t)\cdot\dot{A}(t)+\dot{F}(t)\cdot A(t)=-\varphi_0[F\cdot A(t)]+\varphi_1\sum_j a_j(t)-\varphi_2\sum_j u_j(t)+\varphi_3 W(t) \tag{3''}$$

$$\dot{A}(t)=[\varphi_0-\xi]A(t)+\varphi_2\sum_j a_j(t)-\varphi_2^*\sum_j u_j(t)+1/F_0\, e^{-\xi\cdot t}+\varphi_3 W(t) \tag{3'''}$$

Also, as revealed in equation (3'''), the initial expression of the dynamic condition (3) depicts collective action of communities; i.e. collectively decided adding of trees on land set-aside from farm land u_j. whereas cutting and use of wood are private. Farmers make decisions a_j -calculating statuses (benefits of cutting) of common pool- from which a negative externality, salinity, is derived as a stock.

3 The farmers' objective functions

The economic analysis starts with conditional farm behavior, since this provides the basis for the manager. The focus is on land use and cutting trees. The applied micro-theory is similar to Varian [6]. It focuses on constrained profit functions. With salinity, we distinguish between farming on a remaining field and afforested land. Farmers lose profits on set-aside land; see negative effects of regulating land use. Positive effects of setting aside land (e.g. higher local humidity and yields) appear, but should be distinguished from common property management. The adjusted total profit is calculated using crop yields and gross margins on farm j. The policy variable, tree planting "u_j", might stretch as strip between fields. Combating salinity, a farmer, j, shall recognize salinity in the watershed as a public, given a profit function "$P=P(A_j,a_j,u_j,S)$". Salinity "S" is a negative common property. Land set-aside appears because tree cover already improves the micro-climate. All individual farmers work with a time horizon "T" and discount "ρ".

$$\mathrm{P_j[0,T]} = \int_o^T e^{-\rho t}\{P(A_j(t),a_j(t),u_j(t),S(t))\}dt \tag{4}$$

where additionally: P(t): profit at time t

The profit function needs an explicit specification of (1) land allocation, (2) gross margins, (3) waiver on land use, and (4) recognition of profits from commons.

$$\mathrm{P_j[0,T]} = \int_o^T e^{-\rho t}\{p_j^a d_j^*[A_j^0 - A_j(t)]$$

$$+p_j^f a_j(t) - C(d_j[A_j^0 - A_j(t)], a_j(t), r(t), S(t), A_j(t), u_j(t), z_j)\}dt \tag{4'}$$

where additionally: increase: "⇑" and decrease "⇓":

p^a = gross margins/hectare according to yields per hectare in agriculture, (profit⇑)
p^f = gross margins per ton in sales of fallow products from tree cutting, (profit⇑)
r^f = water price, (cost⇑)
d_j = yields per hectare including size of the field, (profit⇑)
$(A_0$-$A_j)$ = acreage as area cropped, (profit⇑);
a_j = acreage where trees are cut, newly cropped next period, (profit⇑);
C(.) = cost functions of q_j at fields with the yield $a=q_{ij}/l_{ij}$, (cost⇑=>profit⇓)
$(1$-$A_j)$ = production effect on unit costs (ambiguous)

$_{aj}$ = fallow land, individual cost reducing by biological activity (cost⇓=>profit⇑)
r = water costs (cost⇑=>profit⇓)
z = input costs, farm specific (cost⇑=>profit⇓)

Further details of stetting up a treatable function are given in App. A.1 and A.2.

3.1 Farm behavior

Assuming (1) that there is homogeneity in land with respect to cost functions (A.1), which is explained in App.A.1; (2) equal time horizons for all farmers; and (3) interaction of profits with quality, i.e. substitution between other inputs and soil quality, as derived from salinity; the specification of profits (4') can be used for a dynamic farm optimization in the traditional sense. The mathematical tool [7] is a Hamiltonian (5) which is fully expressed in App.A.1 (for the complexity).

$$H_j(S,A,a) = e^{-\rho t}\{p_j^a d_j^*(1-A_j(t)) + p_j^f a_j(t) - [..S_{30}a_j..A_j^2..S_j^2]\}$$
$$+L_1(t)[\varphi_0 A(t) - \varphi_1 a(t) + \varphi_2 u(t) + \varphi_3 W(t)] \qquad (5)$$

Equation (5 as A.5) is given by a quadratic expression. Since it is dynamic optimization we can use control theory [7] expressed as 3 criteria for a dynamic optima:

$$H(t)_{A_j(t)} = -\dot{l}(t) \quad H(t)_{a_j(t)} = 0 \quad H(t)_{l(t)} = -\dot{A}_j(t) \qquad (6)$$

With (5) and (6) we encounter individual rationality. As is shown in App. A.1 a system of equations gives an optimal compromise of immediate cash (short term benefits) and investments into soil quality (low salinity). Note land set-aside for salinity control is given exogenous as mandatory planting (to derive public benefits). The individual farm optimization of land use "A", including tree cutting is contingent. As solution we derive at equations (7a) and (7b). Comparable to incentive constraints in principal agent models, conditions (7a and b) depict behavior given "S", "W", and "u_j". An interesting feature of equations (7) is a dependency between land set-aside and salinity. Given different stages of salinity - guaranteed by an authority - a farmer has different incentives to invest in land set-aside:

$$\dot{L}_j(t) = v_{10}^* + v_{11}^* L_j(t) + v_{12}^* A_j(t) + v_{13}^* S(t) + v_{14}^* W(t) + v_{15j}^* u_j(t) + v_{16}^* r + v_{17}^* e^{\rho t} \quad (7a)$$

where L is a shadow price and A the area under land set-aside (versus cropping)

$$\dot{A}_j(t) = v_{20}^* + v_{21}^* l_j(t) + v_{22}^* A_j(t) + v_{23}^* S(t) + v_{24}^* W(t) + v_{25}^* u_j(t) + v_{26}^* r + v_{27}^* e^{\rho t} \quad (7b)$$

These equations apply to all farmers, which means the sum is $A=\Sigma A_j$ and $L=\Sigma L_j$. Equations (7) are also aggregated positions for a public good manager who wants to infer the tendency to cutting for wood and convert land previously set-aside.

3.2 System behavior

By solving the system dynamics in the farm community, i.e. eliminating the result for the shadow price and tree cutting, we receive a movement of area under trees,

$$\dot{A}(t) = \nu_{20} + \nu_{22} A(t) + \nu_{23} S(t) + \nu_{24} W(t) + \sum_j \nu^*_{25\,j} u_j(t) + \sum_j \nu^*_{26\,j} e^{\rho t} \tag{8a}$$

and for conditions of soil quality we use our treatable linear differential equation

$$\dot{S}(t) = -\kappa_0 S(t) + \kappa_1 W(t) + \kappa_2 [\sum_j [A^t - A_j] + \kappa_3 [F^0 \cdot A^0 - F(t) \cdot A(t)] - \kappa_4 l^l(t) \tag{8b}$$

which we simplify by condensing coefficients as the representation of the system

$$\dot{S}(t) = \nu_{10} + \nu_{11} S(t) + \nu_{12} W(t) + \nu_{13} A(t)_2 + \nu_{14} l^l(t) + \nu_{15} e^{\rho t} \tag{8b'}$$

The differential equation (8a and b') has to be supplemented with the water table development. To do so we have to reconsider that the individual water use (A.9) is dependent on farm behavior and that cutting trees is a behavioral function depending on prices and structural variables. We start rewriting of equation

$$\dot{W}(t) = \zeta_0^* + \zeta_1^* W(t) + \zeta_2^* A(t) + \zeta_3^* \sum_i l_j + \zeta_{14} e^{\rho t} + l_m^l(t) - l_m^p(t) \tag{8c}$$

Then, finally, the effect of the internal optimization of water "l_j" use (App. A.1. Eq. A.2) on a farm, using the behavior model (App. A.1), can be described as

$$\dot{W}(t) = \nu_{30} + \nu_{31} W(t) + \nu_{32} A(t) + \nu_{33} S(t) + \sum_j \nu_{34j} u_j$$

$$+ \nu_{35} x(t) + \zeta_{35} e^{\rho t} + \nu_{35j} l_m^l(t) + \nu_{36j} l_m^p(t) \tag{8c'}$$

Note the water table development is no longer a pure physical process rather the inclusion of explanatory equations "x" (A.9) determines water infiltration. The procedure results in a deliberately modifiable behavior of water tables, being new.

4 Social welfare function and optimization

In the case of a benevolent manager (maximizing social welfare) welfare is the sum of individual welfare (Bentham's utilitarian perspective). The manager of an irrigation scheme should seek to maximize benefits for his/her clients, regardless of distribution consequences. Besides maximizing the short term benefits, s/he should balance them with long term impacts from sustaining soil quality (apparently combating salinity). From a perspective of the management of soil salinity, the task is to create an inter-temporal welfare function which includes all members of the community. We may formally represent the problem of the manager as:

$$W_{[0,T]} = \sum_j P_{j,[0,T]} \tag{9}$$

Drawing on the above representation of individual profit functions P_j, we can establish the problem as a temporal optimization problem of allocating land to be set aside to individual farmers. It is easiest if we start with identical farmers. Presuming "n" identical farmers and optimizing over a horizon 0 to T, we get the objective function (10). Using similar arguments, as given above for gross margins (4') and cost functions (A.1), given an agreed time horizon (T) in terms of integrating long term welfare arguments, uniform time preference $e^{\rho t}$, and recognizing the temporal development of salinity from equations (8a, 8b', and

8c'), we receive an optimal control problem [7] in equation (10) for a benevolent dictator:

$$\begin{aligned} \mathrm{W[0,T]} = \int_o^T \{e^{-\rho t}\sum_j \{&P(A_j(t),u_j(t),S(t),W(t)) - P_j^w l_m^l - P_j^e l_m^p + \Lambda_1(t)[\nu_{10} \\ &+\nu_{13}A(t)+\nu_{11}S(t)+\nu_{12}W(t)+\nu_{14}l_m^l(t)+\nu_{15}e^{\rho t}]+\Lambda_2(t)[\nu_{20}+\nu_{21}A(t) \\ &+\nu_{22}S(t)+\nu_{23}W(t)+\nu_{14}u \;+\nu_{25}e^{\rho t}]+\Lambda_3(t)[\nu_{30}+\nu_{32}A(t)+\nu_{33}S(t) \\ &+\nu_{31}W(t)+\nu_{34}u \;+l_m^l(t)-l_m^p(t)+\zeta_{35}e^{\rho t}+\nu_3 r(t)]\}\,dt \end{aligned} \tag{10}$$

where additionally: p^w: water price
p^c: pumping costs

Note most prominent, in this objective function the dynamic criteria for system behavior (8a, 8b', 8c') appear as dynamic Lagrange conditions which provide shadow prices Λ(t). To add this specification of the temporal management problem by a benevolent dictator, equation (10) includes land allocation "A" as major state variable and for control "$\Sigma\nu_j u_j$," (i.e. tree land given constraint is "A", and "A^0- A" is cropped land). Further state variables are salinity "S" and water table "W". Newly assigned land, to be set-aside, afforested, is $\Sigma\nu_j u_j$, and it is an instrument variable. Costs contain costs for planting. Trees are cut accordingly and "S" changes.

Additionally in the objective, opportunity costs of water p^w, which might be used for leaching, have to be deducted, notably, on the basis of an equilibrium price for fresh water in the watershed. We take a given water price for fresh water which is used from a source outside the system. And, we can also include pumping costs or additionally external costs for salty water p^c. In case of no external effects of water pumped out of the system, pure pumping costs are relevant. In case of down stream problems with water, external costs have to be included. The management problem is solved by control theory [7] as function (A.12):

Again using standard mathematics to solve dynamic optimization problems the control problem has now to fulfill 9 conditions for the dynamic maxima (11):

$$\begin{aligned} &H(t)_{A(t)} = -\dot{\Lambda}_1(t), H(t)_{S(t)} = -\dot{\Lambda}_2(t), H(t)_{W(t)} = -\dot{\Lambda}_3(t), H(t)_{u_j(t)} = 0, H(t)_{l_m(t)} \\ &= 0, H(t)_{l_p(t)} = 0, H(t)_{\Lambda_1(t)} = -\dot{A}(t), H(t)_{\Lambda_2(t)} = -\dot{S}(t), H(t)_{\Lambda_3(t)} = -\dot{W}(t), \end{aligned} \tag{11}$$

These are nine criteria for a Hamiltonian (see A.12) of the objective function (10). Then we can retrieve, as a result, a system of equations. The system is explicitly documented in Appendix A.3 (A.13). The manager controls afforestation, land use, salinity, water table, and leaching; he also recognizes system effects receiving shadow prices. The problem, comprising six differential equations, has to be solved for endogenous variables y (App.7.3 where y =[A(t), S(t), L(t), u(t), l_l (t) , l_p (t), Λ_1 (t), Λ_2(t), Λ_3(t)]′ given exogenous variables (see lists of variables).

$$\dot{y}(t) = a + Ay(t) + Bx(t) \tag{12}$$

The manager solves equation (12). Apparently, further analysis will provide system behavior like steady states, dynamics of salt and sizes of public intervention.

5 Results and conclusions

As a result of the modeling, irrigation system managers are given an analytical tool to combat salinity in the long run. The system (12) can be solved for time dependent paths on the stage variable: (1) soil quality as an index for salinity, S(t)); (2) land set-aside, hence also agricultural area, A_0-A(t); and (3) the water table, W(t). For paths to reach envisaged steady states, the control variables u(t), l(t) and $l_p(t)$ provide necessary annual instructions on mandatory tree planting, leaching and pumping as publicly controlled. Fundamentally the model implicitly caters for tree cutting on farmland $a_j(t)$ since private behavior is anticipated. The results are watershed related. They are dependent on the composition of the farm sector; i.e. the system (12) is a corner solution of an institution, characterized as a benevolent manager, but it could also be applied to a large farm which wants to optimally recognize soil quality dynamics. The aspect of many farms, being involved in common-pool-property management, has not been tackled.

A Appendix

A.1 Individual optimization

Using land allocation as a constraint for farm behavior, the intention of the following intermediate analysis is to explain the cutting- and land-clearing-behavior of individual farms. Farms are primarily interested in crop land and not tree covered land; considering an advantage of firewood if prevalent, perhaps lower salinity is given. Clearing of land for cropping is an instantaneous exercise. It occurs even if mandatory tree planting is a policy instrument of a public manager. Clearing provides land for farm surplus. This can be modeled: To make the analysis operational, we will introduce a quadratic cost function (A.1) to equation (4').

$$\mathrm{P_j}[0,\mathrm{T}] = \int_o^T e^{-\rho t}\{p_j^a d_j^*[A_j^0 - A_j(t)] + p_j^f a_j(t)$$
$$-C(d_j[A_j^0 - A_j(t)], a_j(t), r(t), S(t), A_j(t), u_j(t), z_j)\}dt \qquad (4')$$

In quadratic cost functions (A.1) interactions are presumed; then (A.1) is inserted.

$$C(d_j^*(A_j^o - A_j), S(t), r, a_j, u_j, r_j) = \gamma_{10}A_j + \gamma_{20}S + \gamma_{30}a_j + \gamma_{40}u_j + 0.5\gamma_{11}A_j^2$$
$$+0.5\gamma_{22}S^2 + 0.5\gamma_{33}a_j^2 + 0.5\gamma_{44}r_j^2 + 0.5\gamma_{55}u_j^2 + \gamma_{12}A_jS + \gamma_{13j}A_ja_j + \gamma_{14j}A_ju_j \quad (\mathrm{A.1})$$
$$+\gamma_{23}S\ u_j + \gamma_{24}S\ a_j + \gamma_{34j}a_ju_j + \gamma_{31}r\ A_j + \gamma_{32}r\ S + \gamma_{33j}r\ a_j + \gamma_{34j}r\ u_j$$

Next we can use Shepherd's Lemma to derive water demand per hectare which is:

$$l_j = \gamma_{44} r_j + \gamma_{31} A_j + \gamma_{32} S + \gamma_{33j} a_j + \gamma_{34j} u_j \tag{A.2}$$

This equation can be inserted in the water table differential equation (8c') to reveal a dependency of the water table on the demand for water. Also the production of j is determined by the marginal revenue minus the cost, giving farm sizes:

$$\begin{aligned} & p_j^a d_j^* - \gamma_{10} + \gamma_{11} A_j + \gamma_{12} S + \gamma_{13j} a_j + \gamma_{14j} u_j + \gamma_{31} r = 0 \Rightarrow \\ & q_j^s = d_j [A_j^0 - A_j] = d_j [A_j^0 - \gamma_{11}^{-1} [\gamma_{10j} - p_j^a \overset{*}{d_j} + \gamma_{12} S + \gamma_{13j} a_j + \gamma_{14j} u_j + \gamma_{31} r]] \end{aligned} \tag{A.3}$$

In (A.3) yields per hectare are not yet defined, but we can determine them as

$$d_j = \xi_j l_j = \xi_j [\gamma_{44} r_j + \gamma_{31} A_j + \gamma_{32} S + \gamma_{33j} a_j + \gamma_{34j} u_j] \tag{A.4}$$

Note, we have specified the cost function as determined by state variables of the system "S" and by several behavioral equations. However, farmers do not only behave statically with respect to water demand, given state variables, etc., rather they decide on dynamics: tree planting, duration and cutting of trees, etc. Equation (6 equal to A.5) serves the optimization criteria of a Hamilton function [7]:

$$\begin{aligned} H_j(S,A,a,t) = e^{-\rho t} \{ & p_j^a d_j^* [1 - A_j(t)] + p_j^f a_j(t) - [\gamma_{10} A_j + \gamma_{20} S + \gamma_{30} a_j + \gamma_{40} u_j \\ & + 0.5 \gamma_{11} A_j^2 + 0.5 \gamma_{22} S^2 + 0.5 \gamma_{33} a_j^2 + 0.5 \gamma_{44} r_j^2 + 0.5 \gamma_{55} u_j^2 + \gamma_{12} A_j S + \gamma_{13j} A_j a_j \\ & + \gamma_{14j} A_j u_j + \gamma_{23} S\, u_j + \gamma_{24} S\, a_j + \gamma_{34j} a_j u_j + \gamma_{31} r\, A_j + \gamma_{32} r\, S + \gamma_{33j} r\, a_j \\ & + \gamma_{34j} r\, u_j]\} + L_1(t) [\varphi_0 A(t) - \varphi_1 a(t) + \varphi_2 u(t) + \varphi_3 W(t)] \end{aligned} \tag{A.5}$$

Using control theory [7], as mentioned, the three criteria for dynamic optima are

$$H(t)_{A_j(t)} = -\dot{l}(t) \qquad H(t)_{a_j(t)} = 0 \qquad H(t)_{l(t)} = -\dot{A}_j(t) \tag{6}$$

Applying (6) to (A.5) provides conditions of dynamic behavior on land set-aside:

$$+\gamma_{11} A_j(t) + \gamma_{13} a_j(t) + [\beta - \rho] \cdot L(t) = -\dot{L}(t) + \gamma_{10} - d_j^* p_j^a + \gamma_{12} S(t) + \gamma_{14j} u_j(t) + \gamma_{31} r \tag{A6a}$$

$$\gamma_{13} A_j(t) + \gamma_{33} a_j(t) - \varphi_1 L(t) = p_j^f + \gamma_{24} S(t) + \gamma_{34j} u_j + \gamma_{33j} r \tag{A6b}$$

$$\varphi_0 A_j(t) + \varphi_1 a_j(t) - \varphi_2 u_j(t) + \varphi_3 W(t) + 1/F_0\, e^{-\xi t} = -\dot{A}_j(t) \tag{A6c}$$

After internal solving system (A6) for differentials 2 differential equations prevail:

$$\dot{L}_j(t) = v_{10}^* + v_{11}^* L_j(t) + v_{12}^* A_j(t) + v_{13}^* S(t) + v_{14}^* W(t) + v_{15j}^* u_j(t) + v_{16}^* r + v_{17}^* e^{\rho t} \tag{7a}$$

$$\dot{A}_j(t) = v_{20}^* + v_{21}^* l_j(t) + v_{22}^* A_j(t) + v_{23}^* S(t) + v_{24}^* W(t) + v_{25}^* u_j(t) + v_{26}^* r + v_{27}^* e^{\rho t} \tag{7b}$$

A.2 Deriving system relevant behavioral equations

Next we need the water demand function

$$l_j = \gamma_{44} r_j + \gamma_{31} A_j + \gamma_{32} S + \gamma_{33j} a_j + \gamma_{34j} u_j \tag{A.2}$$

again and solve it simultaneously with the cutting tree function.

$$a_j = \frac{1}{\gamma_{33}}[p_j^f + \gamma_{24}S(t) + \gamma_{34j}u_j(t) + \gamma_{43j}r_j(t) + \varphi_1 L_j(t) + \gamma_{13}A_j(t)] \quad \text{(A.7)}$$

Inserting the cutting of tress incentive function into water demand we receive

$$l_j = \gamma_{44}r_j + \gamma_{31}A_j + \gamma_{32}S + \gamma_{33j}\frac{1}{\gamma_{33}}[p_j^f + \gamma_{24}S(t) + \gamma_{34j}u_j(t) + \gamma_{43j}r_j(t) + \varphi_1 L_j(t)$$
$$+ \gamma_{13}A_j(t)] + \gamma_{34j}u_j \quad \text{(A.8)}$$

which is a function of state variables A and S, and the control variable u, plus exogenous variables. Note further the sum of water applied in fields, as provided by farmers and also delivered, is an estimation of water used in plant production. This can be important for a calculation of water available for leaching.

$$l_m^l = \sum_j l_j = \sum_j [\gamma_{44}r_j + \gamma_{31}A_j + \gamma_{32}S + \gamma_{33j}\frac{1}{\gamma_{33}}[p_j^f + \gamma_{24}S(t) + \gamma_{34j}u_j(t) + \gamma_{43j}r_j(t)$$
$$+ \varphi_1 L_j(t) + \gamma_{13}A_j(t)] + \gamma_{34j}u_j] \quad \text{(A.9)}$$

By these exercises the number of variables can be reduced to core variables.

A.3 Optimizing of management for salinity control in the watershed

Given farm behavior a to be explicated function, optimized, taken above costs, is:

$$W = e^{-\rho t}\int_o^T \{\sum_j \{p_j^a d_j^*[A_j^0 - A_j(t)] + p_j^f a_j(t) - C(d_j[A_j^0 - A_j(t)], a_j(t), r(t), S(t), A_j(t), u_j(t), z_j)\} + P_j^e]\}\}dt$$

$$\text{s.t} \quad \dot{S}(t) = v_{10} + v_{13}A(t) + v_{11}S(t) + v_{12}W(t) \qquad + v_{14}l_m^l(t) \qquad + v_{15}e^{\rho t}$$
$$\dot{A}(t) = v_{20} + v_{21}A(t) + v_{22}S(t) + v_{23}W(t) + \sum_j v_{14j}u_j \qquad + v_{25}e^{\rho t}$$
$$\dot{W}(t) = v_{30} + v_{32}A(t) + v_{33}S(t) + v_{31}W(t) + \sum_j v_{34j}u_j + l_m^l(t) - l_m^p(t) + \zeta_{35}e^{\rho t} + v_3 r(t) \quad \text{(A.10)}$$

and

$$a_j = \frac{1}{\gamma_{33}}[p_j^f + \gamma_{24}S(t) + \gamma_{34j}u_j(t) + \gamma_{43j}r_j(t) + \varphi_1 L_j(t) + \gamma_{13}A_j(t)] \quad \text{(A.11)}$$

where L(t) is practically given by an internal determination of all shadow prices. As discussed in equation (7b) it includes a determination by S(t) and stands alone

$$L(t) = v_{10}^{**} + v_{11}^{*}A(t) + v_{12}^{*}S(t) + v_{13}^{*}W(t) + \sum_j v_{14j}^{*}u_j(t) + \sum_j v_{15j}^{*}e^{\rho t} + v_{16}^{*}r(t) \quad \text{(8d)}$$

in a steady state. We now take a sector- or watershed-wide approach with "n" identical farmers, which implies: (1) control conditions (11) are applied to the function (A.10), (2) we resume a non-varying cost function (a quadratic function provides linear derivatives with similar coefficients, (3) and the cost function of

(A.1) rechecks cross effects. With n farmers and instruments $\Sigma u_j = n \cdot u$, inserted in (A.10), we get a Hamiltonian (A.12) of 3 state variables and 3 control variables:

$$\begin{aligned}
&H(A,S,W,u_j,l_m,l_p,t) = e^{-\rho t}\{P^*[\gamma_{44}r_j + \gamma_{31}A(t) + \gamma_{32}S(t) + \gamma_{33j}[\gamma^*_{00}A(t) + \gamma^*_{02}S(t) \\
&+\gamma^*_{03}W(t) + \gamma_{04}u(t) + \gamma^*_{05}r] + \gamma_{34j}u(t)][1 - A(t)] - [[\gamma^*_{10} - P^f_j][\gamma^*_{00}A(t) + \gamma^*_{02}S(t) \\
&+\gamma^*_{03}W(t) + \gamma_{04}u(t) + \gamma^*_{05}r] - 0.5\gamma^*_{11}A^2(t) - 0.5\gamma^*_{11}S^2(t) - 0.5\gamma_{44}u^2(t) + \gamma^*_{12}A(t)S(t) \\
&+\gamma^*_{14j}A(t)u\ (t) + \gamma_{23}S(t)u(t) - P^w_j l^l_m - P^e_j l^p_m\}dt + \Lambda_1(t)[\nu_{10} + \nu_{13}A(t) + \nu_{11}S(t) \\
&+\nu_{12}W(t) + \nu_{14}l^l_m(t) + \nu_{15}e^{\rho t}] + \Lambda_2(t)[\nu_{20} + \nu_{21}A(t) + \nu_{22}S(t) + \nu_{23}W(t) + \nu_{14}u \\
&+\nu_{25}e^{\rho t}]\Lambda_3(t)[\nu_{30} + \nu_{32}A(t) + \nu_{33}S(t) + \nu_{31}W(t) + \nu_{34}u\ + \nu_{35}l^l_m(t) + \nu_{36}l^p_m(t) \\
&+\zeta_{35}e^{\rho t} + \nu_3 r(t)]
\end{aligned} \tag{A.12}$$

Then the results after getting the derivatives for the state and control variable are:

$$\begin{gathered}
P^*_a\gamma^*_{31} - [\gamma^*_{10} - P^f]\gamma^*_{00} + [P^*_a\gamma^*_{33}\gamma^*_{00} + \gamma^*_{00}]A(t) + \gamma^*_{12}S(t) + \nu^*_{14}u(t) + \nu_{13}\Lambda_1(t) + \nu^*_{21}\Lambda_2(t) \\
+\nu^*_{32}\Lambda_3(t) = \dot{\Lambda}_1(t) - \rho\Lambda_1(t) \\
P^f_j\gamma^*_{32} + [\gamma^*_{10} - P^f]\gamma^*_{02} - [\gamma^*_{33}\gamma^*_{02}P^f_j + \gamma^*_{12}]A(t) - \gamma^*_{11}S(t) - \gamma^*_{14}u(t) + \nu^*_{11}\Lambda_1(t) + \nu^*_{22}\Lambda_2(t) \\
+\nu^*_{11)}\Lambda_3(t) = \dot{\Lambda}_2(t) - \rho\Lambda_2(t) \\
[\gamma^*_{10} - P^f]\gamma^*_{03} - \gamma^*_{33}\gamma^*_{03}P^f_j A(t) + \nu^*_{12}\Lambda_1(t) + \nu^*_{23}\Lambda_1(t) + \nu^*_{31}\Lambda_3(t) = \dot{\Lambda}_3(t) - \rho\Lambda_3(t) \\
[\gamma^*_{40j} - p^f_j] + \gamma_{00}\gamma_{04}A(t) + \gamma_{44}u\ (t) + \gamma^*_{14}A(t)n\gamma_{23}S(t) + \nu^*_{24n}\Lambda_2(t) + \nu^*_{34}\Lambda_3(t) = 0 \\
p^w + \nu^*_{14n}\Lambda_1(t) + \Lambda_3(t) = 0 \\
p^e + \Lambda_3(t) = 0 \\
\nu_{10} + \nu_{13}A(t) + \nu_{11}S(t) + \nu_{12}W(t) + \nu_{14}l^l_m(t) + \nu_{15}e^{\rho t} = \dot{S}(t) \\
\nu_{20} + \nu_{21}A(t) + \nu_{22}S(t) + \nu_{23}W(t) + \nu_{14}u\ + \nu_{25}e^{\rho t} = \dot{A}(t) \\
\nu_{30} + \nu_{32}A(t) + \nu_{33}S(t) + \nu_{31}W(t) + \nu_{34}u\ + l^l_m(t) - l^p_m(t) + \zeta_{35}e^{\rho t} + \nu_3 r = \dot{W}(t)
\end{gathered} \tag{A.13}$$

To solve the system, variables are put as y and x and we obtain a system solution:

$$\dot{y}(t) = a + Ay(t) + Bx(t) \tag{12}$$

where: y is a vector =[A(t), S(t), L(t), u(t), l_1 (t) l_p (t), Λ_1 (t), Λ_2(t), Λ_3(t)]′ and x = [p, r,…]

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Local-scale solute transport in variously structured soils under continuous flood irrigation

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Abstract

This paper reports the results of research carried out to establish the possibility of using Time Domain Reflectometry (TDR) technology in measuring breakthrough curves of anion tracers such as chloride and bromide. The test conditions adopted refer to the case of undisturbed porous media with bimodal porosity under saturated-unsaturated conditions and to a liquid phase of assigned chemical characteristics. The BTCs were measured with vertically installed TDR probes. Interpretation of signal impedance was carried out in a similar fashion to Kachanosky et al. so as to obtain estimates of the minimum impedance load Z_0. The measured BTCs were interpreted to estimate transport parameters by using a two-parameter convective-dispersive model. Finally, a sensitivity analysis of the hydrodynamic dispersion parameter as related both to the average pore water velocity v, and TDR measurement errors were performed.

Keywords: solute transport models, chloride breakthrough curve, TDR calibration.

1 Introduction

Contamination of groundwater has received considerable attention in recent years because of concerns about degradation of this important source of fresh water, with possible toxicological consequences. Contamination has often been associated with point sources such as disposal sites or illegal dumping of chemical and industrial wastes. More recently, non-point pollution has become the center of increased attention by the research community, both in urban and

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agricultural landscapes. Although a vast amount of complex mathematical flow and transport models exist, reliable predictions of flow and transport processes in natural, heterogeneous soils can only be made if expected spatial and temporal variability of the soil-atmosphere interface where diffuse pollution almost always occurs is also addressed. Unfortunately, the limiting step in our understanding of solute transport at field scale is just a lack of reliable and sufficient data. Indeed, at present investigations on solute transport in porous media for assessing solute leaching potential mainly base on time-consuming laboratory or field experiments (Kutilek and Nielsen, [2]; Jury et al., [3]).

Recent studies have demonstrated the potential of Time Domain Reflectometry (TDR) technology as an alternative technique to estimate chemical transport parameters in soil (Kachanosky et al., [1]; Comegna et al., [4]). This procedure could be recognized as an effective means for characterizing the solute transport behavior in soil.

Given the advantages of acquiring in real-time a suitable number of laboratory and field observations, which are particularly useful in parallel basic research, the Institute of Agricultural Hydraulics of the University of Naples "Federico II" together with DITEC of the University of Basilicata set up an equipment with a view to defining sufficiently and completely the parameters of chemical transport in soil for the widespread future use of simulation models. The main objective of this study is to illustrate the application of TDR methodology for estimating solute transport parameters from miscible experiments at laboratory scale. Main problems arising when applying the methodology to undisturbed soils with different aggregation degrees are also addressed. In the last part of the work results of modelling of experimental data are illustrated and a sensitivity analysis is also performed, mainly aiming to verify the robustness of fitted hydrodynamic dispersion parameter as related to experimental errors.

2 Experimental methodology

2.1 TDR in solute transport studies

A time domain reflectometry (TDR) waveform contains information describing both the speed of propagation and the attenuation of an electromagnetic pulse as it travels along a waveguide or probe (Topp et al., [5]; Spaans and Baker, [6]). Use of these properties allows for the determination of both the water content θ and the bulk electrical conductivity EC_a in approximately the same volume of porous medium (Dalton et al., [7]). Through long-established relationships describing the dependence of EC_a on θ and the electrical conductivity of the soil water EC_w, these two measurements promise the ability to determine EC_w from a TDR wave-form. For conditions under which the soil water chemistry is dominated by a single electrolytic solute, EC_w will be linearly related to the solute concentration, allowing for solute concentration measurement with TDR.
Techniques for measuring the parameters of the transport models based on TDR have recently become widespread. Such techniques can be used to measure the mass flux of solute past the ends of TDR probes and characterize the probability

density function of solute travel time. The procedure may be applied to a conservative tracer under steady state leaching condition, provided that a solute pulse causing a measurable reduction in the TDR signal is added to soil surface. As shown by various authors (Dalton and van Genuchten, [8]; Nadler et al., [9]; Kachanoski et al., [1]) the resident solute concentration C_r (ML^{-3}) in the soil may be determined from estimates of bulk soil electrical conductivity EC_a (dSm^{-1}), conducted by means of TDR.

In general, in a porous medium under conditions of steady flow, there are the following relations between the resident concentration C_r, bulk electrical conductivity EC_a and impedance Z_∞ (ohm), hereafter referred as Z, of the transmission line measured by TDR:

$$C_r = a + bEC_a \tag{1}$$

$$EC_a = \frac{K}{Z - Z_c} \tag{2}$$

in which a and b are calibration constants, K (L^{-1}) is the cell constant of the TDR probe and Z_c is the impedance associated to the cable, the connector and the tester (Topp et al., [5]).

Eqn. (1) holds for variable soil salinity levels ranging between 0 and 50 dSm^{-1} and for different values of θ (Ward et al., [10]), even if at higher θ values some nonlinearity was observed for low concentrations. In fact, EC_a is linearly related to EC_w for a range between 1 and 20 dSm^{-1} (Rhoades et al., [11]). As was also shown, EC_w is linearly related to pore water solute concentration C_r for a similar range. Thus the EC_a-C_r relationship is approximately linear for this electrical conductivity range (Kachanosky et al., [1]). The nonlinearity observed is held to be affected by the clay content in the soils and by Na^+ saturation, water content and probe size. Thus, the relation at low EC_w values, with θ constant, is soil-specific and should be estimated.

Direct calibration of the TDR probe in different solutions with known EC_w (0-12 dSm^{-1}) can be used to calculate Z_c and K (Heimovaara, [12]). For salinity levels less than about 3 dSm^{-1} $Z_c \ll Z_\infty$ (Mallants et al., [13]).

The relative concentration of the solute resident in the volume sampled by a TDR probe of length L is given by:

$$C_r^*(L,t) = \frac{C(t) - C_0}{C_0 - C_i} \tag{3}$$

equivalent to:

$$M^*(L,t) = \frac{M(t)}{M_0} \tag{4}$$

where C_0 is the concentration of the applied solution, C_i is the original concentration in the porous medium, *C(t)* is the concentration for greater time values, M^* is the relative solute mass, $M(t)$ (ML^{-2}) is the total mass of solute between the pair of rods at any time t and M_0 is the total mass of solute contained between the rods from soil surface to the bottom end of the probe.

By substituting eqn. (1) in eqn. (3) and by using eqn. (2) to eliminate the constants, the following is obtained (Kachanoski et al., [1]):

$$M^*(L,t) = C_r^*(L,t) = \frac{Z^{-1}(t) - Z_i^{-1}}{Z_0^{-1} - Z_i^{-1}} \tag{5}$$

where Z_i is the initial impedance before applying the solution, Z_0 is the impedance associated with the applied concentration C_0, equation (5) shows that, with θ constant, the distribution $C^*(L, t)$ may be obtained from measurements of impedance $Z(L, t)$ if a particular value of impedance Z_0 can be related to a known concentration such as the concentration of the inlet solution C_0.

In a displacement experiment with a vertical TDR probe configuration, assuming that the TDR probe extends from the surface to a depth L, addition of a solute pulse with total specific mass M_0 at time t_0 immediately leads to a drop in impedance Z. When the finite solute pulse is wholly located in the volume observed by the TDR probe, the impedance will have a constant minimum value Z_0 associated to M_0. However, as the solute moves below the bottom end of the TDR probe, the impedance will tend to gradually increase and reach its initial value Z_i when all the solute is past the probe.

It is currently possible to obtain Z values directly from the display of a *Tektronix* (mod.1502C) cable tester. In this study, the readings were conducted at the intersection of the tester display cursor with the trace of the reflected signal when the width of the latter appeared stabilised. According to Nadler et al. [9], the problem of multiple reflections may be overcome by reading the impedance at a late time ($t \rightarrow \infty$) along the signal when all multiple reflections are suppressed. The differences in Z are used in the calibration process to obtain relative mass distribution (Kachanosky et al., [1]) from which in turn solute flux concentration at $z=L$ can be derived (Elrich et al., [14]).

By deriving eqn. (4) as regards time, the flow density relative to the solute may be obtained:

$$f(L,t) = \frac{1}{Z_0^{-1} - Z_i^{-1}} \frac{\partial}{\partial t} [Z(t)]^{-1} \tag{6}$$

Equation (6), equivalent to the probability density function (*pdf)* of solute travel time, may be considered as a characteristic of the volume of solute transport and may thus be assumed directly as a transfer function in the transfer function model *TFM* (Jury et al., [15]).

2.2 Miscible transport experiments

Methodology illustrated above was verified with reference to three undisturbed soil samples 150 mm in diameter and 170 mm in length from different sites of southern Italy. The samples were collected by means of steel samplers guided by an appropriate hydraulic device, ensuring the simultaneous removal of surrounding material so as to reduce alterations and compaction of the samples.

Samples were identified as *sandA*, *clay* and *sandB* respectively. Their main physical characteristics as determined in the laboratory, together with some pedological characteristics of the horizons and the sampling site, are reported in Table 1 (Comegna et al. [4]).

In the laboratory the samples were saturated slowly from the bottom. Subsequently, the saturated hydraulic conductivity K_s was determined by the constant head method.

Table 1: Physical characteristics of the soils examined.

Texture (ISSS)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)	Organic matter (%)	Pedological classification
Sandy (sand A)	88.0	6.0	6.0	1.297	3.1	Horizon A: crumb structure; *entisol*
Clayey sand (clay)	39.72	25.43	34.85	1.240	1.9	Horizon A: polyedric-subang. structure; *vertisol*
Sandy (sand B)	80.0	12.0	8.0	1.285	2.1	Horizon A: granular structure; *andosol*

Subsequently, in a thermoregulated chamber (20±0.5°C), the samples to be characterised were subjected to very simple one-dimensional flow processes with a specifically constructed experimental leaching configuration. The leaching unit shown in figure 1 consists essentially of a soil column, a rain simulator, a vacuum unit and allows saturated and unsaturated flow experiments to be conducted.

The bottom end cap of the column supports a nylon cloth of 25 μmesh-wire with a bubbling pressure of ≈2.5 kPa. A bubble tower with a movable air entry tube allows the pressure potential *h*, of water to be imposed at the bottom of the sample. The column is then equipped with a vertically installed bifilary TDR probe for measuring the water content θ and impedance *Z*, and with two tensiometers for measuring the water potential *h*.

The laboratory-built TDR probe consists of two 5 mm diameter steel rods, 50 mm apart, 150 mm long extending from a perspex head enclosing a 1:1 matching *ferrite balun* (Spaans and Baker, [6]) and is connected to the measuring device by a 2m-long coaxial cable (RG 58U) with a characteristic impedance of 50 Ω. Porous fritted glass plate tensiometers (10 mm in diameter and with a bubbling pressure of ≈50 kPa) are inserted horizontally 5 cm and 15 cm down the soil column and are connected to pressure transducers. The leaching unit is completed by other basic components, namely: i) a Tektronix Mod. 1502C metallic TDR cable tester equipped with an RS 232 interface (Tektronix Inc.); ii) a personal computer for control, acquisition and data analysis; iii) a 50-needle (id. 0.6 mm) rainfall simulator; iv) a peristaltic pump serving the simulator; v) an automatic fraction collector to collect the effluent in small fractions (10-15 cc).

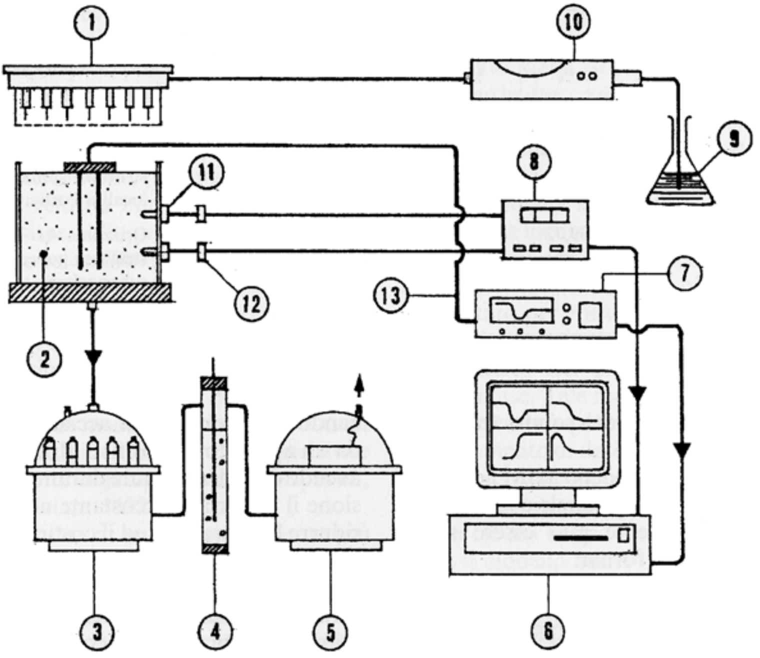


Figure 1: Schematic diagram of the laboratory apparatus showing: (1) rain simulator, (2) soil monolith, (3) fraction sampler, (4) Mariotte vessel, (5) vacuum pump, (6) computer, (7) TDR tester, (8) multiplexer, (9) tracer vessel, (10) peristaltic pump, (11) tensiometer, (12) pressure transducer, (13) coaxial cable.

Each sample thus underwent a preliminary conditioning phase by feeding, with a steady water flux density, the flow system with a 0.01 N $CaSO_4$ solution until the steady flow and initial chloride concentration C_i=0 were reached. Contemporaneous measurements of θ, h and q allowed us to determine the onset of steady-state. At steady state, the solute was applied in a different way depending on the saturation degree during the experiments.

Concerning saturated experiments, the input of water was interrupted and a pulse of KCl of total specific mass M^* corresponding to 26.9 g/cm^2 of chloride, obtained by dissolving 1 g of KCl in 50 cc of water, was applied at the top of the sample for a variable period of time t_0 from 4 to 7 min. The chloride pulse, which had in the meantime completely penetrated the upper layers of the sample, was shifted by re-feeding the sample with the $CaSO_4$ solution.

During leaching tests the leachate was periodically collected. The chloride ion concentration at the outlet boundary was determined by titrating 10 mL of aliquot against standard $AgNO_3$ using 5% K_2CrO_4 as an indicator (=reference method) (Richards, [16]).

The $Z(t)$ time series were obtained and used to estimate by eqn. (5) the relative solute mass $M^*(L, t)$ localized between the surface and end of the TDR probe of length L.

3 Interpretative models of chemical transport

One-dimensional steady flow of an inert solute in homogeneous and isotropic porous media may be described by the classical convection-dispersion differential equation (CD):

$$R\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x} \tag{7}$$

where C (ML^{-3}) is the solution concentration, $v = q/\theta$ (LT^{-1}) is the average pore water velocity, q (LT^{-1}) is the Darcy velocity, θ the volumetric water content, D (L^2T^{-1}) the coefficient of hydrodynamic dispersion, R the retardation coefficient accounting for equilibrium linear sorption processes, x (L) is the distance in the direction of the flow and t (T) is time. Instantaneous concentrations C provided by TDR electrical resistance measurement are defined as the mass of solute per unit of soil volume C_r.

The hydrodynamic dispersion coefficient D has commonly been expressed as $D=\lambda v_0^n+D_0$, where λ and n are constants. λ is a characteristic property of the porous medium usually referred as dispersivity and n is commonly taken as a value between 1-2 (Kutilek and Nielsen, [2]).

On the basis of heuristic reasoning supplied by Jury et al. [3], equation (7) describes simply dispersion on a macroscopic scale in a homogeneous porous medium, hypothesizes implicitly that there is a Gaussian distribution of velocity in the flow domain and typically supplies a signal which may be modelled by a dispersion coefficient D in which all approximation errors are propagated.

During experiments some BTCs could show the establishment of a non-equilibrium indicated by tailing and early appearance of tracer in the effluent, mechanisms that generally cannot be described by analytical solutions supplied by equation (7). The mobile-immobile convection-dispersion concept (MIM) (van Genuchten and Wierenga, [17]; Gaudet et al., [18]) can be used for solute transport in such soils. In this conceptual model the porous medium is divided into two transport regions (*mobile* and *immobile*). Convective transport is assumed to occur only in the so-called *mobile* region, which is a fraction β, of the water filled pore space.

$$\theta_m \frac{\partial C_m}{\partial t} + \theta_{im}\frac{\partial C_{im}}{\partial t} = \theta_m D_m \frac{\partial^2 C_m}{\partial x^2} - \theta_m v_m \frac{\partial\ C_{im}}{\partial x} \tag{8}$$

$$\theta_{im}\frac{\partial C_{im}}{\partial t} = \alpha\left(C_m - C_{im}\right)$$

Chemical exchange between the two regions is assumed to be a diffusive process and is macroscopically described by a first-order kinetic, according to a difference of concentration, with a rate coefficient α.

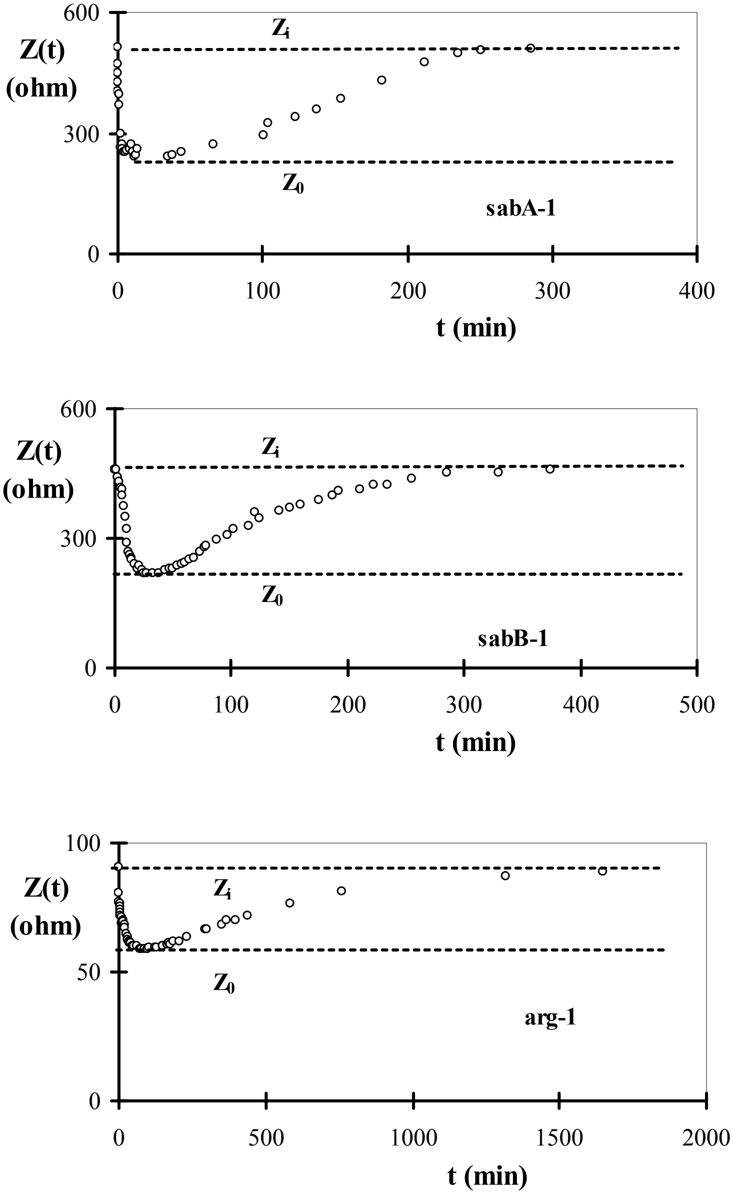


Figure 2: *Z(t)* values measured by TDR.

4 Results and discussion

Overall, seven tests were carried out on *sandA* sandy soil, eight on *sandB* sandy soil and two on *clay* clayey soil. In order to illustrate the characteristic pattern of the electric impedence of transmission line in the soil, figure 2 reports as an example the time series of $Z(t)$ recorded during experiment *sandA*-1, *sandB*-1 and *clay*-1 conducted on respective columns at lclayest v_0 value and at complete saturation.

It may be observed from the figures that the initial impedance Z_i varies from 520 ohm for sandA-1 to 460 ohm for *sandB*-1 to 93 ohm for *clay*-1. Such differences may be attributed to the different chemical and physical characteristics of the soils examined.

Moreover, after application of the solute, significant variations are noted in impedance values, which in a short space of time record minimum Z_0 values of 250 ohm, 220 ohm and 58 ohm respectively for the three different soils. Finally, as shown by the times required to return to the Z_i values, the different physical and chemical characteristics of the soils also resulted in different time dynamics of solute transport.

The obtained values of Z_i, Z_0 and $Z(t)$ were re-used to plot the BTCs, $C(t)$, normalized between 0 and 1. For all the soils a straightforward comparison between TDR derived concentrations and those measured with the reference method may be established in figure 3 which represents the pertaining *pdfs*.

For *sandA-1* and *sandB-1*, the pdfs measured with TDR and the reference method are comparable to a slightly asymmetric bell-shaped curve. The results compare well, showing differences only for $t>80$min ($r^2=0.960$) and for $t>60$min ($r^2=0.974$). By contrast, for *vertisol*, the *pdf*s are typically asymmetric with accentuated tails (figure 4). A differentiation of the *pdfs* is noted, with clear deviations from the reference values, for times $t<120$min ($r^2=0.882$). In this case, the *pdf* measured with TDR leads to a slight overestimate of the time corresponding to the peak concentration and thus to a slight underestimate of the modal velocity of the solute.

Just as an example of results obtained under unsaturated conditions, figure 4 shows the diagram of $Z(t)$ values for the experiment *sandA*-2, along with the comparison between derived concentration values and those measured by the reference method.

The very slight discrepancies between the compared experimental BTCs emphasise the good agreement of the experimental devices and techniques adopted. For all the other experiments conducted, not reported here for the sake of brevity, it was observed that the initial impedence Z_i, corresponding to concentration C_i, varies within a range between 700 and 519 ohm. Such differences may generally be attributed to the variability in bulk soil electrical conductivity, the different water and clay contents of soils. After application of the solute, significant variations in impedence were noted which, with different time laws, showed minimum Z_0 values, corresponding to the applied concentration C_0, between 38-83 ohm.

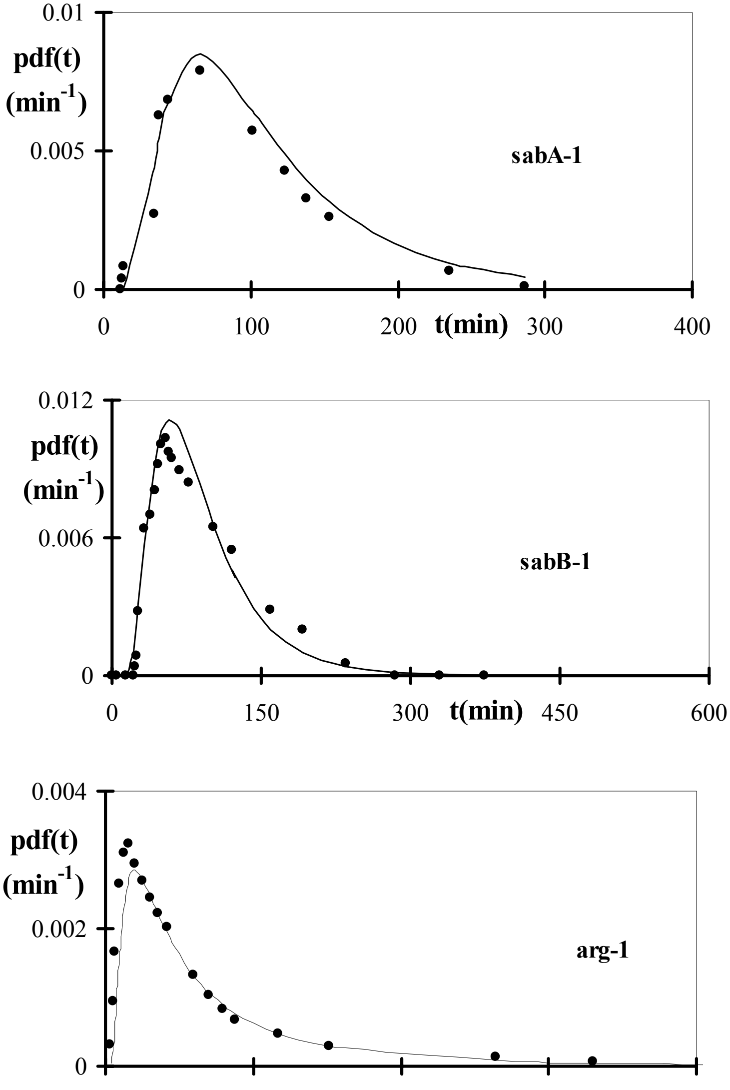


Figure 3: Comparison between pdf(t) obtained by TDR (—) and pdf(t) obtained by the reference method (•).

The experimental BTCs were first modeled with the CD model (equation (6)). The model parameters were determined using the CXTFIT program (Toride et al., [19]) which minimizes the sum of the squares of the residuals between the measured values and those calculated with an analytical solution of type A1 proposed by van Genuchten and Wierenga [17]. So as to reduce the number of iterations, the actual velocity v_0 was set equal to the q/θ ratio and initial estimates used of parameters *R* and *D* were reasonably close to optimal values, obtained with the deterministic methods proposed by Fried and Coubernous [20].

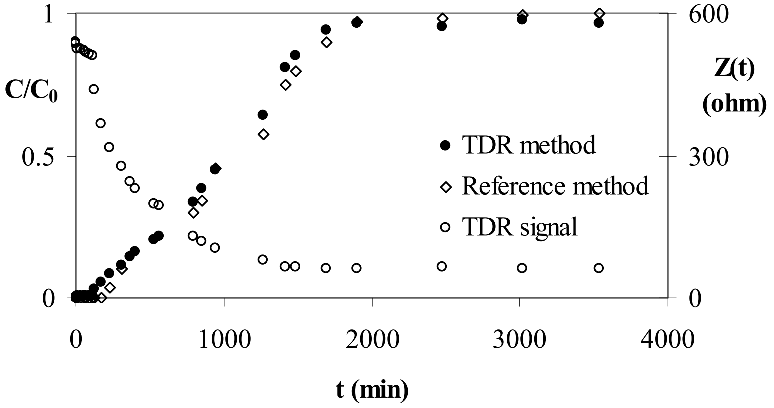


Figure 4: Measured impedance load *Z(t)* (*sandA-2 experiment*) from the cable tester (o); *C(x, t)* values measured with TDR (•) and reference method (◊).

Table 2: Parameters obtained by fitting the CD model to the experimental BTCs. R^* and D^* parameters starting values obtained by using the methods of van Genuchten and Wierenga (1976) and Fried and Combarnous (1971), respectively.

Parameters	*Entisol*	*Vertisol*	*Andosol*
q (cm min^{-1})	0.0715	0.0189	0.0732
Ks (cm min^{-1})	0.0640	0.0343	0.0343
θ_s	0.410	0.489	0.370
v (cm min^{-1})	0.174	0.039	0.198
R^*	1.270	1.092	1.187
R	1.280	1.070	1.201
D^*(cm^2 min^{-1})	0.418	0.184	0.658
D(cm^2 min^{-1})	0.275	0.146	0.451
P	9.512	3.962	6.580
λ (cm)	1.577	3.786	2.280
r^2	0.980	0.997	0.988
MSE	0.024	0.012	0.027

Seemingly a good agreement between calculated and measured BTCs was achieved, as confirmed by the high r^2 obtained also for experiments not shown here.

Though the shape of some breakthrough curves and pertaining parameters seemed indicate the establishment of a non-equilibrium, especially on columns labeled as *sandA* and *clay,* curve-fitting MIM model to experimental breakthrough produced always unimproved fittings and unreliable parameter estimates as compared to the CD results. Thus, deducting physical meanings from the uncertainly parameters obtained by MIM model would have been hazardous and probably meaningless. Accordingly, the obtained MIM parameters are not shown herein and all the following analyses were performed considering the CD as the appropriate model.

3.1 Sensitivity of hydrodynamic dispersion to experimental errors

Impedance Z, and average pore water velocity v, are the experimental parameters mainly involved in the hydrodynamic dispersion estimation. Any error in their measurement propagates on the dispersion coefficient in a way which can be studied through simulations.

Starting from an experimental curve for which the closest fitting was obtained, the sensitivity of hydrodynamic dispersion to errors in velocity determination was investigated by applying fictitious variations to its experimental value in the range –10%-10%. Velocity was first fixed while optimizing both dispersion and retardation coefficients. In this case a different hydrodynamic dispersion was obtained depending on the starting velocity value. To the contrary, a constant dispersion was obtained by optimizing both dispersion and velocity parameters, thus demonstrating the timeliness of optimizing velocity when unstable water content and/or inflow were hypothesized or observed during experiments. Results referring to these trials are observable in figure 5a and 5b.

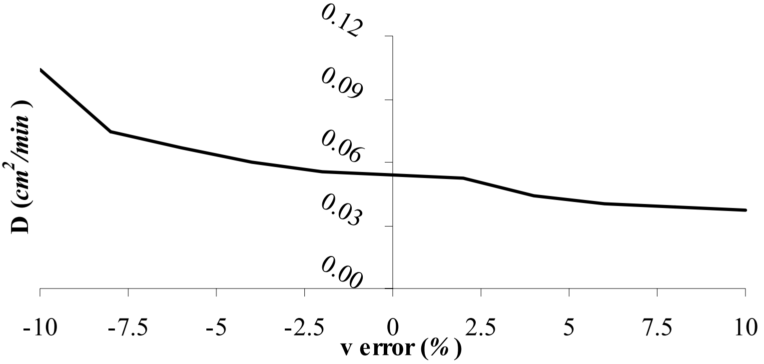
Concerning the influence of impedance determinations on hydrodynamic dispersion, new fictitious experimental curves were calculated by perturbing the experimental $M^{*}(L, t)$ obtained from equation (5) through a random error which was calculated according to the following equation:

$$M_{p}^{*}(L,t) = M^{*}(L,t)\left[1 + 2f(F - 0.5)\right] \tag{9}$$

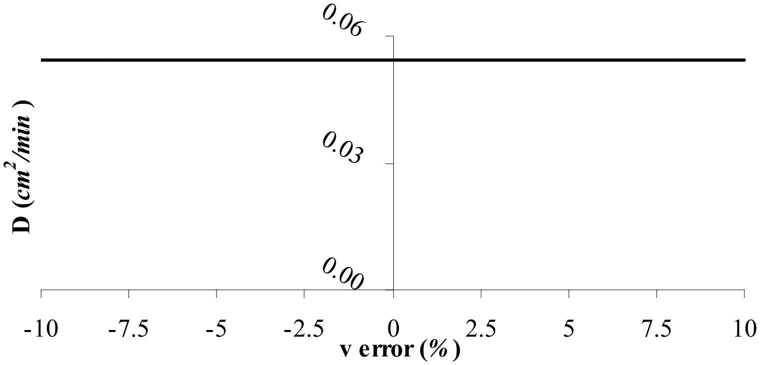
where $M_p^{*}(L, t)$ is the relative solute mass which is assumed to be subject to random measurement error, F is a random number between 0 and 1.

Finally, f is the relative error to which values of 0.05, 0.10 and 0.15 are assigned in order to simulate errors of 5, 10 and 15% respectively. Parameter estimation analysis was carried out on the fictitious realizations of data using values shown in Table 2 for the experiment *sandA*-2 as starting values for transport parameters.

Graphical results are illustrated in figure 6. An appreciable sensitivity to measurement errors was observed just when the 15% error was considered, with a large deviation of D from its “true” value. Nevertheless, when 5 and 10% errors were applied, the observed deviations were limited to 1.1 and 2% respectively.



(a)



(b)

Figure 5: (a) Hydrodynamic dispersion coefficient as obtained by applying measurement errors to pore water velocity, keeping *v* fixed during the fitting; (b) Hydrodynamic dispersion coefficient as obtained by applying measurement errors to pore water velocity *v* is optimized during the fitting.

4 Conclusions

TDR technology, though already used in the field of soil physics and soil hydrology to measure water content in natural porous media, has only recently begun to be used to estimate chemical transport parameters in soil.

The illustrated methodology, which considers laboratory tests on undisturbed soil samples, permits considerable reductions in the number of measurements, while supplying results which are at least as accurate as those obtainable from long-established conventional techniques.

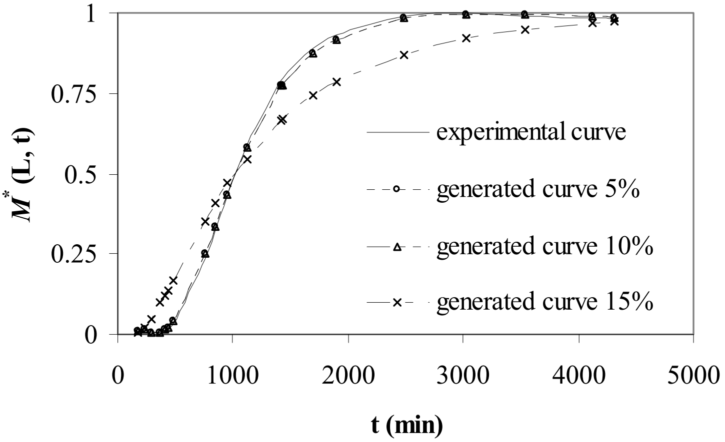


Figure 6: Effect of errors in the determination of M^* (L, t) on the fitted curve.

Tested on soils with clearly different physical characteristics, the method allows reliable definition of transport parameters in steady flow conditions and for water content near saturation.

With regard to sandy soils, the two-parameter CD model supplied optimal estimates of concentrations, $C(x,t)$. As regards clayey soil, the use of the CD equation is not necessarily ruled out although a lower r^2 value was calculated. To reduce the greater discrepancies observed between the calculated curves and the measured data, more sophisticated versions of the CD model must be used, such as the CD-MIM model, which is known to compartmentalise the liquid phase into two domains, *mobile* and *immobile*. Nevertheless, CD appears a very reliable model which is appropriate for mechanistic of the solute transport process. Applying the technique to field trials may be extremely useful. In order to obtain sufficiently precise estimates of transport parameters for applications, techniques will have to be set up which take account of soil heterogeneity and the uncertainty of boundary conditions. Further and more extensive verification of the methodology is, however, necessary both in the laboratory and in the field, as well as on different soils.

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Section 3
Irrigation modelling

AWAM: a model for optimal land and water resources allocation

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Abstract

Planning for irrigation water management in rotational irrigation schemes consists of the preparation of an allocation plan for distribution of land and water resources to different crops up to tertiary or farm level, and water delivery schedules in terms of timing and amount of water delivery for this allocation plan according to the set objectives/targets. It is necessary to consider the heterogeneity in soils and climate, and complexity of the water distribution network, while developing these allocation plans. Further, there is a need to allocate water both efficiently and equitably. The preparation of the allocation plan becomes a complex process when the water availability is less than the demand for water for adequate irrigation of the culturable command area of the irrigation scheme. In the past, several methodologies have been developed to prepare the allocation plans during the planning process. However these models do not consider the above mentioned requirements together. This paper presents the developed model, AWAM (Area and Water Allocation Model) that addresses the heterogeneity in the irrigation scheme and includes the performance measures of productivity and equity while developing the allocation plans. The AWAM model has four phases to be executed separately for each set of irrigation interval over the irrigation season. The paper briefly discusses the applicability of the AWAM model by producing land and water allocation plans and water delivery schedules for case study of the Nazare medium irrigation scheme in Southern India.

Keywords: optimization, irrigation, land & water allocation, productivity, equity.

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1 Introduction

The irrigation schemes in semi-arid and arid regions operate under rotational water distribution. These schemes are usually large and heterogeneous in nature i.e. with several crops, soils and a large network of canals with varying characteristics. Spreading water over a large area has been a strategy of irrigation in these irrigation schemes, mainly to provide protective irrigation and alleviate famine. As a result of this, water is shorter in supply than land and most cultivable command areas do not get enough water (adequate irrigation depth). Hence the irrigation management in such cases is a complex process. It requires decisions on how much water and area should be allocated to different crops when grown on different soils and in different parts or regions of the scheme (the allocation plan), based on water availability, maximization of benefits, equitable water supply, different needs and physical constraints of the scheme. Similarly releasing the appropriate quantity of water at the appropriate time to the different crops in different fields from the reservoir headwork through the canal system (the water release schedule) is also important for the maximum benefits. Hence it is important to identify the optimum allocation plan and corresponding water release schedule for the canal network.

Previous research by the authors [1, 2], identified three possible modelling approaches depending on the water availability in the schemes, based on which decisions can be made regarding the allocation of land and water to different crops and the schedule of operation of the canal system. The first is when the water supply in the scheme is adequate; the second is when the water supply is limited but the cropping pattern (or areas) is pre-decided and the third case is when the water supply is limited and the cropping pattern (or areas) can be chosen freely. The approach adopted in the third category of models is appropriate as the area and water resources are allocated optimally to different crops without assuming the allocation policy for any of the resources as known. This is done by considering several alternative levels of crop water requirement and the corresponding yield over the entire season or over an individual irrigation period.

Analysis based on the entire season considers the optimum distribution of the seasonal irrigation depth over different irrigation periods of the crop season separately for each crop. Therefore, these models may not give the appropriate optimum solution in a multicrop situation. In contrast, analysis based on the individual irrigation period makes use of several combinations of irrigation depth per irrigation application and the corresponding crop yield for each crop. It is therefore most appropriate in a multicrop and water-limiting situation and has been adopted by various researchers [3–5]. However all these models are solved at one level i.e. allocating the resources available at tertiary level to tertiary level or allocating the resources available at scheme level to scheme level (the single field type of model). This makes it difficult to apply the allocation results to the operation of the scheme because these do not specify the spatial distribution of the allocated resources.

In addition, these studies were mainly concerned with maximizing the benefits of agricultural production from the irrigation schemes (i.e. productivity) and did not address the issues of distributing the water to farmers in different parts of the command area of irrigation schemes, in particular whether farmers get an equitable share of water (i.e. equity).

Hence the problem needs to be solved differently. In the present paper, a resource optimization model (Area and Water Allocation Model, AWAM) is presented for rotational irrigation systems where shortages of water prevent adequate irrigation of the whole irrigable command area of the irrigation scheme. This model optimally allocates the area and water to different crops grown in different regions of the irrigation scheme while considering the equity in distribution of resources such as water or irrigated area or output such as crop production or net benefits.

2 AWAM Model

The AWAM model [1, 2] (fig. 1) allocates the land area and available surface water to different crops cultivated in different parts of the irrigation scheme to maximize the net benefits from the irrigation and is developed for the irrigation schemes which operate under rotational water supply. The model is designed for allocating the resources available at scheme level to the tertiary level and for deciding the water release schedule at tertiary level. The irrigation interval is assumed to be pre-determined and uniform for all crop and soil combinations. AWAM model has the following four phases and is executed for each irrigation interval or a set of irrigation intervals over the irrigation season or year.

1. Generation of irrigation strategies
2. Preparation of irrigation programmes
3. Selection of irrigation programmes
4. Optimum allocation of resources

2.1 Phases of AWAM model

2.1.1 Generation of irrigation strategies

The area of an irrigation scheme with similar climate (Region), soil (Soil group) and crop is termed as Crop-Soil-Region (CSR) unit (but this is not a physical division of the irrigation scheme). As stated earlier, water scarcity in these schemes may make deficit irrigation more profitable. There are several ways to provide deficit irrigation for a specified CSR unit in an irrigation scheme. An optimal way has to be selected by considering all CSR units, water availability and characteristics of command area of irrigation scheme together [6]. Hence optimal allocation of water requires estimates of the outputs obtained from several possible strategies that are based on different combinations of deficit (percentage moisture stress in the soil root zone on the day of irrigation) over all the irrigation periods. In this phase (Phase 1) irrigation strategies are generated for each CSR unit for a specified set of irrigation intervals. This results in several irrigation strategies for each CSR unit, each with variable deficit for each irrigation.

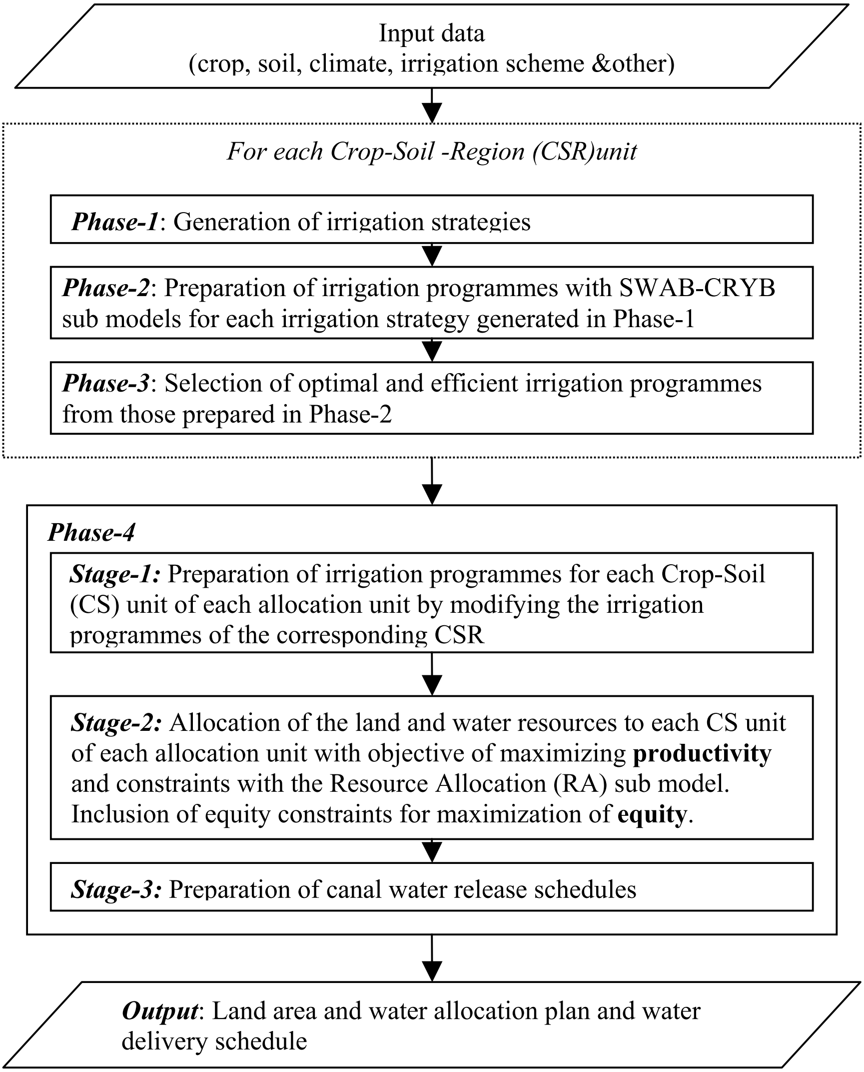

Figure 1: Area and Water Allocation (AWAM) model.

2.1.2 Preparation of irrigation programme

In this phase an irrigation programme that consists of information on yield/benefits and irrigation requirement (depth) per irrigation is prepared for each irrigation strategy of each CSR unit for a specified set of irrigation intervals. The irrigation programme is prepared from the following two sub-models which are described later, and more details can be found elsewhere [1, 2].

SWAB: In response to deficit over each irrigation (specified in irrigation strategy), this sub-model simulates daily soil moisture in the soil root zone, estimates daily actual crop evapotranspiration, the irrigation requirement (depth) per irrigation and the other related parameters.

CRYB: This sub-model estimates crop yield from the actual evapotranspiration estimated in SWAB sub-model and computes net benefits.

2.1.3 Selection of irrigation programmes

Phase 2 may generate many irrigation programmes of which several may not be important. For example the irrigation programmes generated with irrigation strategies having no deficit for successive irrigations may simulate maximum yield but with excessive irrigation water requirement. Moreover some of these programmes may not be optimal and incorporation of all these programmes in the optimization model may also make the problem computationally infeasible to solve. Therefore the number of irrigation programmes for the given unit is restricted by selecting only optimal irrigation programmes. Thus the purpose of this phase (Phase-3) is to select for each CSR unit a specified number of irrigation programmes, which are both optimal and efficient according to specified criteria.

2.1.4 Optimum allocation of resources

This phase (Phase-4) of the model allocates land and water resources optimally to different crops cultivated on different soils in different allocation units. It utilizes the selected irrigation programmes generated in Phase 3.

The entire irrigation scheme is physically divided into a number of smaller units called “Allocation Units” (AU) over which land and water resources are allocated. These units may include different soils and crops however the climate is assumed to be uniform over a particular AU. The need to divide the irrigation scheme into several AUs arises from the heterogeneous nature and large extent of the irrigation scheme. By dividing the scheme in this way it is possible to make allocation of resources, water delivery schedules and management of the irrigation scheme efficient. The largest possible size of an AU is the size of the irrigation scheme itself and the smallest size of an AU is an individual farm. The intermediate sizes are the command areas of the secondary, tertiary and quaternary canals or groups of these canals.

Phase 4 of the model allocates land and water resources optimally to Crop-Soil (CS) units of each AU. A CS unit is a unit with similar crop and soil properties within an AU. This phase performs the allocation in three stages.

Stage-1: In this stage of Phase-4, each CS unit of an AU is assigned with the irrigation programmes of CSR unit having the same crop, soil and climate, using the irrigation programmes for each CSR unit as selected in Phase 3. As stated earlier the CSR unit is not a physical division of the irrigation scheme and hence the distribution and conveyance efficiencies cannot be considered while working out the irrigation requirements for each irrigation of a CSR unit. The AU is the physical division of the irrigation scheme and hence these efficiencies are included at this stage by modifying the irrigation requirements of each irrigation of irrigation programmes appropriately.

Stage-2: In this stage, the resources are allocated to each CS unit of each AU with chosen objective (maximization of net benefits) and constraints (resource availability, physical and output requirement) with the Resource Allocation (RA) sub model (described later). The RA sub model is solved by linear programming. The decision variables are the area to be irrigated under different crops on each soil type (CS) of AU and following different irrigation scheduling underlined in irrigation programmes prepared for the corresponding CS of AU (see equation 1). Note that these irrigation programmes are prepared in Phase-2; screened in Phase-3 and modified in Stage-1 of Phase-4. The output of the model is thus the area to be irrigated under different crops cultivated on each soil type of AU and the corresponding irrigation programme. Thus this stage gives the optimum allocation plan.

Stage-3: In this stage, the water release schedule for the canal system for the optimum allocation plan is prepared by knowing the irrigation scheduling of the selected irrigation programme for each CS unit of AU (obtained in Stage 2 of Phase 4).

2.2 SWAB-CRYB sub models

The SWAB-CRYB sub models [1,2] are formulated to make the model applicable to major field crops grown in the command area of an irrigation scheme. They use the data which are generally available at the irrigation scheme and general data documented by FAO if local data are not available. The soil water balance part of this model represents the system more descriptively than used in most allocation studies. Various inflow and outflow processes and a soil water balance equation used in SWAB-CRYB model are outlined in this section.

Reference crop evapotranspiration (ET) is computed by Penman-Monteith. Crop coefficient values in daily, stage wise or equation form are used to compute maximum crop ET. The actual ET is considered a function of maximum crop ET and remaining soil water content in the root zone. If the remaining soil water content in the root zone drops below a certain threshold value, the actual ET will be less than maximum ET and a deficit in ET occurs. This threshold value depends on a factor called the depletion factor, which is a function of crop, soil and maximum ET. The actual transpiration and soil evaporation are separated by computing actual soil evaporation and subtracting it from actual ET. Actual soil evaporation is considered as the function of potential soil evaporation [7] and crop factors, allowing for various prescribed patterns of soil moisture loss by transpiration, a linear root growth model, and initial soil moisture estimates.

The soil is considered as layered, with each layer characterized by its own physical soil properties. The full application depth on the day of irrigation application is computed to bring the soil moisture in all soil layers to their field capacities, and multiplied by the deficit ratio to obtain the application depth of deficit irrigation. The soil root zone is considered as a reservoir and the day is chosen as the time period for comparing inflows and outflows. Interception and capillary rise of water are assumed to be negligible. Effective rainfall and irrigation water applied constitute inflows, and outflow parameters comprise the actual soil evaporation and transpiration and the water percolated from the soil root zone. The water added through rainfall and irrigation is assumed to be distributed instantaneously to soil layers using a piston flow approach. The amount of water in excess of field capacity in any layer is percolated to the next layer and the water in excess of field capacity of the last layer is deep percolation. The soil moisture of any layer is computed by subtracting the transpiration corresponding to that layer and the soil evaporation from the soil moisture of the same layer on the previous day. The irrigation depth is computed by adjusting the application depth for field application efficiency and minimum possible depth of irrigation for the crop, soil and irrigation method under consideration.

In the present model, an evapotranspiration or transpiration approach can be used to estimate the yield by fitting evapotranspiration or transpiration deficits into either an additive or multiplicative form of the crop growth model. All these forms need information on the stage wise yield response factors (Ky) which depend on the soil, location and climatic conditions for the particular crop. Net benefits are obtained by computing costs as area and yield dependent costs, area dependent costs and yield dependent costs and benefits.

2.3 Resource Allocation (RA) sub model

The objective of the RA sub model is to maximize the net benefits and thus in turn maximize the productivity while maximizing the equity subjected to several constraints related to availability and requirement of different resources. The objective function and constraints are briefly described below. The readers are advised to refer to previous papers [1, 2, 8] for the detailed mathematical formulation of the RA sub model.

2.3.1 Objective function

The objective function proposed for the maximization of the net benefits is given below by eqn. (1).

$$Max \quad Z = \sum_{i=1}^{I} \sum_{j=1}^{J_i} \sum_{k=1}^{K_{ji}} \sum_{l=1}^{L_{kji}} B_{ijkl} A_{ijkl} \tag{1}$$

where i = index for AU, j = index for soil group in allocation unit, k = index for crop in soil group (j^{th} soil group of i^{th} allocation unit), l = index for irrigation programme for crop (k^{th} crop in j^{th} soil group of i^{th} allocation unit), I = total number of allocation units, J = total number of soil groups in i^{th} allocation unit, K = total number of crops in j^{th} soil group of i^{th} allocation unit, L = total number of irrigation programmes of k^{th} crop in j^{th} soil group of i^{th} allocation unit, Z = the value of objective function (currency unit), B = net benefits obtained from k^{th} crop irrigated with l^{th} irrigation programme on j^{th} soil of i^{th} allocation unit (currency unit/ha), A = Area to be allocated to k^{th} crop irrigated with l^{th} irrigation programme on j^{th} soil of i^{th} allocation unit (ha).

2.3.2 Constraints

Physical constraints: Area constraints, Canal capacity constraints, Outlet capacity constraints

Resource availability constraints: Intraseasonal water supply constraints, Reservoir storage constraint, Availability and allocation of other resources
Output requirement constraints: Crop constraints, Food requirements constraints.

These constraints have been described in detail elsewhere [1,2]. In addition the model presented in this paper includes ***Equity constraints*** derived as follows.

Previous studies attempt to maximize the equity in area allocation [e.g. 9] or water allocation [e.g. 10]. The final objective of the allocation may be to achieve equity in distribution of output from the irrigation scheme. In these models, which consider only land allocation and assume the scheme is homogeneous, the particular depth of water diverted from the headworks for irrigating a certain crop results in the same output everywhere. In this case equity in area allocation and water distribution are the same and result in fair distribution of output. But when the heterogeneity in soil, climate and losses is also considered, the equity in area allocation and water distribution produce differing results and the output distribution among various users may not be fair. Therefore the consideration of equity in distribution of output (crop production and net benefits) is also important. Thus the following four means of achieving equity are incorporated in the model through the equity related constraints, and these are considered in turn below.

1) Crop Area 2) Water 3) Crop production 4) Net benefits

It is also important to include in the allocation process the base on which equity should be achieved along with the means of achieving equity. All the previously described models tried to achieve equity in distribution of crop area or water or output produced proportional to the land holding. However there are several arguments over the base of equity. These are discussed in detail elsewhere [6,8]. In this model, therefore, the base for equity in the allocation process is included through 'desired allocation proportion' which indicates the proportion of resources to be allocated to, or the outputs to be ensured for, a specified allocation unit out of the total resources available or total estimated outputs. The desired allocation proportion for the specified allocation unit is the ratio of the value of the base for the specified allocation unit, to which equity should be proportional, and the total value of the base for the whole scheme.

Equity in crop area: By this means, the crop area is allocated for irrigation to the different allocation units as per the given value of desired allocation proportion for equity for different allocation units

Equity in water: By this means the water is distributed to different allocation units as per the value of desired allocation proportion for equity. An irrigation manager may choose to distribute water by considering conveyance and distribution losses, or by considering conveyance losses only, or without considering any of these losses. Accordingly water can be distributed to different AUs. The allocation of water is not only a spatial issue but also temporal. Therefore the developed model considers both seasonal/annual and intraseasonal/irrigation-wise equity in water allocation.

Equity in crop production: By this means the resources are allocated in a way to obtain the crop production to different users as per the proportion.
Equity in net benefits: In multicrop situation crop production cannot be used as output, as yields obtained from different crops are not comparable. Therefore equity in net benefits need to be considered. Thus in this case the expected net benefits obtained from irrigating the land are distributed as per the proportion for equity.

3 Application

3.1 Case study irrigation scheme

The applicability of the AWAM model to obtain the land area and water allocation plans is demonstrated with the help of case study on the “Nazare Medium Irrigation Scheme” in a semi-arid region of Maharashtra State of India. This irrigation scheme is representative of storage reservoir irrigation schemes that operate under rotational water supply in south Asia.

There are three distinct crop seasons: winter (Rabi) (15th October to 14th February), summer (15th February to 14th June) and rainy (Kharif) (16th June to 14th October). Most of the rainfall is received in the Kharif (monsoon) season. Therefore in this study, the irrigation season was considered to spread over Rabi and summer crop seasons only. Normally the irrigation interval in Rabi season is 21 days and in summer season is 14 days.

The cultural command area (CCA) of the irrigation scheme is 3539 ha. The irrigation system comprises a reservoir, a main canal (3.05 km long), one distributory canal (11.75 km long) and four minors. There are 28 direct outlets (4 on the main canal and 24 on the distributory canal) and four minors (all on distributory canal) with 9 outlets. The CCA of all 28 outlets and 4 minors were considered as allocation units, resulting in 32 AUs [1].

The command area is characterized with four different types of soils. Based on the previous trend in the irrigation scheme, a fixed cropping distribution was assumed of -gram-25%, sorghum-20%, onion-10% and wheat-15 % in Rabi and Sunflower –10 % and groundnut-20% in summer season. This fixed cropping distribution was considered for investigating the issues under consideration in this paper, though the AWAM model can also consider the free cropping distribution in which the model is free to select any crops depending on which crops produce maximum total net benefits from the irrigation scheme [1,2].

3.2 Results

The allocation plans and water delivery schedules were obtained for seven sets of irrigation interval. These were: 14 days (I-14); 21 days (I-21); 28 Days (I-28); 35 days (I-35) {both Rabi and summer seasons}; 21 in Rabi and 14 in summer (I-21-14); 28 in Rabi and 21 in summer (I-28-21); and 35 in Rabi and 21 in summer (I-35-21). These were obtained for two scenarios; one did not include equity (no equity) and other included equity in distribution of water over the entire season proportional to the total cultivable area of the AU (with equity). The productivity values associated with the allocation plans for the two scenarios and seven sets of irrigation interval are presented in fig. 2.

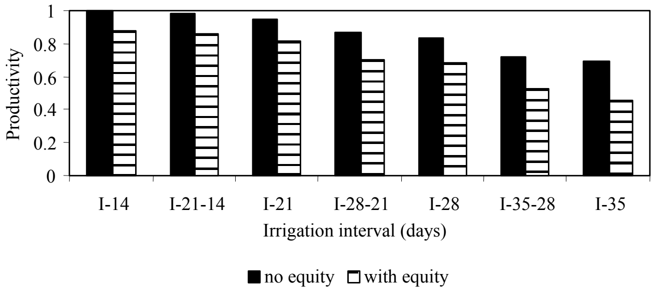

Figure 2: Productivity for 'no equity' and 'with equity' scenarios for different irrigation intervals for Nazare Medium Irrigation Scheme, India.

Productivity is quantified as the ratio of the output (measured as net benefits in monetary units) to the maximum output attainable from the resources available (land and water). The maximum net benefit Bmax, was obtained for the irrigation interval of 14 days under the "no equity" scenario. Hence the productivity values for different scenarios and irrigation intervals were computed with reference to Bmax by considering this value as the maximum attainable. Equity is related to the distribution of water to different allocation units based on cultivable command area (CCA) and can be quantified by allocation ratios of different AUs [1, 6]. The allocation ratio for a specified AU is the ratio of actual allocation proportion as a result of allocation of water to desired allocation proportion for this AU. The interquartile allocation ratio (IQAR) is used as the measure of equity. IQAR is defined as "the average allocation ratio of the poorest quarter divided by the average allocation ratio of the best quarter" [1, 6].

Fig. 2 shows that the productivity values decrease with the irrigation interval for both scenarios. As expected the equity is 1.0 for the scenario of 'with equity'. However it should be noted that for the 'no equity' that do not include equity constraint, the resulting equity is zero. This indicates that the resources are getting allocated to only highly productive allocation units (with no concern for equity). For Nazare Irrigation Scheme under study, where in the objective is to achieve maximum equity with the productivity, the allocation plan for the scenario of maximum equity would be useful. The details of this allocation plan are presented in Table 1.

Table 1: Land area and water allocation plan by proposed methodology.

AU	CCA of AU (ha)	Allocated area (ha)	Water (ha-m)	AU	CCA of AU (ha)	Allocated area (ha)	Water (ha-m)
1	39	18.55	8.04	17	145	61.36	29.87
2	36	15.59	7.42	18	147	62.20	30.29
3	8	3.47	1.65	19	118	51.25	24.31
4	27	11.73	5.56	20	661	223.76	136.19
5	395	146.38	81.38	21	65	28.14	13.39
6	33	14.29	6.80	22	156	67.54	32.14
7	59	25.62	12.16	23	30	12.69	6.18
8	22	9.55	4.53	24	37	15.66	7.62
9	211	73.31	43.47	25	89	37.66	18.34
10	68	29.53	14.01	26	93	39.35	19.16
11	62	26.93	12.77	27	115	48.66	23.69
12	142	49.24	29.26	28	30	12.69	6.18
13	127	55.15	26.17	29	32	13.54	6.59
14	81	35.18	16.69	30	87	36.81	17.92
15	217	94.24	44.71	31	35	14.81	7.21
16	82	37.99	16.89	32	90	38.08	18.54

4 Conclusions

This paper highlighted the importance of considering both productivity and equity while developing the allocation plans and water delivery schedules for an irrigation scheme with limited water supply and presented the approach to develop the allocation plans and the water delivery schedules for optimization of productivity and equity. This enables the irrigation authorities to select the appropriate allocation plans depending on the local situation. The results of the model obtained with one case study on an irrigation scheme in central India indicated that the productivity and equity conflict with each other, if the water resources are allocated optimally.

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Sustainable irrigation in the Yanqi basin, China

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Abstract

The Yanqi basin, located in Xinjiang Province, China is a typical example of an area suffering from soil salinization induced by irrigation. The application of stream water without adequate drainage has raised the groundwater table in recent years, causing significantly increased groundwater evaporation (phreatic evaporation) and triggering soil salinization. The Yanqi basin has abundant groundwater resources recharged by the rivers outside the irrigated area. Groundwater from the second aquifer layer could be used for irrigation purposes as the water quality is high. If a part of the irrigation water directly drawn from the rivers is substituted by river water pumped indirectly from the aquifer, the groundwater table will drop and the process of salinization will be slowed down. However, abstraction from the second layer does include a risk. If the groundwater table in the first layer is lowered due to the abstraction of water in the second layer, water infiltrating from the (saline) first layer to the second layer continuously imports salt into the second aquifer layer. A coupled model of ground and surface water flow was set up to determine the resulting salt concentration of the aquifer system as well as of the irrigation water. Moreover, the ideal amount of groundwater applied to irrigation was determined by using the model. The model was constructed and verified by using spatially distributed input data derived from remote sensing. The simulations revealed that around 50% of the phreatic evaporation is related to irrigation. Moreover, the simulations showed that for every m^3 of groundwater pumped, phreatic evaporation is lowered by 0.75 m^3, and that the salinized area is reduced by 50 km^2. Besides showing the changes in the overall water balance, the simulations proved that the steady state salt concentration in the aquifer system and in the irrigation water remains low, even if groundwater from the second layer is abstracted.

Keywords: remote sensing, groundwater modelling, model calibration, DEM, evapotranspiration.

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1 Introduction

Salinization occurs naturally (primary salinization) or due to human activities (secondary salinization). Comprehensive overviews covering most of the causes, consequences and possibilities to tackle the problem of salinization can be found in Hillel [6]; Jakeman et al. [7]; Richards [10], just to mention a few examples. The consequences of soil salinity have accompanied societies that rely on irrigated agriculture throughout history. Various historical and present examples are described by Hillel [5]. Different forms of irrigation and their influence on salinization have widely been studied (e.g. Hillel [4]; Rhoades et al. [9]).

A shallow depth to groundwater is one of the main causes of soil salinity: As the groundwater table rises, salts stored in the unsaturated zone are dissolved. If the groundwater table has reached a critical depth (extinction depth), groundwater can evaporate directly via capillary rise (phreatic evaporation). Salts dissolved in the groundwater accumulate at the soil surface as the groundwater evaporates. This irrigation induced soil salinization is observed in many semi-arid countries. A typical example is the Yanqi basin. The ongoing irrigation without adequate drainage has continuously raised the groundwater table and caused a soil salinization in the root zone.

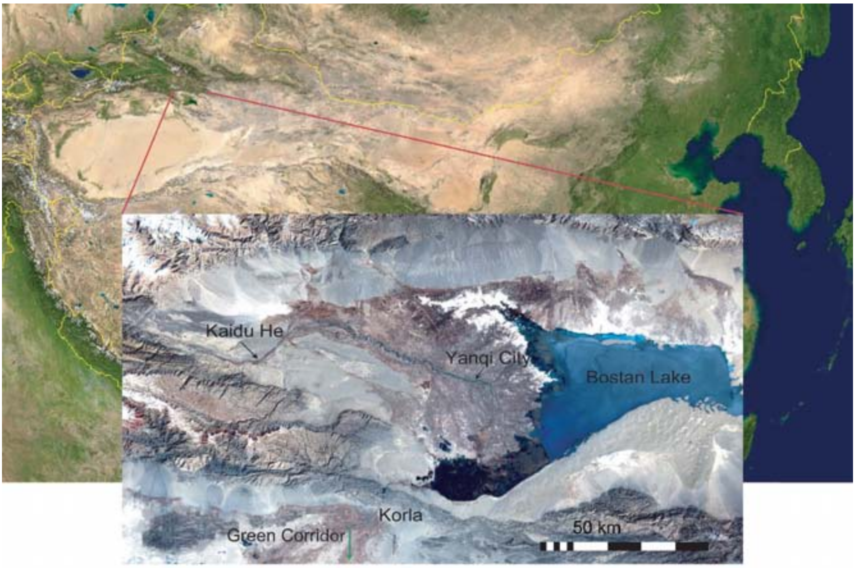

Figure 1: Location of the Yanqi basin.

2 Project area

The project area is the Yanqi basin, located in the far west of China (see figure 1). The intensive irrigation agriculture has led to several environmental problems in the Yanqi basin, especially soil salinization. According to Dong et al. [3], 60% of the irrigated area exhibited a depth to groundwater smaller than 2 m in the year 2000. Agriculture is entirely based on the water drawn from the Kaidu River. The distribution system of irrigation water is inefficient; a large amount of water is wasted both through inadequate supply systems and poor irrigation practices. In the basin itself, agricultural production can still be maintained at a profitable level. This is only possible as surface water resources are abundant and salinization can be controlled by over-irrigation. But the impact for downstream riparians, including both agricultural and natural systems, is high: Surface water resources are not available to the required extent and the salt concentration has increased due to the high evaporation losses upstream, limiting the productivity of the affected systems.

The lowest point of the basin is Bostan Lake. Its main inflow is the Kaidu River. Bostan Lake with over 1000 km^2 of open water surface is the largest fresh water lake in Xinjiang. The deepest point is only 17 m below the water surface. The outflow of the lake, the Kongque River, is regulated by a pumping station. The lake is surrounded by salt marshes. The Kongque River supplies the so called Green Corridor with water.

The Yanqi basin features large groundwater resources recharged by the rivers flowing through it. The stratigraphy along the mountain range is mainly composed of moraine and glaciofluvial sediments, such as loam and gravel (Lin et al., [8]. These sediments (also called Gobi-formation) feature a high hydraulic permeability. Between the surrounding mountains and the central area of the Yanqi basin, these sediments form a weakly heterogeneous aquifer down to the bedrock. The infiltration of river water occurs within this formation. The stratigraphy in the central area of the Yanqi basin is complex. It is the only area where soil could develop and agriculture is possible. The aquifer in the central area of the Yanqi basin can be divided into four layers separated by relatively thin but nearly impermeable silt layers. The hydraulic conductivity of the second aquifer layer is over a magnitude larger than the hydraulic conductivities of the other layers. The high hydraulic conductivity of the second layer allows to abstract groundwater. The confined layers are all connected to the Gobi-formation. The water of the confined layers is therefore of good quality and can be used for irrigation purposes. The large amount of salt deposited over time in the first layer, however, significantly reduces its water quality. The salt deposited in this layer is the main source leading to soil salinization.

3 Strategies for action in the Yanqi basin

Several options to manage the Yanqi basin in a more sustainable way exist. Reducing the irrigated area, improving the efficiency of the irrigation system or planting salt tolerant crops would help to save water and to increase the depth to groundwater. One of the most promising options is the substitution of irrigation water by groundwater. If a part of the irrigation water directly drawn from the rivers is substituted by river water pumped indirectly from the aquifer, the groundwater table will drop and the process of salinization will be slowed down. Groundwater is hardly used today, as due to energy requirements it is more expensive than surface water. However, if the water table can be kept low by pumping groundwater, the conservation of soil for continued agricultural use along the Kaidu River might strike the balance with a higher price of water. The major decision variable to steer the system into a desirable state without reducing the irrigated area is the ratio of irrigation water drawn directly from the river to the water drawn indirectly from the river by pumping groundwater.

Even though pumping groundwater can potentially reduce phreatic evaporation and increase the available water resources downstream, abstraction from the second layer does include a risk. If the groundwater table in the first layer is lowered due to the abstraction of water in the second layer, there must be a water flux infiltrating from the (saline) first layer to the second layer. The infiltrating, saline water of the first layer will inevitably increase the salt concentration in the second layer. To assess the feasibility of groundwater abstraction, a hydrologic model was set up simulating groundwater, surface water and the coupling between them. Two questions are clarified with the model: (1) how large is the potential to reduce phreatic evaporation, and (2) how will the salt concentration in irrigation water, the first and the second aquifer layer develop?

4 Modelling approaches

4.1 Model setup and results

The simplest way to estimate the water and salt fluxes of the Yanqi basin is to set up a box model. Even though such a modelling approach is too simple to assess the feasibility of abstracting groundwater, it demonstrates that the salt concentration of a system will increase until the flux of outgoing salt equals the flux of incoming salt and allows the identification of the key-processes determining the long term sustainability of the planned groundwater abstraction. However, the boxmodel does not allow to determine in which specific regions the groundwater table is close to the surface and where the risk of triggering the salinity problem is high.

To assess these parameters realistically, a distributed hydrological model has to be set up. A considerable amount of input data is required to construct and verify such a distributed model. A digital terrain model was calculated on the basis of radar images and verified by 60 D-GPS measurements on the ground. Recharge rates were quantified on the basis of the distribution of evapotranspiration as well as the documented amount of irrigation water applied. The distribution of evapotranspiration was be calculated on the basis of NOAA-AVHRR data (according to Roerink et al., [11]). The relation between the groundwater table and phreatic evaporation was quantified by calculating phreatic evaporation on the basis of the distribution of stable isotopes in the unsaturated zone (Barnes and Allison [1]). The information required to model the surface hydrology comprises the structure of Bostan Lake as well as the basic geometry of the rivers and drainage channels. Besides all the remote sensing data used, point measurements such as the depth to groundwater at boreholes, the discharge of the drainage net or the discharge of the rivers at several measurement stations were applied. The construction and verification of the model is discussed in detail by Brunner [2].

Three different types of steady state models were set up with the calibrated model: a steady state model representing the average conditions for the period of 1990-1999, a zero irrigation scenario analyzing the water fluxes if no irrigation takes place, as well as a model simulating the effect of groundwater abstraction for irrigation purposes. The zero-irrigation scenario clarified where phreatic evaporation is caused by irrigation and where it occurs naturally. High groundwater tables are found in many areas even without irrigation. The largest areas are the salt marshes along the lake shore. The comparison between the steady state simulations and the zero-irrigation scenario revealed that around 50% of phreatic evaporation is related to irrigation. The calculated distribution of phreatic evaporation is shown in figure 2. The pumping scenario showed that every m^3 of river water substituted by groundwater increases the available downstream resources by at least 0.75 m^3 and reduces the salinized area by 50 km^2. The reduction of phreatic evaporation is exactly the amount of water additionally available for the downstream systems.

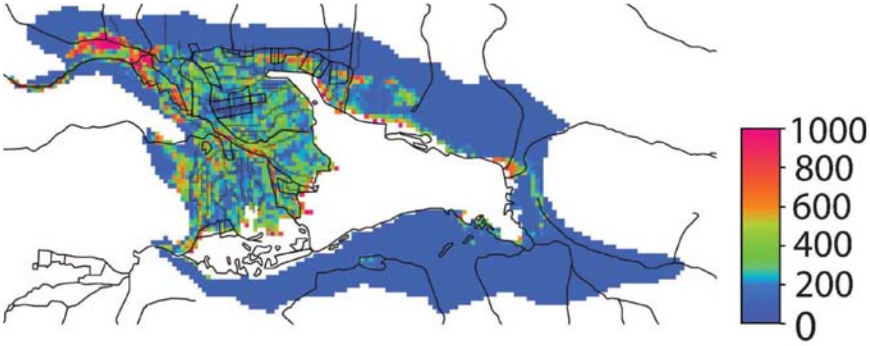

Figure 2: Phreatic evaporation [mma^{-1}] calculated by the calibrated model.

The examination of the exchange rates between the first and second aquifer layer along the lake (for the zero irrigation scenario, the pumping scenario and the calibrated model simulating the situation between 1990-1999) showed that only a small portion of water evaporating in the salt marshes is from the lake, while the major portion comes from the second aquifer layer. This mechanism demonstrates how nature evaporates water in the upstream without increasing the salt concentration in the downstream: by transporting the salt accumulated by evaporation to a zone where it is deposited in the long term. Even though phreatic evaporation along the lake shore is not very high, it constantly removes salt from the system. Salt transported to this area is effectively removed from the system because the only major output flux of water in this area is evaporation. The salts accumulating therefore cannot easily be re-mobilized, in contrast to salt removed by the drainage network which will contribute to the salt load of the downstream systems. However, the drainage net remains very important for the salt balance of the system. The steady state model revealed that the amount of salt removed through the drainage system is of the same magnitude as the salt stored around the lake. A deactivation of the drainage net would therefore lead to a significant increase of the salt concentration. In order to prevent the deactivation of the drainage net as a consequence of the lowered groundwater table, pumps should exclusively be installed in areas where the drainage net is insufficient and where irrigation has induced phreatic evaporation. Such areas can easily be identified by subtracting the map of phreatic evaporation of the calibrated model from the distribution of phreatic evaporation in the zero-irrigation scenario.

Besides steady state simulations, a transient model was set up to examine how phreatic evaporation is reduced in time. These simulations showed that the reduction of phreatic evaporation is reached within only a few years. Besides the changes in the overall water balance, the simulations could show that the flow of water from the second to the first layer along the lake is still maintained, even if groundwater is pumped from the second layer. This flux is an important sink of salt. The water flux from the second to the first layer in the pumping scenario is illustrated in figure 3.

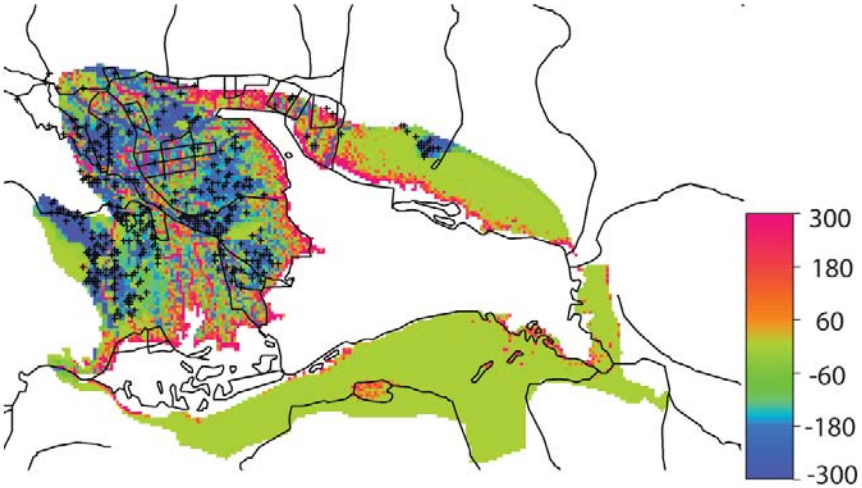

Figure 3: Vertical exchange [m^3d^{-1}] between the second and the first aquifer layer for the confined area in the steady state pumping scenario. Positive numbers indicate a water flux from the second to the first layer. Crosses indicate that a pump is abstracting water. In the areas where no pumps have been installed, the drainage net is still active and an upward flux into the first layer is observed.

4.2 Estimating the resulting salt concentration of the aquifer system

In order to estimate the resulting salt concentration of the first and second aquifer layer as well as of the irrigation water, a box model describing the salt fluxes between the first and second aquifer layer was set up. The water fluxes (calculated by using the pumping scenario) between these two compartments were used to calculate the changes of the salt concentration within the two layers as well as the resulting steady state concentrations. This model is illustrated in figure 4.

The following considerations and assumptions were made: In the salt balance for the first aquifer layer, only the salt flux from the second to the first layer within the irrigated area is considered. These fluxes are not removed from the system and therefore are considered in the salt balance. On the other hand, salt deposited along the lake's vicinity is not easily re-mobilized and therefore cannot be returned into the irrigated system. The portion of the saltflux $Q_{21}c_2$ considered in the salt balance is defined as η.

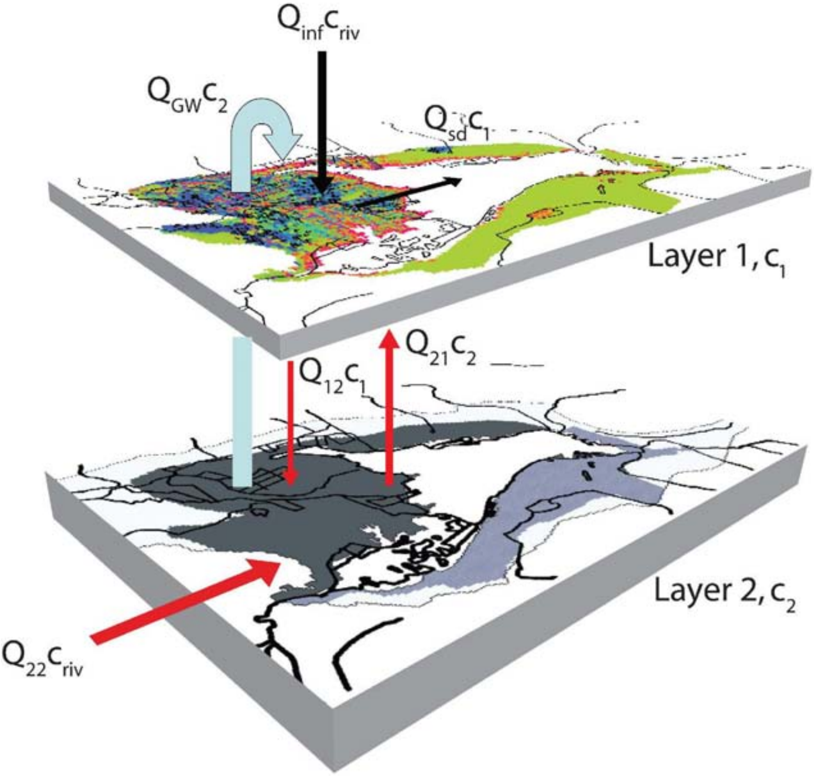

Figure 4: Salt fluxes for the confined area between first and second model layer. The system boundary to calculate the salt balance is plotted in dark gray (see second layer).

It is also assumed that the concentration of the drainage water equals the salt concentration of the first layer. Horizontal fluxes in the first aquifer layer are neglected. The horizontal hydraulic conductivity of the first layer is so small that these fluxes amount to less than 1% of the infiltration rate in the pumping scenario. Moreover, the exchange with the third layer is neglected. The net-exchange rate of water between the second and third layer is less than 3% of the incoming water fluxes (in all scenarios). Moreover, the lateral boundary fluxes of the second layer are very small (less than 2% of the outgoing water fluxes in all scenarios) and are therefore not taken into account. The last assumption is that the concentration of water flowing from the unconfined area of the second layer to the confined area of the second layer equals the concentration of the river water. This is to be expected as the only source of water in the unconfined area of the second layer is the Kaidu River. The analysis of water samples of the second layer showed that this assumption is justified. Based on these assumptions, the salt balance for layer 1 can be expressed by:

$$c_2 \cdot (Q_{GW} + \eta \cdot Q_{21}) - c_1 \cdot (Q_{sd} + Q_{12}) + Q_{\inf} \cdot c_{riv} = V_1 \frac{dc_1}{dt}$$

Q_{GW} is the amount of water pumped from the second layer, Q_{inf} is the sum of water diverted for irrigation and infiltrating directly from the rivers into the system. Q_{sd} is the amount of water removed by surface drainage. c_1 is the salt concentration in the first layer and c_2 the salt concentration of the second layer, as c_{riv} is the concentration of the river water. Q_{12} is defined as the water flux from the first to the second layer, Q_{21} the water flux from the second to the first layer. V_1 is the aquifer volume (taking the porosity into account). For layer 2, the salt balance is given by:

$$V_2 \cdot \frac{dc_2}{dt} = c_1 \cdot Q_{12} + Q_{22} \cdot c_{riv} - c_2 \cdot (Q_{GW} + Q_{21})$$

Q_{22} is the flux of water from the unconfined area of the second layer to the confined area of the second layer. The concentration of the irrigation water consisting of a mix between ground-and surface water can be calculated by the following equation:

$$c_{mix} = \frac{(Q_{GW} \cdot c_2 + Q_{div} \cdot c_{riv})}{(Q_{GW} + Q_{div})}$$

with Q_{div} being the amount of river water applied to irrigation. The steady state concentration in the first layer is given by:

$$c_1 = -\frac{c_{riv}(Q_{22} \cdot Q_{GW} + Q_{GW} \cdot Q_{div} + Q_{21} \cdot Q_{div} + Q_{22} \cdot \eta \cdot Q_{21})}{(Q_{12} \cdot \eta \cdot Q_{21} - Q_{sd} \cdot Q_{GW} - Q_{sd} \cdot Q_{21} - Q_{12} \cdot Q_{21})}$$

and c_2 by:

$$c_2 = \frac{c_{riv}(Q_{12} \cdot Q_{22} + Q_{sd} \cdot Q_{22} + Q_{12} \cdot Q_{div})}{(Q_{12} \cdot \eta \cdot Q_{21} - Q_{sd} \cdot Q_{GW} - Q_{sd} \cdot Q_{21} - Q_{12} \cdot Q_{21})}$$

The water fluxes required to evaluate c_1 and c_2 were determined with the model (steady state pumping scenario). The initial concentration of the first layer is set to 10 g l^{-1}. This is of the same magnitude as the salt concentration in the drainage water.

The development of the salt concentrations within the confined area of the first and second aquifer layers and in the irrigation water is presented in figure 5. The resulting steady-state concentration for the irrigation water is 0.57 g l^{-1}, for the first layer 0.91 g l^{-1} and for the second layer 0.76 g l^{-1} respectively. The concentration of the irrigation water (c_{mix}) increases to a maximum of 0.81 g l^{-1}. This maximum is reached after 20 years. Even though the maximum concentration is by a factor of 2 higher than the concentration of the river water, the quality is still sufficient to irrigate crops. In the long run, concentrations decrease. This is due to the fact that the amount of salt stored in the first layer is gradually removed from the system, either to the downstream or to the salt crust along the lake.

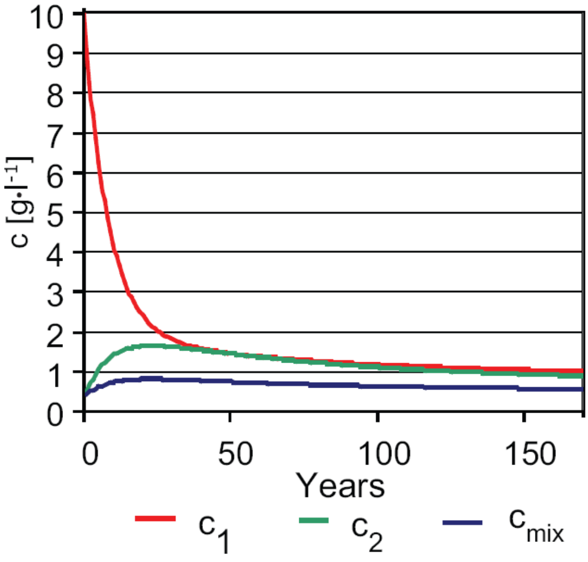

Figure 5: Development in time of the salt concentration of the irrigation water and of water in the first and second aquifer layer.

5 Conclusions

The overall conclusion of this modelling approach is that the productivity of the agriculture can be maintained in the Yanqi basin and that the available resources for the downstream systems can be increased by substituting a part of the irrigation water drawn from the river by pumped groundwater. Besides the creation of the new infrastructure for groundwater abstraction, the old infrastructure of the drainage network must be maintained. Owing to the output fluxes through the drainage network, the steady state salt concentration of the system remains below a critical level. The drainage network accounts for up to 50 % of the output salt fluxes and therefore significantly reduces the steady state salt concentration of the first and second aquifer layers as well as the quality of the irrigation water.

Besides pumping groundwater, an increase of the irrigation channel efficiency is highly recommended. Even though only 13 m^3 s^{-1} of water are consumed by plants, the available water resources for the downstream systems are reduced by 23 m^3 s^{-1}. This loss contributes to phreatic evaporation. Installing pumps close to the fields where the water is applied for irrigation will reduce the channel losses and again will contribute to the downstream resources.

Considering the large amount of salt stored in the soil column as well as the high groundwater tables in some areas of the basin, it becomes clear that sustainable irrigation in the Yanqi basin is indeed a difficult undertaking. It is therefore recommended not to increase the irrigated area. This recommendation can be relaxed only if the total amount of water applied for irrigation is kept at the present level by increasing the efficiency of the irrigation system. If new fields are claimed for irrigation, they should not be located in areas where the groundwater table is already high.

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Water productivity: a basic tool for sustainable irrigation

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Abstract

The rapid population, economic and standard of living growth with the global climate changes is increasing the per capita demand on water. This increase in water demand is resulting in less available fresh water supply for agriculture. To sustain irrigated agriculture, better water management is necessary at all levels. Water supply in the Middle East and North Africa region (MENA) is unequally distributed in space and time. This region has among the lowest per capita water supply in the world. On the other hand, the intensive extraction and use of water without proper planning and provisions for the protection of their water resource has led to serious water pollution. Agriculture consumes 70–80% of water in this region. This leads to a fundamental problem for water-short countries that should manage between their renewable water resources and their capacity for food production. Water-short countries do import food commodities, which has imbedded water called “virtual water”. The aim of this paper is to present a model with the general objective to maximize water productivity (monitory units per cubic meter of water). The mathematical model resulted in a maximum water productivity of 6.92 $\$/m^3$ with eight crops out of 43 crops grown on site. The remaining 35 crops induced a saving 3,408 m^3/ha, which equals the virtual water. Three sets of scenarios were tested. First a decrease in available water from 100% to 50% showed a decrease in the objective function value from 6.92 to 4.727 $\$/m^3$, second a decrease in on farm crop prices by 10, 20 and 40% caused decreases in the objective function value by 4.8%, 9.66% and 20.29% respectively, while an increase in prices increased the objective function value and third an imposition of certain crops in the project area decreased water productivity.

Keywords: water productivity, virtual water, water use efficiency, crop yield.

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1 Introduction

The rapid population, economic, and standard of living growth with the global climate changes is increasing the per capita demand on water. This increase in water demand (both in domestic and industrial water supply) is resulting in less available fresh water supply for agriculture. So, the area of land irrigated per capita is decreasing. Proper water resources management becomes essential in order to optimally allocate water among domestic, industrial and agricultural domains. Meanwhile, a major issue is still disregarded, this issue being whether there will be enough water for the next generations.

Water supply in the Middle East and North Africa (MENA) region is unequally distributed in space and time, both at regional and international level. The Southern Mediterranean and Middle East sub-regions have among the lowest per capita amount of water supply in the world. It is estimated that 7% of the entire Mediterranean population (28 million persons) lie below the severe scarcity line of 500 m^3/year per capita and another 29% (115 million persons) are below the poverty line of 1000 m^3/year per capita as defined by the United Nations. In certain countries, exploitation indexes of renewable natural fresh water resources have reached and exceeded 100%. In the Mediterranean countries, agriculture consumes 70-80% of water; the remaining is shared between domestic and industrial uses. The Food and Agricultural Organization estimates that an overall expansion of 2.25% per year in irrigation is needed to meet the word food demand; yet expansion in irrigation has slowed down to less than 1% per year [1].

Will humanity face water scarcity? Will the “blue gold” be scarce, expensive and source of conflicts between states? This increase in number of inhabitants will have to share the same amount of water that we use nowadays. There is a major threat that the water available may be inadequate to meet growing food demands particularly in water short countries (Rosegrant et al [2]). Two other threats should be considered. The first one is pollution arising from wastewater, agricultural pesticides, fertilizers, and industrial wastes discharged to rivers and the ground water. In this case, one cubic meter of polluted water renders 8 to 10 m^3 unusable. The other threat that is difficult to quantify, is global warming. It could modify the hydrologic systems of various regions of the world. This leads to a fundamental problem for water-scarce countries that should balance between their renewable water resources and their capacity for food production. Every year, farmers and traders in the MENA move volumes of virtual water equivalent to the flow of the Nile into Egypt, or about 25% of the region’s total available freshwater through the import of food and fibre (Allan [3]).

Virtual water and water productivity combine agronomic and economic concepts, with emphasis on water as a key factor of production. The agronomic component addresses the amount of water used to produce crops, while the economic component involves the opportunity cost of water, which is its value in other uses that may include production of alternative crops. The virtual water perspective is consistent with the concept of integrated water management, in which many aspects of water supply and demand are considered when determining the optimal use of limited water resources (Bouwer [4]). The net productivity or gross margin is the value of crop productivity (MU/ha^{-1} or MU/m^3) minus all applicable production costs. For the purpose of this study, water productivity is defined as monetary units per unit of water (MU/m^3). The current approach for demand management in irrigated agriculture recommended by international organizations and governmental agencies is to adopt ‘water-saving’ irrigation methods such as localized irrigation. Localized irrigation is not a miracle technology, since excellent as well as, poor results were obtained. Moreover, most farmers and irrigation operators lack the understanding of the soil-plant-water-climatic relationship in order to better operate and manage this new adopted technology (Nimah et al [5]).

The theme of an alternative water demand management is to have more “monetary value per drop of water”. To achieve this alternative, the virtual water and water productivity concepts are combined as an approach to deal with water scarcity (Moukarzel and Nimah [6]). This new approach does prioritize and arrange in a descending order what food commodities to import and what crops to grow locally. The general objective of this study is to combine and maximize the virtual water and water productivity concepts.

The specific objectives of this study are to (a) Develop a mathematical model to optimize the crops to be produced by maximizing water productivity per unit water i.e. monetary units per unit of water and (b) Estimate the volume of virtual water within the context of national water need and water availability for future strategic planning of water management.

2 Methodology

2.1 Model description

A linear mathematical model is developed to solve the problem of how best to allocate water among different crops to have the best combinations of net revenue per cubic meter of water and quantity of water under conditions of limited water available. In addition the model satisfies the different constraints imposed by the decision manager of the irrigation project. The optimization model developed in this study required input data generated from a set of implicit equations. This input data consist of crop water requirements, crop water demand, and water use efficiency.

2.2 Objective function

The objective function of the model is to maximize the water productivity (MU/m^3) subject to linear constraints such as cost of production constraint, water requirement constraint; and non-negativity constraint. This optimization model is developed in such a way that determines the crops that are most suitably grown locally and their respective quantities. The rest of the crops that are not advised to be grown locally will be imported. The objective function is presented by the formula:

$$MaxZ = \sum_{i=1}^{n} p_i x_i \tag{1}$$

where Z represents the total water productivity ($\$/m^3$), i is the Index of crop type, p_i is local farm-gate price of crop i (\$/kg), x_i the quantity of crop i to be grown locally (kg/m^3), and n is the number of crops. The model is subjected to the following constraints:

2.2.1 Water availability constraint

This constraint make the production capacity water needed not exceed water availability in the project area.

$$\sum_{i=1}^{n} w_i x_i \leq 1 \tag{2}$$

where W_i is specific water demand (SWD) (m^3/kg).

2.2.2 Cost of production constraint

Each crop requires a specific cost of production. These costs are disaggregated into cost of water, cost of irrigation system and its maintenance depending on the system used (surface, sprinkler and trickle) as well as other costs including fertilizers and other cultural practices. In order to grow these crops locally, they should not exceed the price of the same crop imported. This constraint is defined mathematically as follows:

$$\sum_{i=1}^{n} (C_{w_i} + C_{ir_i} + C_{p_i}) x_i \leq P_{p_i} \tag{3}$$

where C_{wi} is the cost of one m^3 of water (\$/Kg), C_{iri} is the cost of the irrigation system (\$/Kg), C_{pi} is the cost of production for crop i including fertilizers (\$/Kg), P_{pi} is the price of crop i imported at Beirut port (\$/kg).

2.2.3 Non-negativity constraint

It assures the non-negativity of the study decision variable and is formulated as:

$$x_i \geq 0 \tag{4}$$

2.3 Data needed and analysis

The following input data is needed to solve the mathematical model. Crops suitable to be planted in this area, Crop planting and harvesting pattern over the year, Yield of crop i per unit area (Kg/m^2), Crop water requirements per growing month (mm/month), Cost of production of one kilogram of crop i at the farm gate (\$), Selling price of one kilogram of crop i at the farm gate in dollars, Cost of different irrigation systems per unit area ($\$/m^2$), cost of 1 m^3 of water ($\$/m^3$), and total available water over the year.

2.4 Water requirement, crop yields and price

The data generated is specific to the South Bekaa region for the 6700 hectares area specified as phase 2 area of the South Bekaa Irrigation Scheme project. Data for this research were extracted from the feasibility study of the project. The crops that were chosen totalled 43 crops. The crops were divided into three subsets: vegetables, fruit trees, and field crops. The different crops, their respective net irrigation requirements, water use efficiency, crop water yields, and farm prices are listed in table 1. Crop water yield is better defined as the quantity in kilograms of crops i produced in one cubic meter of supplementary irrigation as calculated in eqn. (6).

In addition to the cost of production of the crops, the irrigation system installed, as well as, its operation and maintenance costs and the price of water is considered. Three types of irrigation systems are usually used: surface, sprinkler, and trickle. The total annual costs are: 0.0438, 0.0510 and 0.0544 $\$/m^3$/year for surface, sprinkler and trickle irrigation systems, respectively.

2.5 Solving the model

The mathematical model was solved using the LINDO (Linear Interactive Discrete Optimizer) software after all the parameters were defined. The output data of the model are: crops to be cultivated locally; the crops to be imported, the quantity of each crop to be grown per cubic meter of water, and the maximum water productivity with respect to combination and quantities of crops produced locally.

In order to test the sensitivity of the model, different scenarios were analyzed. The first scenario was tested with respect to the production constraint, i.e. certain crops were imposed to be grown with a specific percentage for each crop, because of strategic planning issues. The second scenario dealt with water scarcity constraint. The third scenario was to test the reactivity of the model to an increase or decrease of the imported crops prices.

3 Results

3.1 Optimization model results

The initial model output is the model results without any applied constraints. The sensitivity of this model to the imposition of: production, water availability, and to the change in price of imported crops constraints will be presented and discussed later.

The initial results indicate that the maximum water productivity is 6.92032 $\$/m^3$ if only eight crops are grown in the project area instead of the 43 crops that are actually being grown. The eight crops are garlic, green beans, onions, radish, spinach, chickpea, lentils and janarek. The remaining 35 crops can be imported, and their cost of importation is less than their cost of production locally. This means that this irrigation project can be sustained and the saved water (virtual water) can be used to expand the irrigated area. Results also showed land use area for each crop. The term land use is defined as the square meters that can be irrigated by one cubic meter of water to achieve the objective function.

Table 1: Yield, net irrigation requirement (NIR), crop-water yield, water use efficiency (WUE) and farm price for different crops grown in Lebanon.

Crop	Yield per m^2	NIR	Crop Water Yield	WUE	Farm Price
	(Kg/m^2)	$m^3/m^2/yr$	m^3/kg	Kg/ m^3	$/Kg
Broad beans	0.892	0.132	0.148	6.778	0.460
Cabbage	2.012	0.138	0.069	14.569	0.230
Carrot	2.203	0.528	0.239	4.176	0.185
Cauliflower	1.312	0.141	0.108	9.292	0.335
Cucumber	1.289	0.276	0.214	4.679	0.403
Eggplant	1.323	0.512	0.387	2.582	0.322
Garlic	0.631	0.020	0.031	32.194	0.511
Green beans	0.646	0.103	0.159	6.290	0.617
Okra	0.810	0.310	0.383	2.611	0.861
Lettuce	2.183	0.145	0.066	15.066	0.233
Melon	1.325	0.400	0.302	3.311	0.382
Peas	0.580	0.113	0.195	5.133	0.645
Potato (early)	2.640	0.232	0.088	11.365	0.239
Radish	1.259	0.047	0.037	26.902	0.257
Spinach	1.511	0.073	0.048	20.841	0.351
Squash	0.978	0.276	0.282	3.550	0.403
Tomato	2.049	0.587	0.287	3.489	0.305
Water melon	1.225	0.299	0.244	4.092	0.245
Alfalfa	2.212	0.297	0.134	7.445	0.250
Barley	0.300	0.134	0.447	2.235	0.280
Chickpea	0.650	0.056	0.086	11.566	0.400
Lentils	0.580	0.066	0.114	8.735	0.400
Lupine	0.670	0.418	0.624	1.602	0.383
Dry pea	0.650	0.418	0.643	1.554	0.533
Vetch	0.750	0.070	0.093	10.760	0.283
Wheat	0.300	0.199	0.663	1.509	0.313
Almond	0.400	0.072	0.179	5.594	0.526
Apple	1.494	0.797	0.534	1.874	0.537
Apricot	0.874	0.275	0.315	3.178	0.693
Cherry	1.190	0.254	0.213	4.685	0.535
Grape	0.825	0.388	0.470	2.128	0.409
Janarek	0.900	0.072	0.079	12.587	0.713
Peach	1.193	0.473	0.396	2.524	0.679
Pear	1.300	0.645	0.496	2.017	0.702
Plum	1.085	0.275	0.253	3.945	0.400
Quince	1.493	0.254	0.170	5.878	0.533
Walnut	0.600	0.672	1.121	0.892	0.267

3.2 Effect of different scenarios

3.2.1 Scenario I

The model was tested to its sensitivity to alternative cropping pattern. The eight crops that were selected in the initial model output were eliminated from the cropping pattern. The model reaction was positive and selected a new array of seven crops. The new selected crops are: four vegetable crops, one field crop, and two fruit crops, with an objective function value equal to 3.319 $/m^3. In both the initial and this scenario, the model selected the least water demanding crops with competitive prices (like cabbage, cauliflower, lettuce and vetch/ winter crops and short season fruit trees like almonds and cherries).

On the other hand, for strategic planning issues, some crops need to be produced locally. Alfalfa and vetch for example are needed for animal feeding. These crops were imposed to be part of the cropping pattern solution of the model. In the initial model, the maximum water productivity is attained at 17.38 m^2/m^3 of land use Alfalfa and vetch are imposed to be produced on 10% of these 17.38 m^2, divided into 57% (one m^2) for alfalfa and 43% (0.73 m^2) vetch of the 1.73 m^2.area. The results obtained from this imposition were seven crops beside the two imposed crops, and the objective function became 6.306 $/m^3. Also, the same procedure was followed for fruit trees. Ten percent of the allocated land is already planted to apples, apricots and Janarek with the following allocation: 23%: 34.7%: 42.3% of the 1.73 m^2/m^3. The objective function decreased to 4.429 $/m3. By imposing certain crops as outlined before, the objective function or the maximum revenue per unit water decreased by 8.88% when alfalfa and vetch were imposed and by 36 % when fruit trees were imposed.

The above results shows clearly on the effectiveness of the model in choosing a cropping pattern that will yield the best revenue per unit water. Thus, applying this model will help in sustaining the irrigation of agricultural land.

Table 2: Selected crops and water productivity according to different scenarios: I-a removing initial crop; I-b imposing alfalfa and vetch; and I-c imposing fruit trees.

Scenario I-a		Scenario I-b		Scenario I-c	
Crop	Return $/kg	Crop	Return $/kg	Crop	Return $/kg
Cabbage	0.270	Garlic	0.521	Garlic	0.521
Cauliflower	0.084	Onions	0.221	Onions	0.221
Lettuce	0.354	Radish	1.625	Radish	1.625
Peas	0.422	Spinach	0.366	Spinach	0.366
Vetch	0.520	Alfalfa	0.555	Chickpea	0.505
Almond	0.681	Chickpea	0.392	Apples	0.318
Cherry	0.988	Vetch	0.154	Apricot	0.286
		Janarek	2.472	Janarek	0.587
Z ($/m^3) = 3.319		Z ($/m^3) = 6.306		Z ($/m^3) = 4.429	

3.2.2 Scenario II

Five different quantities of available irrigation water volumes were applied to test the sensitivity of the model towards water scarcity. The amount of available water was imposed to decrease from one cubic meter in the initial model to 90%, 80%, 70%, 60% and 50% (fig. 1). The reduction of available water that might be caused by dry years or any other factor is pronounced in the results obtained from the model. The decreases in water productivity are 5.25%, 1.68%, 16.67%, 23.08% and 31.69% for 90%, 80%, 70%, 60% and 50% of available water, respectively. Also, the land use decreased from 17.39 m^2/m^3 to 9.63 m^2/m^3 in the above ranges of available water, which is an approximate decrease of 45% Moreover the cropping pattern did change. The number of selected crops decreased as water scarcity increased.

The decrease in water productivity as related to water shortage was found to be curvilinear and this relation fits the following mathematical equation:

$$Z = -0.0255w^2 - 0.2521w + 7.183 \qquad \left(R^2 = 0.9992\right) \tag{5}$$

where Z is the water productivity ($\$/m^3$), and w is the fraction of available water in decimal.

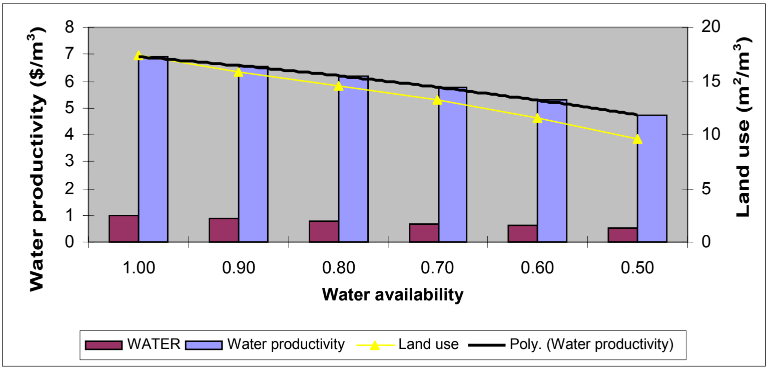

Figure 1: Changes in water productivity and land use as affected by irrigation water scarcity.

3.2.3 Scenario III

The import prices might be subject to increases because of increases in transportation costs due to increases in energy costs or other factors. In other cases, these prices might decrease due to competition because of globalization. Different sets of changes were considered. The import prices were subjected to decreases and increases from the initial model prices respectively by 10%, 20% and 40%. When price decrease was imposed in the model, the number of selected crops to be grown locally was increased and the water productivity did decrease by 4.8%, 9.66% and 20.29% respectively for decreases of 10%, 20% and 40% respectively. While an increase in import price was imposed the number of selected crops by the model decreased but the water productivity increased from 7.253$/m^3 at 10% import price increase to 8.166 $/m^3 at 40% increase. The trend in water productivity changes due to price increase or decrease is shown in fig. 2.

On the other hand the land use per cubic meter of water decreased from 17.388 m^2/m^3 to 13.813 as the import prices of crops decreased to 40%; and reversed with increases in the import prices from initial prices. The land use was increased from 17.388 to 18.873 m^2/m^3. The water productivity-import price relationship is defined in the mathematical equation below.

$$Z = -0.0089p^2 - 0.3311p + 8.4 \qquad (R^2 = 0.9831) \tag{6}$$

where Z is the water productivity ($/m^3), and p is the percentage change in import prices.

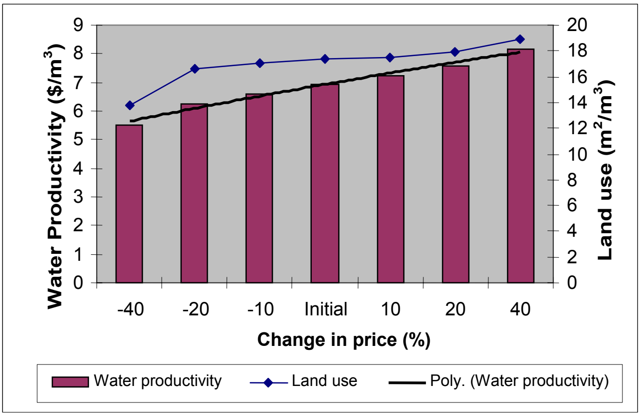

Figure 2: Changes in land use and water productivity with changes in import prices of crops.

4 Discussion

The model developed generated the maximum water productivity and selected the crops to be grown in a certain irrigated project according to the input data and assumptions previously mentioned. When high water demanding cops were imposed like alfalfa, apples, apricots, the model reacted but the water productivity decreased as presented in the results above. On the other hand, when the price of imported crops was deflated, the model reacted by choosing more crops but the water productivity decreased as well as the land used per cubic meter.

Thus, by importing the 35 crops, the net water saving will be 3408 m^3/ha. Therefore, in the 6700 hectares project area 22.8 million cubic meters could be saved and thus imported as virtual water, these findings are in general agreement with what reported [7, 8].

The results obtained in this study are not the ultimate solution for managing the use of water resources. But, they can help in strategic planning for saving water resources. It can help formulating long term agricultural plans in specific water scarce projects based on importing high water consuming crops with least price competitiveness, thus sustaining irrigated area. Since, population growth is continuing in the coming years, there will certainly be challenges in providing water for food security.

5 Conclusion

The formulated model links water productivity and virtual water and did optimize the water productivity or net return per unit of water i.e. "more revenue per drop" based on set constraints. It is certain that if the data on water requirements, yield, cropping pattern, and prices are changed, the value of water will change. The reliability of the model output depends on the reliability of the input data, which can be updated easily. The strength of the study is that by applying linear programming, it was possible to quantify the link between water scarcity or limited water availability, virtual water and sustainable irrigation.

This model can be applied to similar cases with the proper input data. Also it can simulate strategic planning for allocating the scarce water available in an irrigation scheme to keep it sustainable.

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Kerman weighing electronic lysimeter error analysis

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Abstract

Lysimeter is an important instrument to measure evapotranspiration in the field of irrigation management. The error analysis and calibration of the system is very critical for quality control of collected data. The error sources are many and different. The Kerman weighing electronic lysimeter is a complex of two cultivation tanks, load cells, data logger, and data processing weighing system with 48 m^2 under ground building. In this study, ten-minute interval measured evapotranspiration data were analyzed. The Fourier's series were used to model discrete measured time depended evapotranspiration data. By differentiation of the fitted model the quantity of selected time interval evapotranspiration was computed. By comparing the measured and estimated data the time depended errors were calculated. Computed errors were analyzed, and the statistical distributions of the errors were discussed.
Keywords: evapotranspiration, ET, weighing lysimeter, error analysis, Kerman.

1 Introduction

Crop evapotranspiration (ET) is a major component of any local hydrologic system. It is an important factor in planning and developing water resources. It should be estimated as correctly as close to avoid any consequence of over or under estimating in local water resources planning. Lysimeter is an instrument to measure actual crop evapotranspiration in field of agricultural irrigation management. It has been used in the United States since the 1930s mainly to measure evapotranspiration (Malone et al. [1]). An excellent summary of

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weighing lysimeter in the United States are presented by Market et al. [2]. After 1970 most constructed lysimeters used load cells to determine mass and have a reported accuracy less than 0.05 mm which has been suggested as the maximum value necessary to measure hourly ET (Market et al. [2]). According to Allen et al. [3] lysimeter-computed ET is subject to uncertainly, mainly from two sources: measurement uncertainly and representatives of the lysimeter data, although nonrepresentative data may contribute substantially more error. The lysimeter facility provides a unique tool for botanists, agronomists and other plant scientists. By recording information such as soil moisture conditions with in the lysimeter and plant characteristics such as growth rates and maturation it will be possible to more closely evaluate and model the influences of environment on plant growth (Evett et al. [4]). Harrold and Dreibelbis [5] described the lengthy and laborious technique used to obtain the undisturbed monoliths used in the Coshocton, Ohio lysimeter installations. Rapid techniques have been developed to obtain deep undisturbed soil monoliths by pushing cylinders in to the soil. Weighing lysimeter measurements are more reliable method of determining effective rainfall because all components of the water balance are measured. Design factors involved in lysimetry were reviewed by Harrold and Dreibelbis [5]. Two different types of weighing lysimeters have been developed. These involve counterbalancing the dead load (scales approach) of the lysimeter [6, 7], or using sensitive load measuring devices [8, 9].

In order to measure ET in Kerman area, southeast of Iran, a large weighing lysimeter was built and its data may used to calibrate available ET estimation equations. The over all purpose of this article is to introduce the Kerman weighing electronic lysimeter and by a Fourier’s series model to present discrete measured data by continuous equation and to study the residual error of measured and fitted model.

2 Kerman weighing lysimeter and instrumentation

Kerman is located at south east of Iran by latitude $30^{\circ},15'$ and longitude $56^{\circ},58'$. In order to measure actual evapotranspiration in this area an electronic weighing lysimeter was used. The general concept of a weighing lysimeter requires four major elements. These include the container to hold the soil, water and vegetation; a rigid foundation and house; the force measuring or weighing system; and the data acquisition and analysis system. Accessory instrumentation is also required to measure and record climatic data. The lysimeter designed and installed in this research is illustrated schematically in Figure 1. It consisted of two cylindrical containers. The cylinders contained the soil, water and vegetation, and its weight was measured using three strain gage load cells. One of the load cells and foundations is illustrated in a schematic shown in Figure 2. After installation was completed, undisturbed soil and vegetation was placed on the cylinders and reference crop was placed around the cylinders to restore the original ground surface elevation and vegetation. Cylinder dimensions were selected based on maintaining a suitable diameter to depth ratio (greater than one), and the availability of large diameter steel pipe. The cylinder was 1067 mm in outside diameter with a 9.5mm wall thickness and 1372mm long. Three load cells are used to translate weighing changes in the lysimeter to voltage changes. Also the data logger and data processing weighing system with 48 m^2 under ground building are used. These instruments, measure cultivation cylinders mass in ten-minute intervals, and record them on PC hard disk. An example of hourly printout during a 24-hr period is given in Table 1. Because profile measurements (wind, temperature and moisture) are more easily taken over a very low-growing crop, it was decided that for the first phase of the project reference grass would be used.

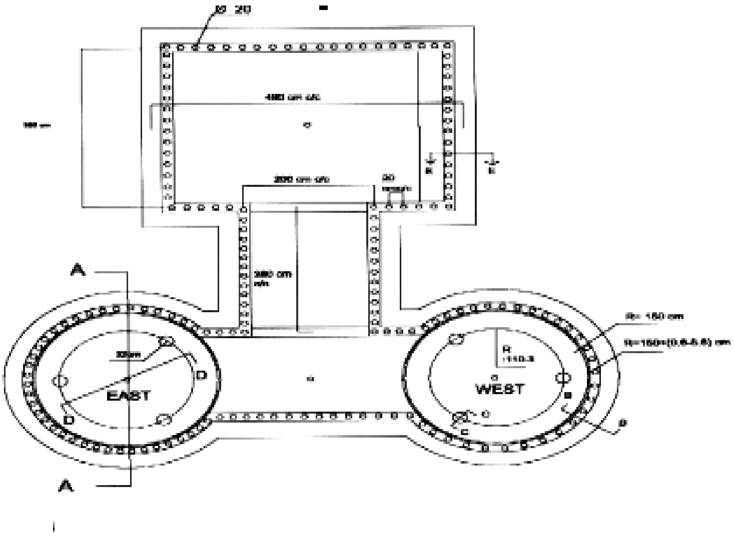

Figure 1: Plan configuration of the lysimeter underground building.

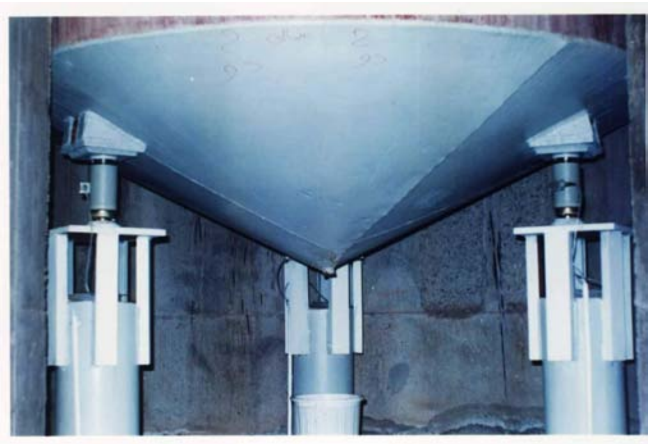

Figure 2: The load cells and foundation of the cylinder.

Table 1: Example of hourly printout of lysimeter recording system.

Date (d m y)	Time (h:m)	Relative Humidity (%)	Air Temp. ('C)	Wind speed (m/sec)	Wind Direction (degree)	Weight-North cylinder (1000Kg)	Weight-South cylinder (1000Kg)
01/06/2002	07:01	52.9	15.2	0.2	36	23.084	23.178
01/06/2002	07:11	49.2	16.3	0.2	74	23.085	23.18
01/06/2002	07:21	46.5	17.5	0.2	57	23.085	23.179
01/06/2002	07:31	45.6	18.1	0.2	19	23.085	23.18
01/06/2002	07:41	44.5	18.6	0.5	42	23.084	23.178
01/06/2002	07:51	44.1	19.8	0.7	45	23.085	23.18
01/06/2002	08:01	41.7	20.5	0.7	42	23.085	23.178
01/06/2002	08:11	40.1	21	0.5	77	23.084	23.178
01/06/2002	08:21	39.6	22.2	0.6	31	23.085	23.178
01/06/2002	08:31	38.8	23.5	0.2	22	23.084	23.179
01/06/2002	08:41	39.1	23.3	0.6	24	23.084	23.178
01/06/2002	08:51	36.5	24.2	0.6	35	23.084	23.178

3 Modeling lysimeteric data

The lysimeter weighing system, measures cultivation cylinders masses in ten-minute intervals. Each data points include total measurement error. In order to eliminate random error and built a continue record by discrete data, Fourier's series were used. The suggested model for each day from June1-3, 2002 is:

$$ET_C = [C_1 + C_2 \times \cos(\frac{ij}{T} + C_3) \times (\frac{ij}{T})^3 + C_4 \times (\frac{ij}{T})^2 + C_5 \times (\frac{ij}{T})]/7 \qquad (1)$$

where ET_C is cumulative evapotranspiration (mm/hr), C_1 is phase factor, $C_{2,} C_{3,} C_4, C_5$ are constant coefficients, j is day of the year (1Jan. =1), i is hour of the day, $T = \frac{2\pi}{24 \times 364}$ and 7 is surface of cylinder (m^2).

Estimated eqn. (1) coefficients by least square method were presented in Table 2. In this model the correlation coefficient in level of 1% is significant. The observed, fitted curve and their residual data for north and south cylinders for three days are shown in Figure 3.

The suggested model for three days respectively from June 1-3, 2002 is:

$$ET_C = \left\{ C_0 + \sum_{J=1}^{n} [C_1 \times \cos[(\frac{ij}{T}) + C_2] \times (\frac{ij}{T})^3 + C_3 \times (\frac{ij}{T})^2 + C_4 \times (\frac{ij}{T})] \right\} / 7 \qquad (2)$$

The constant coefficient and the observed fitted curve and their residual data for north and south cylinders for three days are shown in Table 3 and Figure 4.

Table 2: The coefficients of model for three days individually.

	Date	01/06/2002	02/06/2002	03/06/2002
Day of the Year (J)		152	153	154
North cyl.	Coefficient			
	C1	22963.81	23008.95	22988.05
	C2	27.05	14.84	18.43
	C3	3.79	3.60	3.76
	C4	-172.19	-106.81	-13.1.82
	C5	290.009	183.76	221.94
R-squared		0.996	0.998	0.998
South cyl.	Coefficient			
	C1	23044.26	23132.17	23111.55
	C2	35.98	10.94	14.35
	C3	3.95	3.43	3.71
	C4	-211.49	-76.03	-102.16
	C5	336.14	123.86	162.04
R-squared		0.993	0.996	0.995

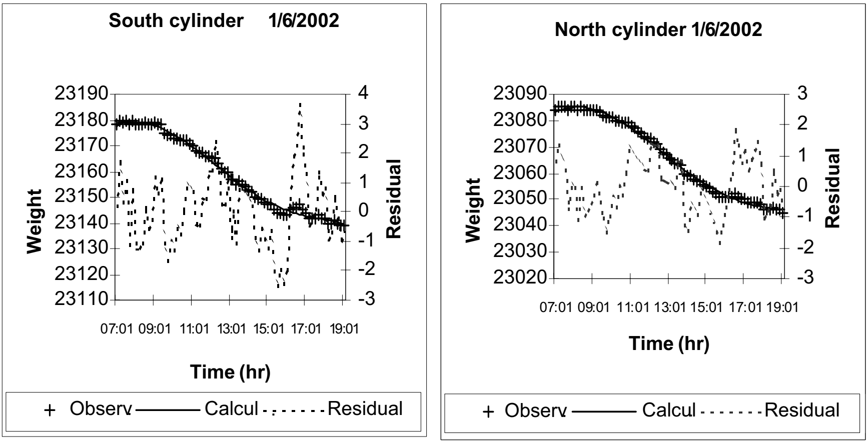

Figure 3: Measure cylinder mass as function of time on June 1, 2002.

4 Evapotranspiration computation

By modeling the cylinder time depended on mass reduction by eqn. (1), timely, evapotranspiration was computed by differentially of that equation respect to time. In that order the general differential of eqn. (1) can be written as:

$$ET_i = ET_{i-1} + \Delta I[-C_2 \times \sin(\frac{ij}{T} + C_3)(\frac{i^3 j^4}{T^4}) \\ + 3C_2 \times \cos(\frac{ij}{T} + C_3)(\frac{i^2 j^3}{T^3}) + 2C_4(\frac{ij^2}{T^2}) + C_5(\frac{j}{T}) \tag{3}$$

Table 3: The coefficient of model for three days respectively.

	Date	01/06/2002	02/06/2002	03/06/2002
North cyl.	Coefficient	J=152	J=153	J=154
	Co	23004.17		
	C1	17.038	15.98	14.18
	C2	3.48	3.65	3.59
	C3	-109.45	-114.11	-105.86
	C4	192.76	195.18	182.41
R-squared	0.998			
South cyl.	Coefficient	J=240	J=241	J=242
	Co	23127.66		
	C1	13.92	11.89	10.16
	C2	3.399	3.513	3.39
	C3	-82.076	-82.88	-74.53
	C4	135.36	134.62	121.29
R-squared	0.994			

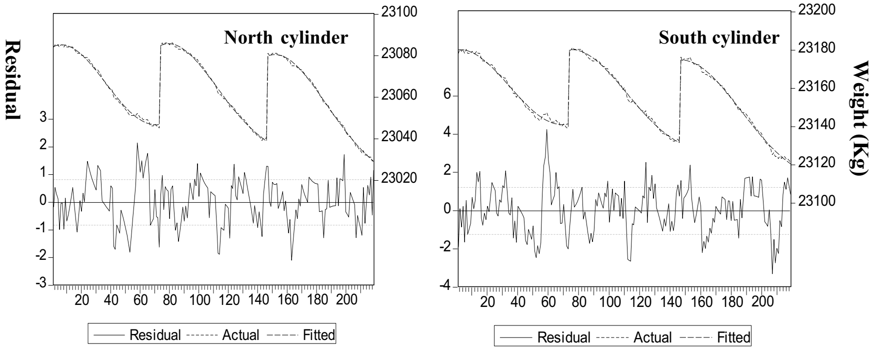

Figure 4: The observed fitted curve and their residuals for two cylinders.

where ET_i is evapotranspiration in i th time stage and ΔI is any time interval.

For ΔI equal to one hour the hourly ET are computed and shown in Figure 5. These charts show the hourly evapotranspiration for three days under the study. The variation of the ET depends on time of day with different temperature, solar radiation, wind speed and other meteorological parameters.

5 Error analysis

The residual error was tested for normality with zero means and 1SD by chi square test [10]. Comparing the theoretical and sample values of the relative frequency or the cumulative frequency function can test the goodness of fit. In the case of the relative frequency function, the chi square test statistic χ_C^2 is given by [10]:

$$\chi_C^2 = \sum_{i=1}^{m} \frac{n[f_s(x_i) - p(x_i)]^2}{p(x_i)} \tag{4}$$

where: m is the number of intervals, $f_s(x_i) = \frac{n_i}{n}$, n_i is the number of observations in interval i, $p(x_i) = F(x_i) - F(x_{i-1})$.

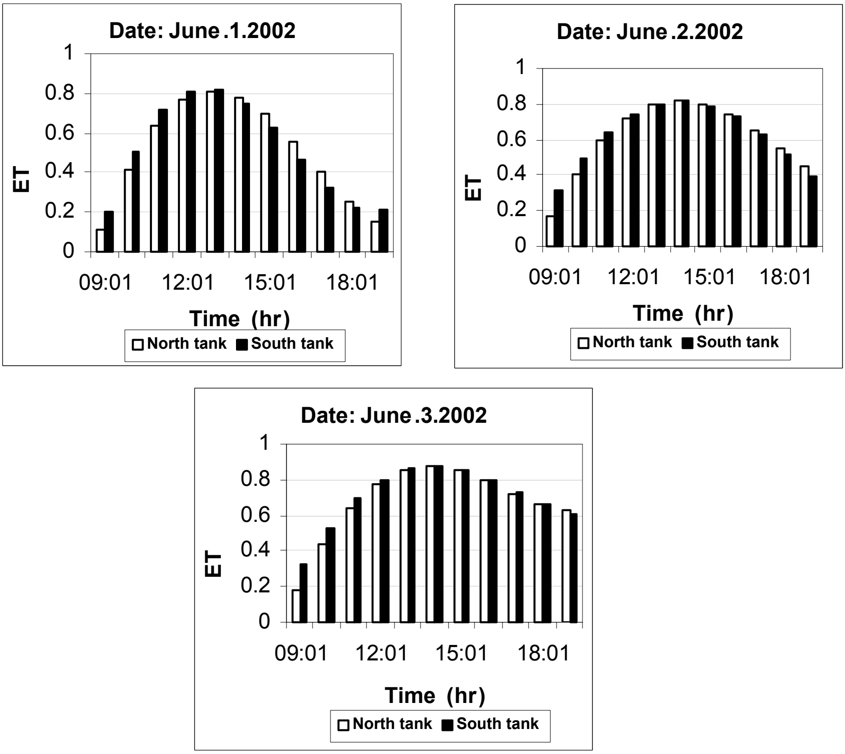

Figure 5: The hourly evapotranspiration (mm/hr) for three days.

To describe the χ^2 test, the χ^2 probability distribution must be defined. A χ^2 distribution with ν degrees of freedom is the distribution for sum of squares of ν independent standard normal random variable Z_i. In the χ^2 test, ν=m-p-1, where m is the number of intervals, and p is the number of parameters used in fitting the proposed distribution. A confidence level is chosen for the test; it is often expressed as $1-\alpha$, where α is termed the significance level: A typical value for the confidence level is 95 percent. The null hypothesis for the test is that the proposed probability distribution fits the data adequately. This hypothesis is rejected if the value of χ_C^2 is larger than a limiting value, $\chi_{v,1-\alpha}^2$, determined from the χ^2 distribution with v degrees of freedom as the value having cumulative probability $1-\alpha$.

For analyzed the computed residual error, the fitting normal distribution was tested. Tables 4 and 5 show the parameters of error analysis lysimeteric data for north and south cylinders. To fit the normal distribution function, the sample statistics $\bar{x} = 0.00029$ in and SD=1.166 in are calculated for the residual data for south cylinder. The standard normal variate Z corresponding to the upper limit of each of the data intervals is calculated and shown in Tables 4 and 5.

The relative frequency functions $f_s(x_i)$ and $p(x_i)$ from Tables 4 and 5 is plotted in Figure 6 and also the cumulative frequency and probability distribution functions $F_s(x_i)$ and $F(x)$ in Figure 6 for north and south cylinders. From the similarity of the two functions shown in each plot, it is apparent that the normal distribution fits these residual data very well. To check the goodness of fit, the χ^2 test statistic is calculated by eqn. (4) as shown in column 9 of Table 4. The total of values in column 9 is $\chi_C^2 = 0.0511$. The value of $\chi_{v,1-\alpha}^2$ for a cumulative probability of $1-\alpha = 0.95$ and degree of freedom $v = m - p - 1 = 9 - 2 - 1 = 6$ is $\chi_{6,0.95}^2 = 12.6$ [10]. Since this value is greater than χ_C^2, the distribution fits the residual data cannot be rejected at the 95 percent confidence level; the fit of the normal distribution to the lysimeteric residual data is accepted.

Table 4: Fitting a normal distribution to residual for north cylinder.

i	Range	n_i	$f_s(x_i)$	$F_s(x_i)$	z_i	$F(x_i)$	$p(x_i)$	χ_c^2
1	<-2	1	0.005	0.005	-2.484	0.006	0.006	0.042
2	-2,-1.5	5	0.023	0.027	-2.174	0.027	0.022	0.009
3	-1.5,-1	21	0.096	0.123	-1.553	0.123	0.096	0
4	-1,-0.5	35	0.160	0.283	-0.932	0.283	0.160	0
5	-0.5,0	48	0.219	0.502	-0.311	0.502	0.219	0
6	0,0.5	41	0.187	0.690	0.310	0.690	0.187	3.6047E-30
7	0.5,1	48	0.219	0.909	0.931	0.909	0.219	0
8	1,1.5	16	0.073	0.982	1.552	0.982	0.073	0
9	>1.5	4	0.018	1.000	1.863	1.000	0.018	0
total		219						0.051

Mean=6.55E-05.
Standard deviation=0.805.

Table 5: Fitting a normal distribution to residual for south cylinder.

i	Range	n_i	$f_s(x_i)$	$F_s(x_i)$	z_i	$F(x_i)$	$p(x_i)$	χ_c^2
1	<-3	1	0.005	0.005	-2.574	0.006	0.006	0.042
2	-3,-2	11	0.050	0.055	-2.145	0.055	0.049	0.004
3	-2,-1	32	0.146	0.201	-1.287	0.201	0.146	0
4	-1,0	60	0.274	0.475	-0.429	0.475	0.274	0
5	0,1	76	0.347	0.822	0.429	0.822	0.347	0
6	1,2	34	0.155	0.977	1.286	0.977	0.155	0
7	2,3	4	0.018	0.995	2.144	0.995	0.018	0
8	>3	1	0.005	1.000	2.573	1.000	0.005	1.48E-28
total		219						0.046

Mean=0.00029.
Standard deviation=1.166.

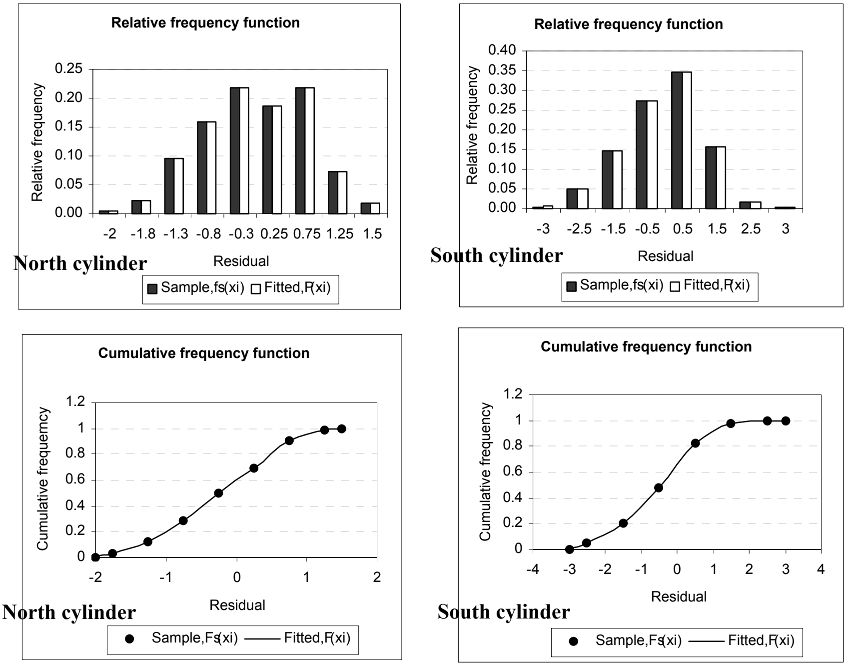

Figure 6: Frequency functions for a normal distribution fitted to residual for north and south cylinders.

6 Conclusion

A lysimeter design has been derived and implemented which will meet the needs of evapotranspiration research for the Kerman province, southeast of Iran. So a large weighing electronic lysimeter was designed, constructed and installed in this area by ACECR- Kerman branch. The parameters of wind disturbance, water infiltration, drainage, thermal continuity, sidewall water percolation, scale stability and safety were considered in the design. Automated cylinder's weight and weather data acquisition were saved in the computer. The main purposes of this article were to present a statistically error analysis for total measurement lysimeteric data. Also in order to estimate random data and built a continuous record by discrete data, the Fourier's series were used and the best model for estimate ET for three days in Kerman was computed. The residual frequency function curves show that the normality distribution fits the residual data at the 95% confidence level and the fit of the normal distribution at the residual data is accepted. According to Figure 5, the maximum hourly evapotranspiration in Kerman is about 0.8 mm in 14:00 pm. in pick month June 1-3, 2002.

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Improving irrigation practice in New Zealand

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Abstract

The Canterbury Plains are the major cropping area, and an increasingly important dairying area, in New Zealand. Irrigation is necessary on most of the Plains to achieve high productivity. However, competition for limited water resources means that farmers increasingly have to justify their demands for water. Farmers need to know when to irrigate, how much water to apply, and the yield penalty if the crop is not irrigated. For annual arable crops, we have used the maximum potential soil moisture deficit (MPSMD) model and a large rainshelter to answer these questions. Total or economic yield of nearly all the crops tested decreased linearly as MPSMD increased, regardless of the timing of drought. The slope of the regression line is the yield loss with increasing MPSMD. For ryegrass dairy pastures, which grow throughout the year, the model has been adapted to simulate actual soil moisture changes. As most farmers do not measure pasture production directly, we have developed a model for potential pasture production, and a simple relationship between grass growth restrictions and actual soil moisture deficits, that fits experimental farm data. Farmers can also reduce the amount of water they apply by improving the water application efficiency of their irrigation systems. Protocols had been developed to identify causes of poor performance in the field, and how these may be addressed. This information is being used by farmers to improve their irrigation decisions, and irrigation system performance, and has been included in decision support systems for arable and vegetable farmers, and is being developed for dairy farmers.

Keywords: drought, crops, pasture, irrigation application efficiency, rainshelter, modelling, decision support systems.

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1 Introduction

The Canterbury Plains of the South Island of New Zealand lie in the rain shadow east of the Southern Alps mountain range, and can experience drought at any time of the year. Daily potential evapotranspiration often exceeds 6mm/day over summer. This is double the mean summer daily rainfall, which has a coefficient of variation of 42% [1]. Soil water storage over much of the Plains is restricted because of shallow soils, with less than 30 cm soil depth over gravel [2], and so irrigation is vital to achieve the high productivity essential for profitability in a deregulated agricultural economy.

Irrigation accounts for 70% of all water used in New Zealand and contributes USD500M to the local economy [3]. The area under irrigation has increased four fold over the past 10 years to 475,700 ha, mainly under intensive cropping or dairying. Demand for irrigation has placed pressure on the limited river and aquifer water sources. Farmers now have increasingly to justify their demands for irrigation water, and regional authorities are looking at ways to ensure that farmers efficiently use the water that they are allocated [4].

The questions that farmers need to ask are when to irrigate, how much to put on, and the yield penalty if the crop is not irrigated or only partially irrigated. Armed with this information, they can make decisions that use the water resource more efficiently, and achieve the best economic outcome on both a crop and farm scale.

2 Arable crops

To answer the questions posed above, farmers need to know how dry their soil is. This is time consuming and expensive to measure directly. However, we have found that, the model of Penman [5], as refined by French and Legg [6], works well for annual arable crops. This model quantifies the yield response to drought by using the maximum potential soil moisture deficit (MPSMD) experienced during the growth of the crop as the measure of stress. Potential soil moisture deficit (PSMD) is readily calculated from potential evapotranspiration (PET), rainfall and irrigation data, and has practical meaning in that PSMD can be equated with irrigation applications (or lack of them). Responses to the MPSMD are given in terms of reductions in yield below the much more stable fully irrigated yield. The model produces two meaningful numbers: a critical deficit beyond which yield is reduced, and a reduction in yield per unit of potential deficit when the critical deficit is exceeded.

The model needs to be calibrated for individual crops, as they differ in their susceptibility to drought. We have used a mobile automatic rainshelter [7] to exclude rainfall from experimental plots, which are otherwise exposed to normal weather. This has allowed us to reliably impose a range of drought treatments, based on actual soil moisture, which have included timing and duration of drought periods, and irrigation amounts and frequencies. Up to twelve irrigation treatments, based on timing or intensity of drought, were set up for each of the experimental crops. The PSMD was calculated for each treatment by adding the maximum weekly Penman PET from the fully irrigated control treatment to the irrigation deficit (the difference between the amount of water applied to the treatment and to the fully irrigated control). The deficit was adjusted for incomplete ground cover using the modified model of Ritchie [8].

Total, grain, root or tuber yield of all the crops tested, with the exception of oats and white clover seed, generally decreased linearly as the MPSMD experienced during crop growth increased (Figure 1). The slope of the regression line between yield and MPSMD is the yield loss with increasing deficit. This varies from 8 kg/ha/mm for peas [10] up to 25 kg/ha/mm for barley [11]. A critical deficit, below which there is no loss in yield with changing deficit, was able to be determined analytically for wheat [11], but not for any of the other crops.

This linear reduction in yield with increasing deficit occurred regardless of the timing of drought. Consequently economic yield in most crops was related to the intensity and not the timing of drought. How the drought stress influences yield components can vary with timing of stress, as grain size and harvest index in some crops were reduced by late drought [10, 11].

In oats and white clover, frequent irrigation to maintain very small deficits reduced yield, due to excessive vegetative growth, causing lodging in oats [12], and shading of the flowers, and hence reduced pollination, in white clover [13]. In these cases, stress at a particular growth stage is beneficial for seed production, but not for total dry matter production.

The relationship between crop yield and MPSMD is also affected by the water holding capacity (WHC) of the soil; the lower the WHC, the lower the yield at a given MPSMD. However, we have successfully extrapolated the results from the rainshelter experiments to other soil types by adjusting the model for crop rooting depth (about 0.8 m for peas to about 2 m for maize), depth of soil (WHC 165 mm/m) to gravel (55 mm/m) or to a pan, which impedes rooting [14].

The MPSMD model provides very straightforward calculations of the value of irrigation, capable of being done quite simply in a spreadsheet or even on paper. However, we have developed more complete DSSs [15] based on simulation models such as Sirius [16] that deal with the crop in mode detail, keep a proper water balance including an estimate of the actual soil moisture deficit (ASMD) through time.

3 Perennial pastures

One of the main advantages of simulation models is that they don’t need an estimate of potential yield – they account for yield forming processes through the life of the crop. This is particularly important for perennial pastures, which continue to grow through the summer and autumn, when accumulated potential deficits are high, but rainfall can stimulate growth, or if potential deficits continue through the winter.

So we have to use ASMD to account for these features of perennial pasture. ASMD can be measured on farms by numerous methods, such as using neutron probes or time domain transmission. It can also be calculated from PET using models of varying complexity. We have used a simplified version of a published model [17] using soil available WHC, depth and bulk density, together with pasture cover, rainfall and irrigation, to calculate actual evapotranspiration (AET) from PET. Model outputs have related well to field measurements under grazed pasture (Figure 2).

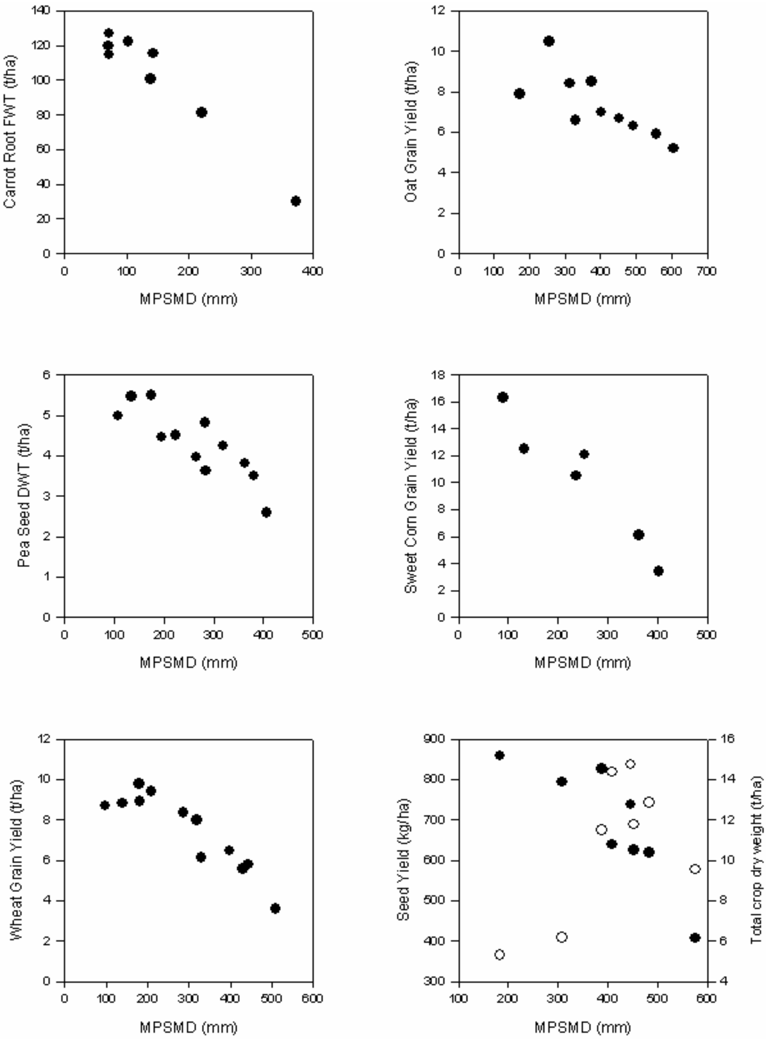


Figure 1: Effect of maximum potential soil moisture deficit (MPSMD) on yield of carrot roots, oat grain, pea seed, sweet corn fresh grain yield, wheat grain yield and white clover total biomass (●) and seed (○) yield (from [9]).

We have determined actual ryegrass pasture growth rates from pasture cuts in fields on high performing commercial dairy farms in Canterbury. These farms produce up to 18,000 kg pasture dry matter (DM)/ha/year under rotational grazing, and are irrigated and fertilised to avoid any restrictions on growth. The highest performing fields produced 0.4 kg of DM/MJ of intercepted solar radiation (the upper line in Figure 2). For the development of the model, we have taken this to be the potential growth rate under non-limiting conditions on dairy farms in Canterbury. Using this growth rate, a relationship between light interception and pasture mass, and a relationship between yield and AET similar to those with PET in Figure 1, we have successfully predicted pasture growth under very different irrigation regimes elsewhere in Canterbury. Figure 3 shows predicted and actual cumulative DM yields for rostered border-dyked flood irrigated pasture on very shallow soils under sheep grazing, compared to predicted yields on high performing dairy farms under sprinkler irrigation on deep soils.

4 Irrigation application efficiency

Figure 2 shows that fields on some dairy farms produced only about 60% of the measured pasture DM yield of the four highest producing farms, and Figure 3 that the surface irrigated sheep fields were producing only about a third of the measured pasture DM compared to those highest producing dairy farms. One of the major reasons for these differences is poor irrigator performance on farm.

We have evaluated the performance of several sprinkler irrigation systems used for irrigating pasture under normal operating conditions in the field. Figure 4 is an example of a centre pivot irrigator on a dairy farm where the measured radial low quarter distribution uniformity [19] was 0.76, which is rated only fair for a centre pivot. Problems specific to this irrigator included incorrectly operating sprinklers (especially by the towers), insufficient pressure, and wheel track rutting. On other monitored farms with rotating boom irrigators, excessive application rates and depths, variable operating speeds and distances between runs were identified as causes of poor uniformity. Multiple spray line systems had very poor uniformities on farm (as low as 35%), partly due to poor sprinkler spacing, throw and pattern, and insufficient system pressure. In addition, the distribution pattern of rotating boom and multiple spray line systems was greatly affected by wind speed and direction in the windy Canterbury environment [1].

On surface flood irrigation schemes, where water is supplied on a roster, irrigation efficiencies are lower, ranging from 31 to 61%, the variation being due mainly to variable flow rates and over-irrigation if irrigation restrictions were forecast [20]. Improvements in border-dyke construction techniques, such as laser levelling, can increase irrigation efficiencies considerably, but they are still very variable on-farm [21]. Surface schemes are often located on stony soils in New Zealand, and up to two thirds of the applied water can be lost through drainage [20].

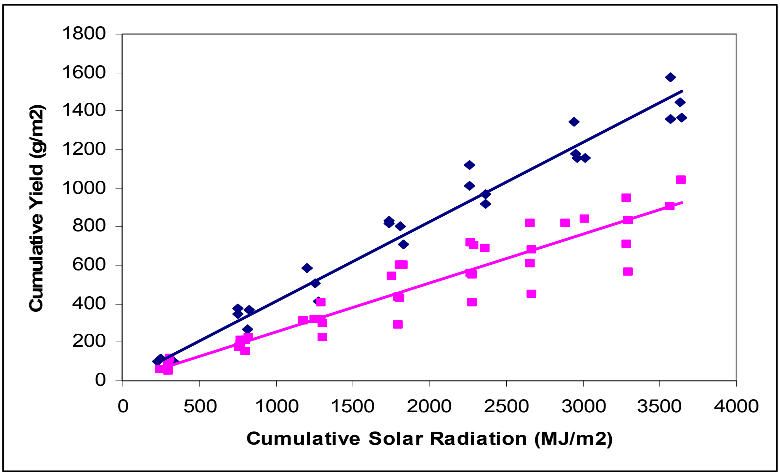


Figure 2: Cumulative dry matter yield per hectare versus total incoming solar radiation from the top four monitored grazed dairy fields (▲, slope 0.412, r^2 0.97) and from another six fields (■, slope 0.253, r^2 0.88).

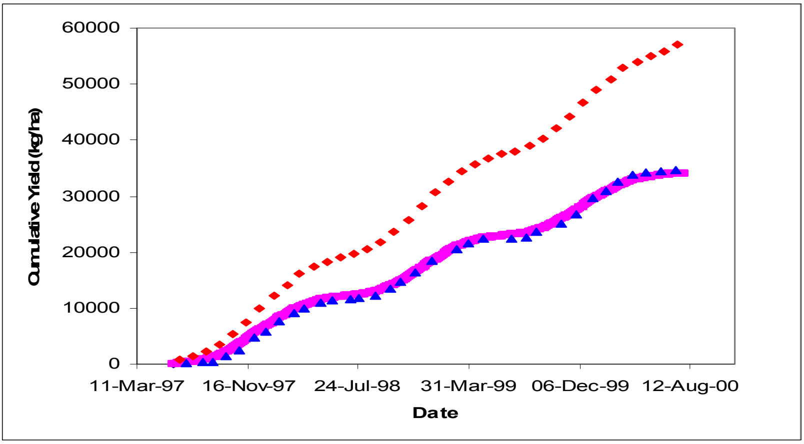


Figure 3: Measured (▲) and modelled (■) cumulative pasture dry matter yield over three years on a sheep farmlet study under flood irrigation [18], and modelled pasture dry matter yields (●) from the high performance dairy farms in Figure 2.

To assess and improve actual-on farm irrigation system performance, a code of practice and computer software has been developed for evaluation of sprinkler irrigation systems in New Zealand [19]. Protocols have been developed for an on site evaluation of an irrigation system using selected measurements to describe the performance of the system, and its management, and to identify causes of poor performance and how these may be addressed. The primary focus is to determine distribution uniformity, application rates and depths, and the causes of non-uniformity. Based on these measures, clear recommendations are made to the farmer on how to improve irrigator system performance.

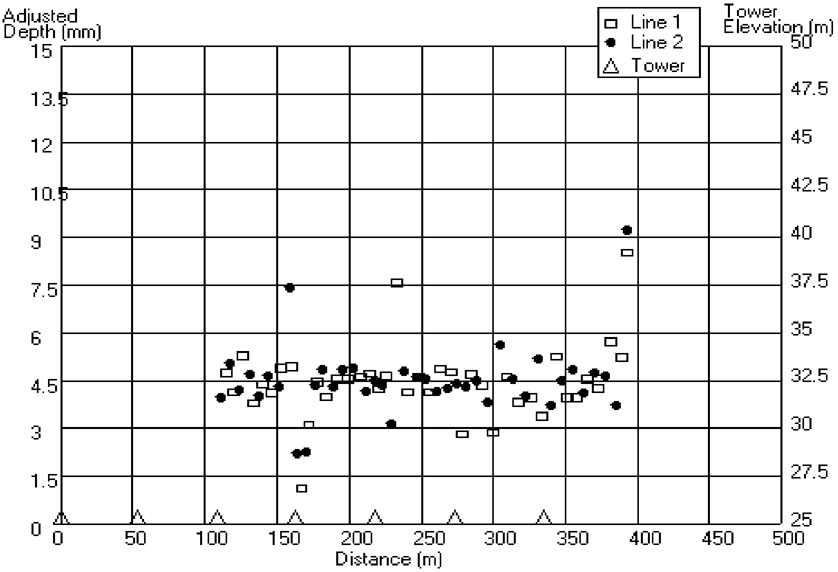


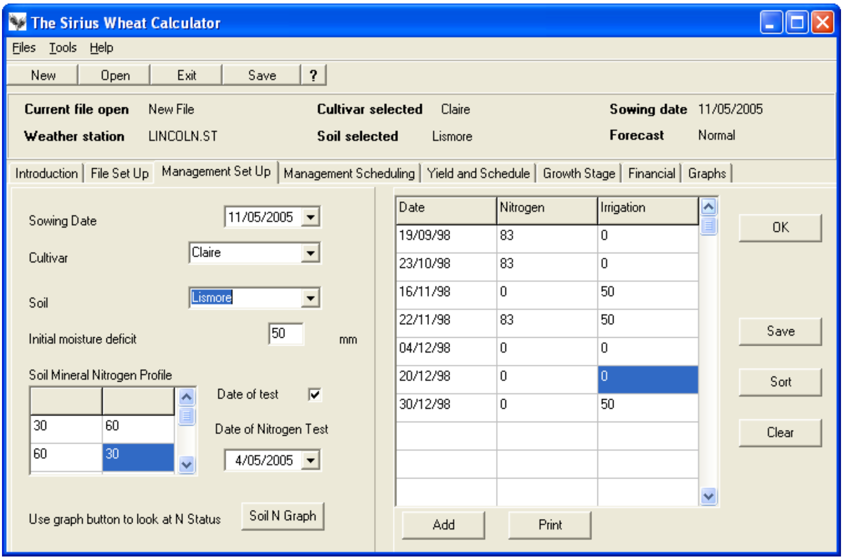
Figure 4: Application depth adjusted for distance along the boom of a centre pivot irrigator operating on a commercial dairy farm in Canterbury, New Zealand.

5 Applications

The information from these experiments has enabled clear irrigation scheduling information to be given to farmers. It has also been included in computerised decision support systems developed for wheat, pea, maize, potato and carrot farmers in New Zealand, which enable farmers to see the effects of altering their irrigation and other practices on estimated yields and grain nitrogen [14, 15].

The wheat calculator is now commercially available in New Zealand. An input screen image from this programme, where farmers can see the effects of adjusting irrigation timings and amounts, is shown in Figure 5, and an output screen, which shows the predicted effects of a selected irrigation regime on soil moisture deficits, in Figure 6. A simpler model based on data presented here is being developed into a pasture irrigation calculator for dairy farmers to use in the field.

These, and the improvements in irrigation application efficiency resulting from on farm evaluations of irrigator systems performance, are enabling Canterbury farmers to use their irrigation water more efficiently and economically, benefiting both them and the environment.



Current file open New File
Cultivar selected Claire
Sowing date 11/05/2005
Weather station LINCOLN.ST
Soil selected Lismore
Forecast Normal

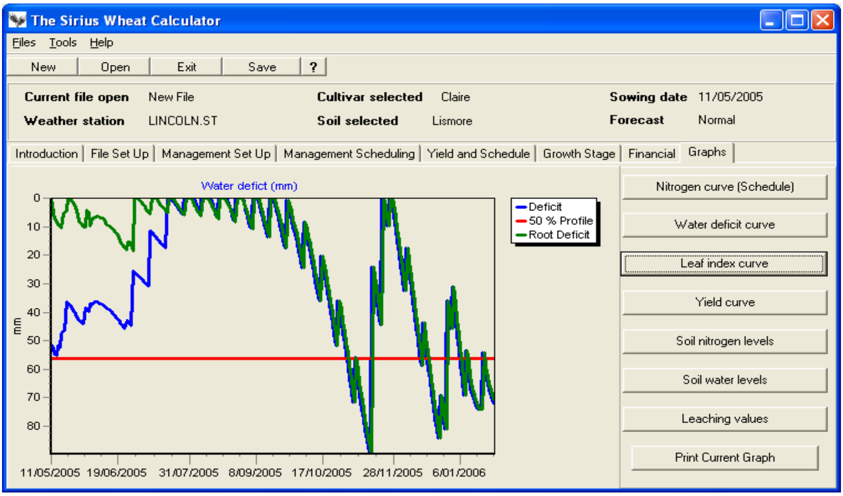
Sowing Date 11/05/2005
Cultivar Claire
Soil Lismore
Initial moisture deficit 50 mm
Soil Mineral Nitrogen Profile

30	60
60	30

Date of test ☑
Date of Nitrogen Test 4/05/2005
Use graph button to look at N Status

Date	Nitrogen	Irrigation
19/09/98	83	0
23/10/98	83	0
16/11/98	0	50
22/11/98	83	50
04/12/98	0	0
20/12/98	0	0
30/12/98	0	50

Figure 5: Input screen from the Sirius Wheat Calculator showing the nitrogen and irrigation input page.



Current file open New File
Cultivar selected Claire
Sowing date 11/05/2005
Weather station LINCOLN.ST
Soil selected Lismore
Forecast Normal

Figure 6: Output screen from the Sirius Wheat Calculator showing the development of predicted potential soil moisture deficits over the season.

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Hydraulic modelling of drip irrigation systems used for grass establishment on steep slopes

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Abstract

Erosion damage to railway embankment and cutting steep slopes (batters) causes a significant cost of remediation within the coal railway network of Central Queensland, Australia. It has been established that grass cover of 60% reduces erosion by over 90%. Given that water is a scarce commodity in the semi-arid environment, a more efficient water use cost-effective drip irrigation system is imperative. The hydraulic modelling of drip irrigation systems design is presented. It takes into account the velocity head change and a proper selection of the friction coefficient formula based on the Reynolds number. Fittings and emitter insertion head loss are incorporated into the hydraulic model. A case study of the use of the hydraulic model to analyse the drip irrigation systems is presented.

Keywords: steep slopes, drip lateral, irrigation, hydraulics, embankment, grass establishment.

1 Introduction

Erosion of railway embankment and cutting batters within Central Queensland, Australia, increases maintenance costs, risks of outages and derailments, interruptions of normal train operations and environmental degradation. The QR (Queensland Rail) funded HEFRAIL Research Project with Central Queensland University has demonstrated that 60% grass cover on railway embankment batters reduces erosion by over 90% compared with the bare scenario. Further increase in grass cover increases the erosion reduction up to 99% [1–3]. Drip irrigation systems, consisting of laterals with equally spaced emitters and uniform slope, have been identified as an integral part of grass establishment to

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control erosion on railway embankment steep slopes (batters) within the semi-arid region [2, 4–6]. Water is a scarce commodity and may be sourced from existing water mains, existing or temporary excavated ponds/ dams/ creek water holes, or temporary tanks filled periodically by water trucks. The choice of water source depends on availability and costs.

There have been several studies of the hydraulics of drip laterals [e.g. 7]. Yildirim and Agiralioglu [8] have reviewed and compared the performance of some approaches for solving the hydraulics of drip laterals. Basic differences in the approaches are essentially the inclusion or not of the velocity head and minor losses due to emitter insertion, and the treatment of the emitter discharges as constant or variable along the lateral. However, the forward-step method proposed by Hathoot *et al* [9] has been described by many authors [e.g. 10, 11] as the most accurate method. This method takes into account the velocity head change and a proper selection of the friction coefficient formula based on the Reynolds number which varies along the lateral. Recent studies have shown that emitter insertion head loss contributes to a significant proportion of the total head losses, in particular where the emitter numbers are high within the lateral, and needs to be taken into account [11–13].

Field values of emitter characteristics may be significantly different from the manufacturer supplied values as a result of manufacturing variations, micro-topography, clogging, and water quality [12, 14]. Gyasi-Agyei [14] has presented a novel approach for field scale assessment of the uncertainties associated with the drip lateral parameters. This paper gives an example of the use of the hydraulic model presented in Gyasi-Agyei [14] to simulate drip lateral designs at multiple sites of a new railway spur line.

2 The hydraulic model

2.1 Single Lateral

Emitter discharge varies along the lateral with maximum value at upstream and zero at the end. Consider the lateral in fig. 1 having inlet pressure head H_0 and discharge Q_0, and equal emitter spacing s. It is more convenient to cut the lateral midway between two emitters at the connection point to the submain. Hence the head loss in this small section needs to be taken into account when estimating the pressure head at the first emitter. The discharge q_i (L.h^{-1}) from an emitter i is determined by the rating curve

$$q_i = kH_i^x \tag{1}$$

where H_i (m) is the pressure head in the lateral at the emitter i, x is the emitter discharge exponent characterizing the flow regime and emitter type, and k is emitter discharge coefficient.

The Forward-Step Method equation [14]

$$H_{i+1} = H_i + \frac{3}{2gA^2}\left[Q_i^2 - Q_{i+1}^2\right] - \left[\frac{8s}{\pi^2 gD^5} f_{i+1} + \frac{\alpha}{2gA^2}\right] Q_{i+1}^2 - ss_o \tag{2}$$

is used to solve for the emitter pressure and discharges forwards. In eqn. (2) $s_o=(z_{i+1}-z_i)/L$ is the constant slope of the lateral (positive for uphill and negative for downhill), D(m) is diameter, A(m^2) is cross-sectional area, H_i(m) is the pressure head at emitter i, Q_i(m) is discharge flowing to emitter i, s(m) is emitter spacing, and L(m) is the length of the lateral. The friction coefficient f_{i+1} is defined by

$$\begin{aligned} f_{i+1} &= \frac{64}{R_{i+1}}, & R_{i+1} &\le 2000 & &\text{laminar flow} \\ f_{i+1} &= \frac{0.316}{R_{i+1}^{0.25}}, & 3000 < R_{i+1} &\le 10^5 & &\text{turbulent flow} \\ f_{i+1} &= \frac{0.130}{R_{i+1}^{0.172}}, & 10^5 < R_{i+1} &< 10^7 & &\text{fully turbulent flow} \end{aligned} \tag{3}$$

where R_{i+1} is the Reynolds number. Eqn. (2) was proposed by Hathoot *et al* [9] except for the addition of the local head loss term due to emitter insertions estimated as kinetic head multiplied by the emitter head loss coefficient α.

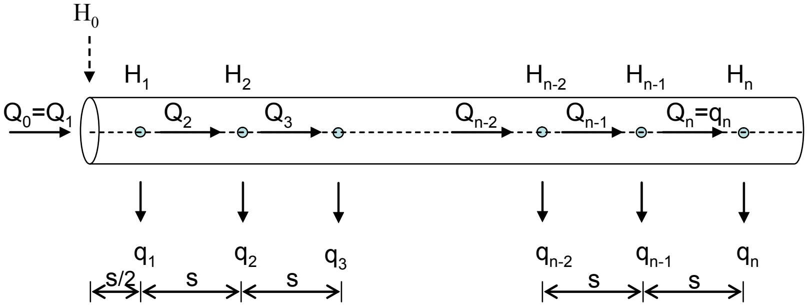

Figure 1: Single drip lateral hydraulic features.

For a given lateral inlet pressure H_0 the emitter discharges are obtained by solving eqn. (2) forwards. Initially the inlet discharge $Q_0=Q_1$ is assumed and used with eqn. (3) to evaluate the friction coefficient f_1. With eqn. (2) H_1 is calculated, followed by the calculation of q_1 using eqn. (1), and then calculation of Q_2 which equals Q_1-q_1. The calculation is repeated for the next emitter downstream until the last emitter discharge q_n is estimated. For a given lateral's characteristic parameters and inlet pressure, there is a unique solution of Q_0 such that

$$Q_0 - \sum_{i=1}^{n} q_i = 0, \quad Q_n = q_n > 0 \tag{4}$$

In other words, it is a problem of finding the root (Q_0) of a non-linear function of eqn. (4). The greater than zero condition is important since below a threshold value of Q_0 for a fixed inlet pressure there is no flow through the last emitter. Any root finding algorithm can be used to solve eqn. (4). Brent root finding algorithm, which combines root bracketing, interval bisection, linear interpolation and inverse quadratic interpolation, is used with the lower and upper values of Q_0 defined by $0.1nkH_0^x < Q_0 < nkH_0^x$ to solve eqn. (4).

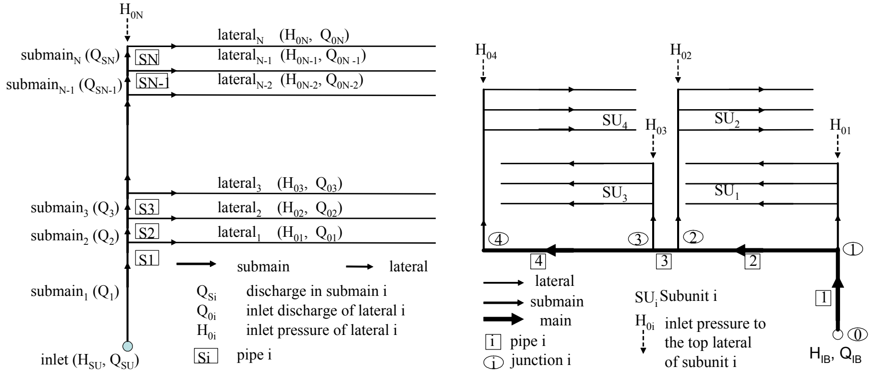

Figure 2: An irrigation subunit (left) and an irrigation bay with multiple subunits (right).

Similar concepts used for a single lateral are used for the subunit simulation as depicted in fig. 2 (left). The subunit inlet discharge Q_{SU} is a unique function of the top lateral inlet pressure H_{0i}. Given H_{0N}, Q_{0N} is estimated as explained for the single lateral case. Since Q_0 is the same as the discharge through the top submain, H_{0N-1} is estimated using the Backward-Step energy formula

$$H_{0i-1} = H_{0i} + f_{Si}\frac{8L_{Si}}{\pi^2 g D_{Si}^5}Q_{Si}^2 + L_{Si}s_o + k_{eSi}\frac{Q_{Si}^2}{2gA_{Si}^2} \tag{5}$$

where L_{Si} is the length of submain pipe Si between the laterals. The last term represents changes in geometry and fittings head loss with k_{eSi} the total upstream coefficient for pipe Si. The remaining symbols are as previously defined. Knowing H_{0N-1}, Q_{0N-1} can be estimated and added to Q_{0N} to give the discharge in the submain SN-1, Q_{SN-1}. The process is repeated for the next lateral and submain backwards until the subunit inlet pressure H_{SU} and discharge Q_{SU} are estimated. Hence pressure H_{0N} can be optimised to match the given Q_{SU} and simulated Q^*_{SU} subunit inlet discharges. Hence it is a problem of finding the root (H_{0N}) of a non-linear equation formulated as

$$Q_{SU} - Q^*_{SU}(H_{0N}) = 0 \tag{6}$$

satisfying the conditions given in the single lateral case. Eqn. (6) is solved using a modified Powell's hybrid algorithm which is a variation of Newton's method using a finite-difference approximation to the Jacobian.

To illustrate the principles for multiple subunits consider fig. 2 (right) which consists of four subunits joined to the main pipeline to form a single irrigation bay. Each subunit requires only the inlet pressure (H_{0i}) of the top lateral to estimate the pressure and discharge at the inlet of the subunit as described in the preceding paragraph. From hydraulic principles, pipes flowing away from a junction should have the same upstream pressure equal to the downstream pressure of the pipe flowing into the junction. To satisfy the continuity principle, the total flow into a junction must equal the total flow out of the junction. Therefore the problem can be formulated into a system of M (equal to the number of subunits) non-linear equations with M unknowns (the inlet pressures of the top laterals of the M subunits). Hence

$$\begin{aligned}
&\text{at junction 0:} \quad Q_{IB} - Q_{p1}(H_{01}, H_{02}, H_{03}, H_{04}) = 0 \\
&\text{at junction 1:} \quad H_{0SU1}(H_{01}) - H_{p2up}(H_{02}, H_{03}, H_{04}) = 0 \\
&\text{at junction 2:} \quad H_{0SU2}(H_{02}) - H_{p3up}(H_{03}, H_{04}) = 0 \\
&\text{at junction 3:} \quad H_{0SU3}(H_{03}) - H_{p4up}(H_{04}) = 0
\end{aligned} \tag{7}$$

where H_{piup} is the upstream pressure of main pipe i, H_{0i} is the inlet pressure of the top lateral of subunit i, and H_{0SUi} is the inlet pressure of subunit i, Q_{pi} and Q_{IB} are the discharges in pipe i and the total of the irrigation bay, respectively. Again the conditions given in the single lateral case must be satisfied. The system of non-linear equations is solved by the same procedure used for the single subunit case.

3 Case study: site 7 embankment of Bauhinia Regional Rail Project

3.1 Site description

Bauhinia Regional Rail Project (BRRP) is the construction of a 110 km spur line linking the new Rolleston Coal Mine to the Blackwater rail network at Kinrola in Central Queensland, Australia [6]. Big cuttings and embankments, and bridges and culverts, are major construction activities as a result of the route crossing various terrains from rocky mountainous country in the north to expansive black soil river plains in the south. In order to reduce the treatment costs, only the top 3 m of batters of all embankment sections exceeding 4 m in height and the downstream side embankment batters of the two major flood plains were irrigated. Three rows of driplines (17.6 mm internal diameter, 0.3 m emitter spacing, and 2.5L/h nominal emitter discharge) at 1 m row spacing were set up at the top batter sections of the selected embankments. Field scale assessment of the selected dripline characteristics [14] has indicated the effective parameter values are: $x = 0.493$, $k= 0.71$ and $\alpha=0.252$ which is significantly different from the manufacturer's supplied values of $x = 0.55$, $k= 0.68$ and $\alpha=0.15$. The variations in the dripline parameter values are attributed to manufacturing variations of the emitters, as well as environmental factors and water quality. Site 7, with a maximum height of 11.6 m, is located between 12880 m and 13480 m marks. Fig. 3 shows the layout of the irrigation system and the line drawings of the pipes of the eastern side, noting that the western side line drawings are the same as the eastern except for length of pipe 57.

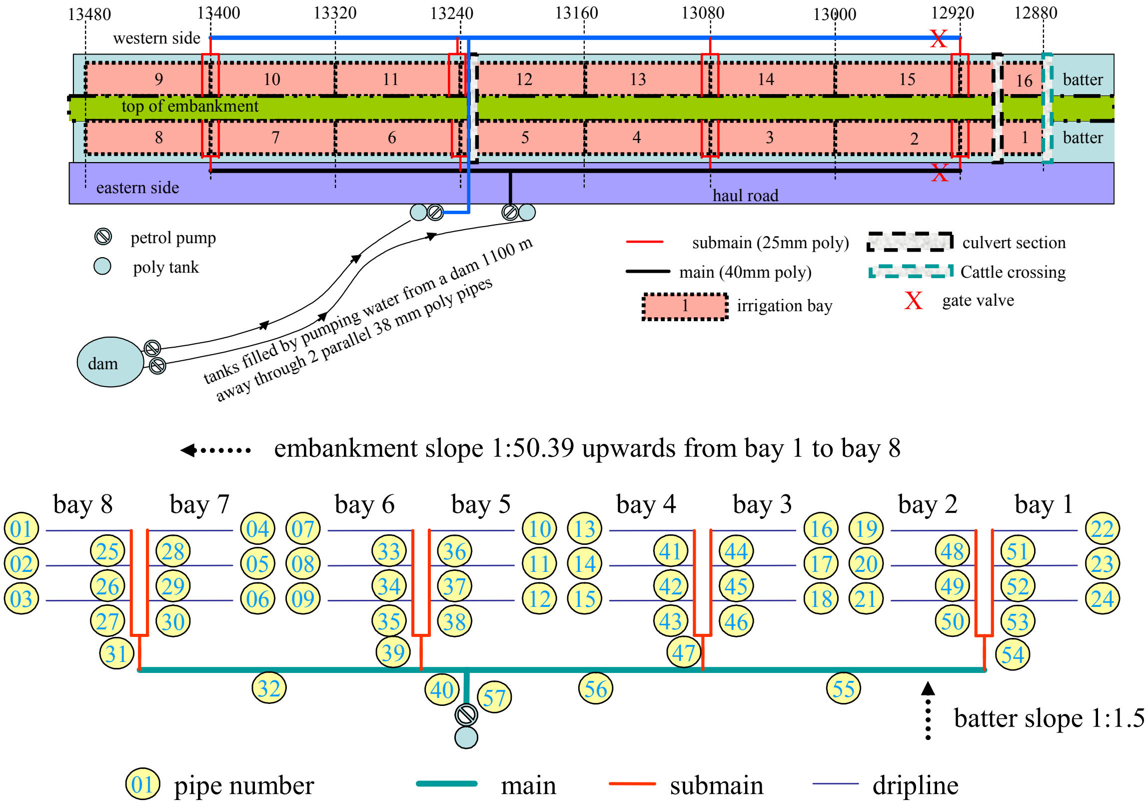

Figure 3: Layout of irrigation systems at Site 7; b) line drawing of the eastern side.

3.2 Hydraulic simulation of eastern side

Table 1 provides the pipe characteristics used in the modelling. Initial experiments at some selected sites of the BRRP project established that to achieve a good uniform wetting front the driplines should not exceed 80 m. A gate valve was installed in the mains to bays 1, 2, 15 and 16 to reduce the higher emitter discharges due to the high elevation drop. The opening area of the gate valves is judged by visual inspections of the wetting fronts. However, the local head loss coefficient ke due to the gate valve is estimated as the value to give similar emitter discharges as for bays 1 and 8.

Fig. 4 depicts the irrigation system curve superimposed on the pump performance curve. ke value of 100 for the gate valve yielded a similar emitter discharges for bays 1 and 8. This implies the gate valve will be nearly shut. For the given conditions, the pump operating point is about 240 L/min at 32 m head. Table 2 gives the characteristics of the 24 driplines at this pump operating point. It is observed that the coefficient of variation (standard deviation/ mean) of the emitters of all bays is small, the maximum being less than 6%.

Water was pumped from a dam 1100 m away through two parallel 38 mm poly pipes to 25,000 L tanks located at the bottom of the embankment as shown in Fig. 3. The measured flow rate through each supply pipe, with independent pump, was about 60 L/min. Hence for one hour irrigation, each pump on the dam has to run for 4 hours (240/60). Due to the expected increase in frictional head losses and emitter clogging by fine sediments in the irrigation water, this factor may be reduced. To minimise this risk, the driplines are flushed on a continuous basis. The hydraulic simulation is therefore a valuable tool to make a prior judgement of costs associated with the drip irrigation.

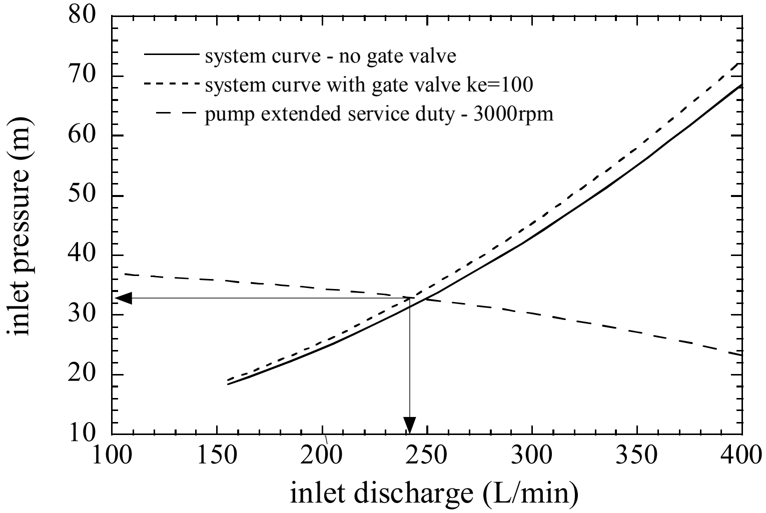

Figure 4: Pump characteristics and system curves.

Table 1: Pipe characteristics used in the simulation.

1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1	1	25	1	80.00	247.289	248.877	1.08	30	2	31	30	16.00	238.566	247.289	2.70
2	1	26	2	80.00	245.289	246.877	1.98	31	2	32	31	0.01	238.566	238.566	0.18
3	1	27	3	80.00	243.289	244.877	1.98	32	3	40	32	163.00	233.768	238.566	0.60
4	1	28	4	80.00	247.289	245.702	1.08	33	2	34	33	1.00	244.114	244.114	0.60
5	1	29	5	80.00	245.289	243.702	1.98	34	2	35	34	1.00	244.114	244.114	0.60
6	1	30	6	80.00	243.289	241.702	1.98	35	2	39	35	19.00	233.768	244.114	2.70
7	1	33	7	80.00	244.114	245.702	1.08	36	2	37	36	1.00	244.114	244.114	0.60
8	1	34	8	80.00	242.114	243.702	1.98	37	2	38	37	1.00	244.114	244.114	0.60
9	1	35	9	80.00	240.114	241.702	1.98	38	2	39	38	19.00	233.768	244.114	2.70
10	1	36	10	80.00	244.114	242.527	1.08	39	2	40	39	0.01	233.768	233.768	2.11
11	1	37	11	80.00	242.114	240.527	1.98	40	3	57	40	21.00	234.300	233.768	1.80
12	1	38	12	80.00	240.114	238.527	1.98	41	2	42	41	1.00	240.939	240.939	0.60
13	1	41	13	80.00	240.939	242.527	1.08	42	2	43	42	1.00	240.939	240.939	0.60
14	1	42	14	80.00	238.939	240.527	1.98	43	2	47	43	16.00	234.636	240.939	2.70
15	1	43	15	80.00	236.939	238.527	1.98	44	2	45	44	1.00	240.939	240.939	0.60
16	1	44	16	80.00	240.939	239.351	1.08	45	2	46	45	1.00	240.939	240.939	0.60
17	1	45	17	80.00	238.939	237.351	1.98	46	2	47	46	16.00	234.636	240.939	2.70
18	1	46	18	80.00	236.939	235.351	1.98	47	2	56	47	0.01	234.636	234.636	2.11
19	1	48	19	80.00	237.764	239.351	1.08	48	2	49	48	1.00	237.764	237.764	0.60
20	1	49	20	80.00	235.764	237.351	1.98	49	2	50	49	1.00	237.764	237.764	0.60
21	1	50	21	80.00	233.764	235.351	1.98	50	2	54	50	15.00	232.736	237.764	2.70
22	1	51	22	40.00	237.764	236.970	1.08	51	2	52	51	1.00	237.764	237.764	0.60
23	1	52	23	40.00	235.764	234.970	1.98	52	2	53	52	1.00	237.764	237.764	0.60
24	1	53	24	40.00	233.764	232.970	1.98	53	2	54	53	15.00	232.736	237.764	2.70
25	2	26	25	1.00	245.289	247.289	0.60	54	2	55	54	0.01	232.736	232.736	100.18
26	2	27	26	1.00	243.289	245.289	0.60	55	3	56	55	163.00	234.636	232.736	0.60
27	2	31	27	16.00	238.566	243.289	2.70	56	3	57	56	141.00	234.300	234.636	1.80
28	2	29	28	1.00	245.289	247.289	0.60	57	3	58	57	3.00	234.300	234.300	0.00
29	2	30	29	1.00	243.289	245.289	0.60								

Column headings

1) pipe number; 2) pipe type 1 for dripline, 2 for 25 mm submain, 3 for 38 mm mains; 3) upstream connected node; 4) downstream connected node; 5) length (m); 6) upstream elevation (m); 7) downstream elevation (m); 8) upstream connection friction loss coefficient, ke.

NB: additional ke=100 for pipe 54 is due to gate valve.

Table 2: Dripline characteristics at the pump operating point (240 L/min, 32 m).

1	2	3	4	5	6	7	8	9
1	9.51	1.51	0.46	0.023	11.32	2.14	9.40	4.42
2	9.75	1.58	0.49	0.045	11.88	2.20	9.89	4.29
3	10.00	1.66	0.52	0.047	12.47	2.26	10.42	4.17
4	10.14	1.76	0.55	0.027	11.21	2.29	10.71	0.86
5	10.37	1.83	0.57	0.051	11.77	2.34	11.20	0.86
6	10.61	1.91	0.60	0.053	12.37	2.39	11.74	0.86
7	11.88	2.29	0.73	0.036	17.24	2.68	14.76	3.51
8	12.07	2.36	0.75	0.069	17.81	2.72	15.25	3.45
9	12.28	2.43	0.78	0.071	18.41	2.77	15.80	3.40
10	12.38	2.53	0.81	0.040	17.12	2.79	16.07	0.99
11	12.57	2.60	0.84	0.075	17.69	2.83	16.55	1.00
12	12.77	2.68	0.87	0.077	18.30	2.88	17.11	1.02
13	10.66	1.87	0.59	0.029	14.03	2.40	11.85	3.90
14	10.87	1.94	0.61	0.056	14.59	2.45	12.34	3.82
15	11.11	2.02	0.64	0.058	15.19	2.51	12.88	3.74
16	11.23	2.12	0.67	0.033	13.92	2.53	13.17	0.89
17	11.43	2.19	0.70	0.062	14.49	2.58	13.66	0.90
18	11.65	2.26	0.72	0.064	15.09	2.63	14.20	0.92
19	7.90	1.06	0.32	0.016	8.05	1.78	6.46	5.52
20	8.19	1.14	0.34	0.032	8.61	1.85	6.95	5.28
21	8.49	1.22	0.37	0.034	9.19	1.91	7.47	5.05
22	4.58	0.19	0.05	0.005	8.45	2.06	8.71	1.05
23	4.72	0.20	0.06	0.011	9.01	2.13	9.25	0.97
24	4.85	0.22	0.06	0.011	9.57	2.19	9.80	0.90

Column headings

1) total discharge (L/min); 2) total friction loss (m); 3) friction loss due to emitter insertion (m); 4) friction loss due to dripline connections (m); 5) dripline upstream pressure (m); 6) average emitter discharge (L/min); 7) average emitter pressure (m); 8) emitter discharge coefficient of variation (standard deviation / mean) (%).

4 Conclusions

Drip irrigation systems are being routinely used to aid the establishment of grasses on railway embankment steep slopes to control erosion within the semi-arid region of Central Queensland, Australia. The hydraulic modelling approach used to aid the design of the drip irrigation systems has been presented in this paper. It takes into account the velocity head change and a proper selection of the friction coefficient formula based on the Reynolds number. Fittings and emitter insertion head loss are incorporated into the hydraulic model. The hydraulic model was use to design drip irrigation systems at 37 sites on the recently constructed BRRP spur railway line. One of the sites has been used as a case study in this paper. The hydraulic simulation has been found to be a valuable tool to make a prior judgement of costs associated with the drip irrigation system.

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Development of a crop water use module for the WAS program to determine scheme-level irrigation demand

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Abstract

The water use sector in South Africa is currently implementing the National Water Act (Act 36 of 1998), which requires, amongst other things, improved planning of expected water demands. A need was identified for the development of a computer model that can assist Water User Associations (WUAs) to easily and effectively capture data for management and planning purposes. The existing Water Administration System (WAS) computer program was used and a new module developed to capture data and perform calculations so that irrigation demand can be determined for different time periods (daily, seasonally, annually, etc.) and management levels (field, farm, and scheme). The crop yield (ton/ha) can also be captured at the end of a growing season and used to calculate the total yield (ton) and the yield per unit of water (g/m^3). A summary of water demand for a specified period can easily be generated per crop type, and all the crop water demand information can easily be linked to a geographic information system (GIS). The module was implemented at the Orange-Riet WUA where it is used to model irrigation demand for 16700 ha of mixed crops irrigated from river and canal distribution systems.

Keywords: irrigation planning, crop water requirements, WAS program, water conservation and demand management.

1 Introduction

South Africa is a semi-arid country where water is of critical strategic importance to all development, in any sector of the economy. Recognising the

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potential limiting effect that water could have on future economic expansion in this country, it is of utmost importance that this resource be optimally utilised to the benefit of all current and future users.

The National Water Act (Act 36 of 1998) (NWA) provides for water to be protected, utilised, developed, conserved, managed and controlled, in a sustainable and equitable manner (Department of Water Affairs and Forestry (DWAF) [1]).

The water use sector in South Africa is currently implementing the NWA, part of which is the Water Conservation and Water Demand Management (WCWDM) strategy. In the agricultural water sector, the WCWDM strategy requires each Water User Association (WUA) to develop a Water Management Plan (WMP) that, amongst other things, reflects current and expected water demand (DWAF [2]). A need was identified for the development of a computer model that can assist WUAs to perform this task easily and effectively for management and planning purposes.

To address this need, the existing Water Administration System (WAS) computer program (Benadé et al [3]) was used and a new module developed to capture data and perform calculations so that irrigation demand can be determined for different time periods (daily, seasonally, annually, etc.) and management levels (field, farm, and scheme).

The main function of the Crop Water Use module is to calculate the volume of water required between two specified dates for all the planted crops on a scheme based on the planting date, irrigated area and the crop water demand curve. The crop yield (ton/ha) can be captured at the end of a growing season which is used to calculate the total yield (ton) and the yield in (g/m^3). A summary of water demand for a specified period can easily be generated per crop type, and all the crop water demand information can easily be linked to a geographic information system (GIS).

The paper addresses the development of the Crop Water Use module as well as its implementation at the Orange-Riet WUA where it is used to model irrigation demand for 16700 ha of mixed crops irrigated from river and canal distribution systems.

2 Module development and functions

One of the key components of the agricultural WMP is the calculation of benchmarks according to which the WUA's performance can be assessed. The primary benchmarks for irrigation water use are firstly the crop water requirement of a specific crop (ET_{crop}) in a specific area at a specific time of year. ET_{crop} does not take irrigation efficiency factors into account. Secondly, the ET_{crop} benchmark can be used to calculate the gross irrigation water requirements (GIR) for a specific crop in a specific area and at a specific time of year by adjusting the crop water requirement for appropriate irrigation efficiency factors such as leaching requirements, irrigation application efficiency, effective rainfall and reasonable transmission losses (mainly evaporation). These benchmarks can, in turn, be used to calculate the expected irrigation water requirements for the WUA as a whole by taking into account actual irrigated areas for each type of crop (DWAF [1]).

Research on crop water use and irrigation requirements for a wide range of commercial crops in different climatic regions and on different soil types has been ongoing in South Africa for over 25 years. The standard approach recommended in the WCWDM strategy is based on the following two components:

- The Penman-Monteith method of estimating reference evapotranspiration (ET_o) in any given zone and
- The FAO method of linking reference evapotranspiration to any given crop by way of a standard crop factor (K_c) for any given period during the growing season of the crop. This method is described in the FAO Irrigation and Drainage Paper No. 56 (FAO 1998).

It can be expressed as shown in eqn (1):

$$ET_{crop} = ET_0 \, x \, K_C \tag{1}$$

In contrast to the crop factors used with A-pan, reference evaporation, K_c can be adjusted consistently and with confidence to accommodate differences in climatic zone and farming practice. Because the short grass reference evapotranspiration already accounts for many of the implications of differences in climate, it is often possible to use a single set of crop coefficients for different climatic zones. The ET_0 – K_c approach has become a widely accepted international standard and has therefore been accepted by DWAF as a basis for establishing crop water requirement and irrigation requirement benchmarks. The WAS program is structured in accordance with these principles

The program allows the user considerable freedom to develop crop coefficients that are well suited to specific cropping circumstances. Because the ET_0 – K_c approach has been so well accepted internationally, a wealth of information is available, especially through another South African model, SAPWAT, which is recognised as the irrigation planning tool for SA by DWAF (Crosby & Crosby [4]).

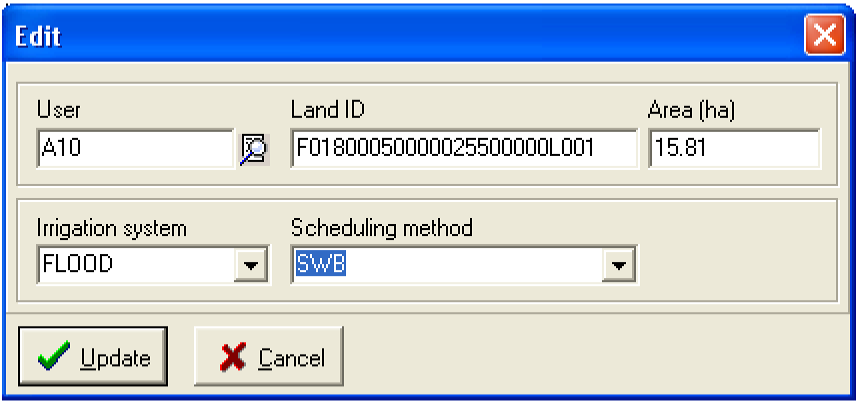
The crop water use module of the WAS program can be used to calculate the total water demand value for an irrigation scheme consisting of different sized fields where various crops are planted as daily, weekly, monthly, annually or any other periodic values. These calculations need to be viewed as guidelines for irrigation water requirements and may need to be tempered by local experience.

2.1 Inputs required

The program requires three types of inputs in order to perform the most basic calculations: planted area information, crop types and water use values for the crop types.

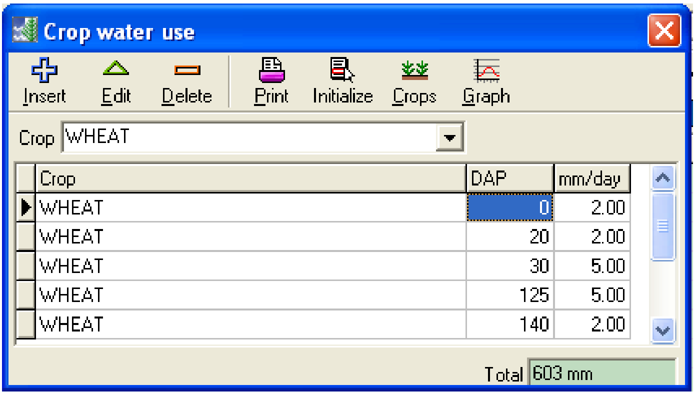
2.1.1 Lands

The planted area information is captured as irrigated land areas (in hectares) per water user. A Land ID must be specified and there is no limit to the number of lands that can be captured per water user (Figure 1). The irrigation system and scheduling method can also be specified. This information can be used with a geographic information system (GIS) to link different land areas to a map.



User A10
Land ID F01800050000025500000L001
Area (ha) 15.81
Irrigation system FLOOD
Scheduling method SWB

Figure 1: Form for capturing planted areas information.



Crop WHEAT

Crop	DAP	mm/day
WHEAT	0	2.00
WHEAT	20	2.00
WHEAT	30	5.00
WHEAT	125	5.00
WHEAT	140	2.00

Total 603 mm

Figure 2: Crop water use data capturing form.

The total land area captured under the Lands form is used to verify the total area on the Crops & planted areas form where a land may be planted with more than one crop on different areas. The difference between the land area and the planted area will be displayed in red at the bottom of the Crop water use and planted areas form.

2.1.2 Crops

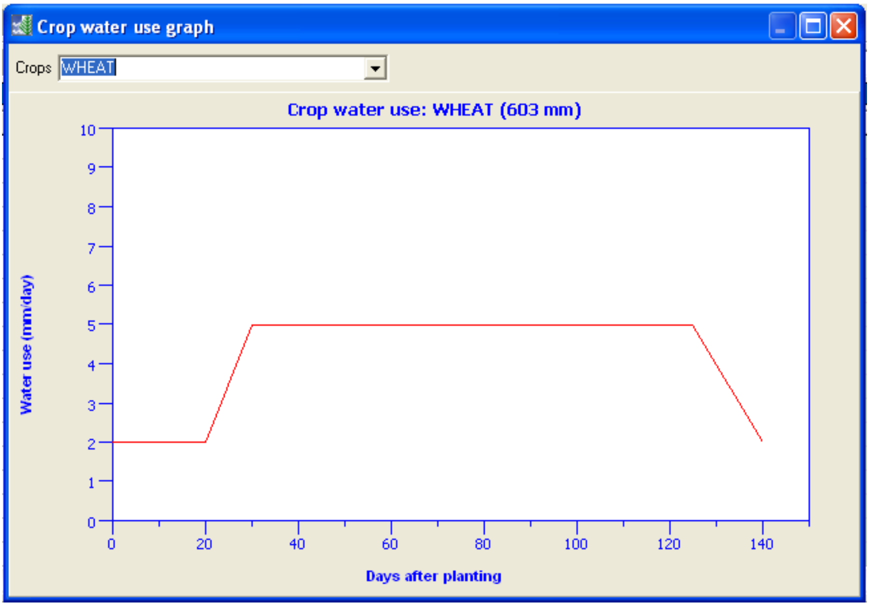
All the different crops planted on a scheme must be captured on the crops lookup form to make it available in the dropdown list on the capturing forms.

The Crops speed button is used to maintain the crop lookup list. For each crop, a crop ID nr and a description have to be entered. The description may refer to a specific crop variety or planting season (e.g. early or late).

2.1.3 Water use

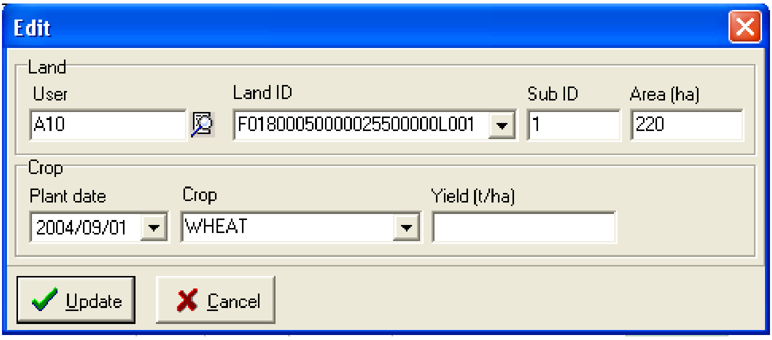
The Water Use speed button is used to capture the crop water use information per crop type (Figure 2). The information needed are the days after planting

(DAP) and the corresponding water use per day (mm/day). There is no limitation on the number of points that can be captured to describe the crop water use graph. The crop water use graph shown in Figure 3 can be generated from the crop water use data.



Crops WHEAT

Figure 3: Typical crop water use graph.



User A10

Land ID F01800050000025500000L001

Sub ID 1

Area (ha) 220

Plant date 2004/09/01

Crop WHEAT

Yield (t/ha)

Figure 4: Linking the planted area to a specific crop.

2.1.4 Other inputs

The last step is to link all the planted areas to a specific crop and indicate the planting date for the specific field. This is done by editing any of the entries on the planted areas list as shown in Figure 4. The expected (for planning) or actual (for reporting) yield is an optional entry on the data capturing form.

2.2 Functions

Once all the required data have been captured, the crop water use module can be used to display, calculate and summarise water use reports per crop for different time periods and /or specific users using the links at the top of the window (Figure 5).

Display from 2004/03/31 Display to 2006/04/30

Calc from 2005/03/31 Calc to 2006/04/30

Sort User User *ALL*

Crop *ALL* Ward *ALL*

Figure 5: Display options.

2.2.1 Display options

The "Display from" and "Display to" date dropdown boxes are used to specify the period in which all the crops that are planted must be displayed, while the "Calc from" and "Calc to" date dropdown boxes are used to specify the period which is used to calculate the crop water use volumes.

The "User" dropdown box is used to filter the crop water use records according to a specified user. This option will be relevant for cases where a user has more then one Land ID.

The "Crop" dropdown box is used to filter the crop water use records according to the selected crop, and the "Ward" dropdown box is used to filter the crop water use records according to the selected water ward.

2.2.2 Calculating results

The "Calc" speed button is used to calculate the crop water use volume (m^3) for the options decided on by the user and it opens a dropdown menu with two further options. The "Current volume" option is used to calculate the crop water use for the current record shown and the "All volumes" option will calculate it for all the records in the database. The total volume of water use during the specified period and the total planted area are displayed in the bottom right corner of the screen (see Figure 4).

2.2.3 Output options

The "Summary" speed button generates a Crops & planted areas summary report per crop that can be printed. Information regarding planted areas, volume of water, average irrigation requirement per season, yields, and yield per water unit is presented per crop, for the information that had been entered.

3 Results from the Orange-Riet case study

The crop water use module was originally developed specifically for the Orange-Riet WUA (ORWUA) in South Africa. The ORWUA is located along the Orange and Riet Rivers in the north-western region of the country, which has a semi-arid climate with mean annual rainfall typically less than 400 mm. Irrigated agriculture has been practised in the area since 1945.

An area of approximately 16 780 ha is dependent on irrigation water from the Orange-Riet Canal, which is a transfer scheme between the two rivers, and includes the Riet River settlement, development along the Orange-Riet Canal, Scholtzburg and Ritchie Irrigation Boards and the lower Riet River Irrigation Board. The first 74 km of the canal has a capacity of 16 m^3/s while the last 38 km has a capacity of 13 m^3/s. Water is pumped at the Scheiding Pumping Station at the terminal of the main canal to an elevation of 47 m above the river to the entrance of the Orange-Riet Canal.

Due to the harsh climate and the limited canal capacity, water use planning is an essential component of the ORWUA's water management system and water users are strongly encouraged not to plant larger areas than for which they have water rights. Supply and demand has to be carefully matched, especially during peak periods to ensure that all the water users receive their fair share and pumping costs are kept to a minimum. For these reasons the ORWUA was selected as one of three irrigation schemes in South Africa for which draft a WMP has been developed and is currently being implemented.

The crop water use module has been used at the ORWUA since 2002 to capture data, plan water requirements and compare theoretical water demand with actual use.

3.1 Data inputs

A wide range of crops are grown in the area. A summary of planted area data per crop type that have been captured over the last 4 years is shown in Table 1. The ORWUA operates according to a water year that runs from 1 April to 31 March, with most of the rain event occurring between October and April and the peak irrigation demand periods occurring in November and February.

The table shows that the most important crops grown in the area are maize, wheat and lucerne (alfalfa). However, due to the poor maize prices in 2004 and 2005, there has bee a sharp decline in maize planting, with farmers instead opting for crops such as pastures, sunflowers and peanuts as well as favouring wheat.

It is interesting to note that there has been a steady decrease in the total planted areas in the ORWUA since the 2003/2004 season. Tough economic conditions and other contributing factors such as new labour laws and crime in rural areas have resulted in farmers leaving the agricultural sector to pursue other business interests.

The benchmark water use values for the crops have been developed over a number of years by monitoring and recording irrigation applications for the various types of irrigation systems and scheduling approaches used by farmers in the area. The crop water use graphs entered in the crop water use module had to be developed so that the total seasonal water requirements as shown in the program matched the benchmark values.

Table 1: Planted area data for the ORWUA (2002-2006).

	Planted areas per water year (ha)				Benchmark (m^3/ha)
Crop	2002/03	2003/04	2004/05	2005/06	
Maize	14036	12304	11979	5583	7820
Wheat	8736	11623	9738	10132	6250
Lucerne	2243	1846	2391	2852	12150
Potatoes	366	566	518	567	6980
Pastures	361	950	1595	2342	11800
Vineyards	358	325	274	242	8650
Peanuts	259	858	437	809	6800
Onions	204	232	144	548	6660
Sunflowers	196	564	548	869	5880
Vegetables	196	150	48	508	5880
Dry beans	143	337	108	331	4490
Pecan nuts	78	84	60	70	9340
Cotton	39	308	127	151	8300
Fruit trees	37	21	23	17	9940
Olives	16	49	32	35	4600
Soya beans	0	116	22	123	4820
Totals	27268	30333	28044	25179	

3.2 Results

The results of the four year long data collection process is summarised in Figure 6. It shows the irrigation water demand, the bulk water supply and planted areas for the four water years.

The irrigation water demand values were obtained from the crop water use module output as calculated for the planted areas shown in Table 1. The bulk water supply values were obtained from records of the Scheiding Pumping Station that supplies water to the ORWUA.

The irrigation water demand values also reflect the changes in planted areas over the four years, with water demand peaking in 2003/2004. The average irrigation water demand per planted area was 6556 m^3/ha during the four years, and this can be seen as the net irrigation demand for the WUA. This value has increased continuously over the last three water years (from 6482 to 6722 m^3/ha), and it is possibly due to a shift away from maize to higher value crops that require more water per hectare per year.

The average bulk water supply per planted area was 8655 m^3/ha, which is the gross irrigation demand. This value has decreased the last two years, and would have done so for the last three years if the ORWUA hadn't experienced water shortages during the 2003/2004 season due to large planted areas and limited canal capacity. This would possibly have increased the volume of water supplied during that season.

The ratio between the average net and gross values is 0.757, which means that on average 24.3% of the water abstracted at the Scheiding Pumping Station can be allocated to operational losses such as evaporation, seepage, spills, etc. The ratio has been increasing over the last three years (from 0.74 to 0.78) indicating that water use efficiency at scheme level has improved and operational losses have been reduced.

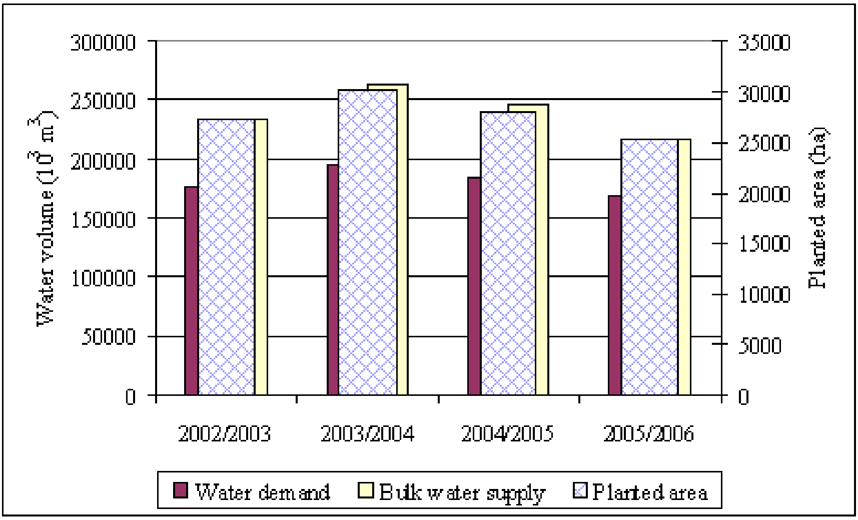


Figure 6: Water supply and demand at the ORWUA (2002 to 2006).

4 Conclusion

The crop water use module that has been developed for the WAS program has proved to be a useful and simple tool for recordkeeping, water management planning and benchmarking.

It is used by the ORWUA to plan pumping rates for the main water supply to the scheme, and to assess water availability according to the farmers' planting programmes. The results of four years' data collection and analysis at the ORWUA have shown that:

- There has been a decline in planted areas in the scheme during the last four water years;
- The net irrigation demand per planted area has increased during the last three water years, probably due to a shift in crop selection;

- The gross irrigation demand per planted area have decreased over the past three water years, probably due to an improvement in water management and
- The ratio of net to gross irrigation demand per planted area has remained almost constant over the four years at 0.747 with no significant upward or downward trends.

The program has been very effective to evaluate the available data but the following recommendations for improvement can be made:

- A data export function should be added so that results can be exported to a spreadsheet program for further analysis; and
- The "sort by user" function should be changed so that multiple individual users can be randomly selected.

The researchers would like to thank the staff of Orange-Riet Water User Association for their assistance in collecting and capturing the data, and making it available for use in this paper.

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Subsurface irrigation by condensation of humid air

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Abstract

Condensation Irrigation (CI) is a combined system for solar desalination and irrigation. Solar stills are used to humidify ambient air flowing over the saline water surface in the stills. This warm, humid air is then led into an underground system of drainage pipes where it is cooled and vapour precipitates as freshwater. The condensed water and some humid air percolate through the pipe perforations and irrigate and aerate the ground. Mass and heat transfer in the soil-pipe system has been modelled to evaluate the theoretical productivity for these types of systems. For a presumed pipe configuration and climate, 3.1 kg water per pipe-meter and day was condensed inside the buried pipe, yielding 2.3 mm/d irrigation water. Pilot plants on the CI system and are now in operation in Tunisia and Algeria. Another CI plant is planned in Libya.
Keywords: condensation, irrigation, subsurface, solar driven, desalination, modelling, mass and heat transfer.

1 Introduction

The accelerating land degradation and declining agricultural productivity in Africa constitute major problems for its population's future economic and food security. Predictions indicate that the continent only will be able to feed 40% of its population in another 20 years [1]. Since only 10% of the African land has the potential of rain-fed cultivation, and since water availability often is the most limiting factor for root growth [2], irrigation expansion is of highest importance for Africa's future development. However, more than 90% of the available freshwater is already used for irrigation in some parts of Africa [3], and groundwater tables in some areas are dropping rapidly due to increasing tube well installations [4].

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The only sustainable way to produce more freshwater is through desalination of seawater. In oil rich countries such as Kuwait, Saudi Arabia, and the United Arab Emirates, about 95% of all freshwater is already supplied by desalination technologies using fossil fuels [5]. In view of future oil shortages, desalination must, however, be driven with renewable energy.

Solar powered desalination is an obvious choice for remote and sunny regions as it is reliable, environmentally sound, and easily maintained [6]. The main problems with using solar thermal in large-scale desalination plants are relatively low production rates (about 3-4 $kg/m^2/d$ in passive solar stills [7]), low thermal efficiency and the considerable land area required [8].

However, because the plants are also characterised by free energy and an insignificant operating cost, the technology is suitable for small-scale production, especially in remote arid regions and islands, where conventional energy and the supply of freshwater is erratic, but the solar potential is high [9].

1.1 Condensation Irrigation

In the Condensation Irrigation (CI) system ambient air is warmed and humidified when flowing over a saline water surface in solar stills. The air is then led into an underground pipe system, where it is cooled and vapour precipitates as freshwater on the inner walls of the pipes.

Using drainage pipes to conduct the airflow enable the condensed water and some humid air to infiltrate the ground around the pipes, thereby irrigating and aerating it. If non-perforated pipes are used, the formed freshwater can instead be collected at the pipe endings and used for e.g. drinking. The CI system is outlined in Figure 1.

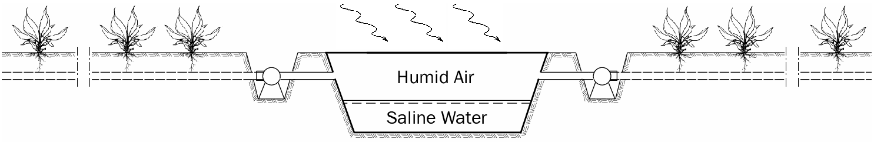

Figure 1: Outline of a condensation irrigation system. Ambient air flows over the solar heated saline water surface in solar stills and led into buried pipes, where it is cooled and vapour precipitates as freshwater.

The condensation process in the pipes occurs during the hours when the sun is able to evaporate water inside the stills. As the air dehumidification inside the pipes proceeds during the day, the surrounding ground gradually becomes heated, resulting in a reduced condensation rate. To enhance the condensation rate the succeeding day, cool air is circulated through the pipes at night.

Due to the low-flow irrigation water distribution occurring throughout the day, water uptake by crops should be efficient and the risk for land degradation is greatly reduced. The sub-surface irrigation scheme also contributes to a reduced water loss through surface evaporation and run-off and deep percolation due to flooding. Since the air heating and humidification is solar driven, more irrigation water is formed inside the buried pipes on sunny days, when the irrigation need is high.

Although solar stills are suitable for humidifying air, many other methods and heat sources are possible, depending on the geography and other site specific conditions. A solar driven alternative would be to use existing lined irrigation canals that are impermeable to salts. Converting these to air humidification canals would require a transparent cover and possibly a radiation absorbing material onto the canal borders.

Work concerning the Condensation Irrigation system started at the Luleå University of Technology (LTU) as a series of Masters Theses [10–12], and the technology was used in the construction of a greenhouse climate control facility in Övertorneå, Sweden [13].

Independently of these studies, the Swiss company Ingenieurbüro Ruess und Hausherr constructed a CI plant where seawater had evaporated in plastic tubes, with the condensation occurring in buried drainage pipes. A reported 50% reduction in the water consumption of tomato plants was observed in the system [14].

Recent studies on Condensation Irrigation has involved theoretical analyses on one drinking water system and one sub-surface irrigation system using buried drainage pipes [15,16].

2 Subsurface Condensation Irrigation

To examine the potential for the Condensation Irrigation (CI) system a theoretical simulation model of air dehumidification inside buried drainage pipes was developed in Matlab using a transient finite difference scheme in three dimensions.

In the simulations, the air was dehumidified for 12 hours each day using constant airflow properties at the pipe inlet (Table 1). The rest of the day was devoted to nightly ground cooling, when cool ambient air at varying temperatures was circulated through the pipes. The pipe configuration in the models comprised 50 meter long parallel pipes placed 1.0 meter apart at 0.5 meter's depth [15,16] in a soil with properties set according to Table 1.

The heat and mass transfer in the soil-pipe system were simulated for a period of three months, during which time the diurnal mean condensation rate and vapour flux through the perforations in the 50 m long pipe varied according to Figure 2.

The daily condensation rate in the reference system soon became steady at 3.1kg/m pipe and day as the soil temperature around the pipe seized to increase from one day to another. Since the pipe spacing was set to 1.0 m this corresponds to 3.1 mm/d irrigation yield. During the nightly ground cooling with colder and drier air, some of the formed irrigation water re-entered the pipes. In the reference system the resulting irrigation yield was for this reason reduced to 2.3 mm/d.

Table 1: Properties of the sand and airflow at the inlet.

Humid air at pipe inlet	Temperature, $T_{av,in}$	60	ºC
	Relative humidity, $\phi_{av,in}$	70	%
	Velocity, $c_{av,in}$	3.5	m/s
Sandy soil	Porosity, θ,	0.43	m^3/m^3
	Residual water saturation, S_r	0.10	m^3/m^3
	van Genuchten parameter, a	6.9	m^{-1}
	van Genuchten parameter, n	4.6	-
	Intrinsic permeability, k_i	10^{-12}	m^2
	Tortuousity coefficient, τ	0.62	-

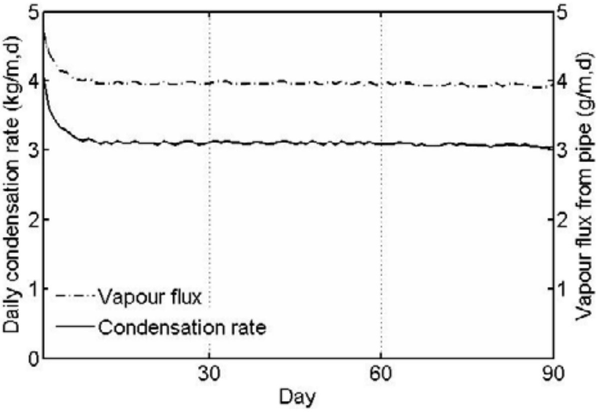

Figure 2: Mean condensation rate (——), and vapour flux through perforations (-··-··-), per pipe meter of a buried drainage pipe during the first 90 days of irrigation in the reference system.

The potential evapotranspiration (PET) from irrigated crops usually range between 4 and 7 mm/d [17], which is significantly more than the irrigation yield in the simulated reference system. It should however be noted that including plants in the simulations would increase the water added to the soil since root suction enhance water movement in the soil, thus lowering the ground temperature and increasing the condensation rate in the pipes.

Solar radiation was excluded from the models, which resulted in the ground being cooled from above. The irrigation water from the buried drainage pipes therefore experienced an upward motion, accumulating in the soil above and around the pipe. Figure 3 shows the soil water saturation and liquid water flux density in the cross-section at 25 m distance from the pipe inlet.

The air dehumidification process inside the pipes heated the ground in the pipe's surrounding, influencing not only the water production inside the pipes, but also crop root development.

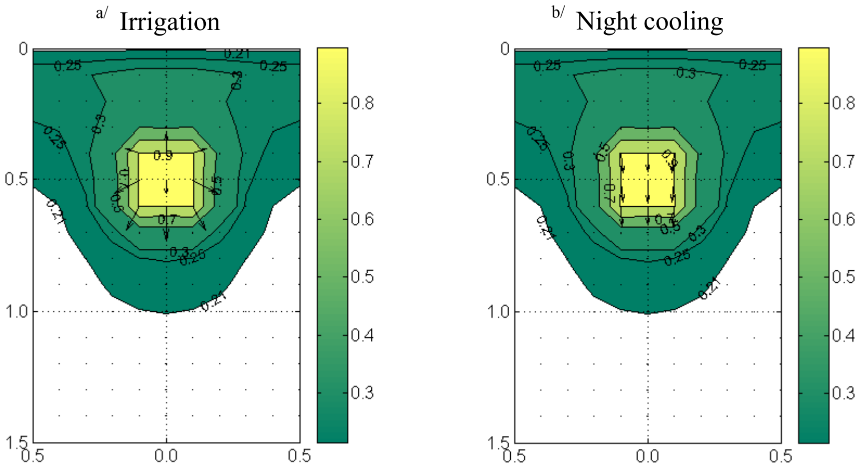

Figure 3: Soil water saturation and liquid water flux density in the midsection of the pipe during the 6th hour of a) irrigation and b) night cooling on the 91st day.

Generally, the optimum temperature interval for roots is about 17-35°C [18], and higher temperatures may injure or destroy them. In the CI system, the temperature at the pipe walls should therefore exceed this interval in order to prevent roots from growing into the pipes and block the airflow. The soil temperature in the rooting zone between the pipes must however always be tolerable for the roots.

The cross-sectional soil temperature distribution and vapour flux density 25 m along the buried drainage pipe is shown in Figure 4 for the sixth hour of irrigation and night cooling at steady diurnal condensation rate.

During the daily air dehumidification, some vapour from the humid airflow infiltrated to the soil through the pipe perforations resulting in an increased vapour flux density away from the pipe. At night, the cool ambient air circulating inside the pipes gave rise to an opposite direction of vapour flux density near the pipe wall, thereby reducing the irrigation yield.

In the simulated reference system the soil between the pipes was 35-40°C, which is too warm for crops. To reduce the soil temperature the pipes could be placed further apart, which also increase the condensation rate in the pipes further. Doubling the spacing in the reference pipe configuration previously described resulted in approximately 5°C cooler ground in the rooting zone and a mean condensation rate of 3.3 kg/m/d. The irrigation yield using 2.0 m spacing was reduced to 1.4 mm/d due to the larger soil volume each pipe had to irrigate.

When studying the presumed parameters in the simulated CI system it was apparent that the presumed inlet airflow properties, in particular the inlet airflow temperature, had the greatest effect on the resulting condensation rate in the pipe.

The high temperature dependence of the condensation rate is mainly due to the temperature driven mass transport in the soil matrix, which increases as the temperature difference between the pipe and the surrounding increase.

In Table 2 the mean condensation rate is shown for simulations where the inlet air temperature, humidity and velocity has been increased or reduced 20% from the reference value specified in Table 1.

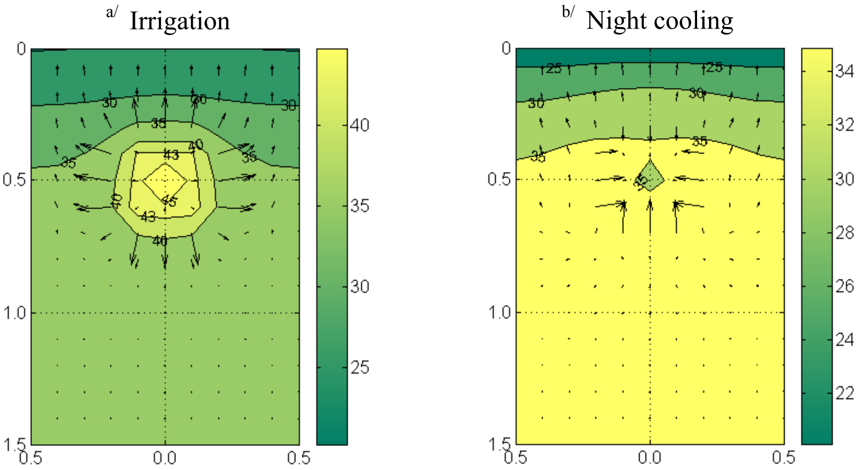

Figure 4: Temperature and vapour flux density in the midsection of the pipe during the 6th hour of a) irrigation and b) night cooling on the 91st day. The centre of the 0.2 m diameter drainage pipe is located at 0.5 m depth.

Table 2: Dependence of mean condensation rate on humid air properties at the pipe inlet.

Inlet air parameter	+20%		-20%	
Temperature	5.86 kg/m/d	(+90%)	1.12 kg/m/d	(-63%)
Relative humidity	3.89 kg/m/d	(+26%)	2.19 kg/m/d	(-30%)
Velocity	3.48 kg/m/d	(+11%)	2.71 kg/m/d	(-13%)

Increasing the inlet airflow temperature from 60 to 72°C led to 90% higher condensation rate, and 4.1mm/d of irrigation yield to the soil. The temperature in the rooting zone was however raised to 40-50°C, which far exceeds the tolerable temperature levels for crop roots. When these high airflow temperatures are achievable from the air humidification, the pipes must therefore be placed wide apart.

3 Field testing and experiments

To evaluate the developed theoretical model, a small-scale indoor test rig has been constructed at Luleå University of Technology (LTU), Sweden. The setup is designed to resemble the boundary conditions and presumptions used in the numerical simulations of the described subsurface CI system [19].

Measuring the humid airflow properties inside a drainage pipe, and logging the temperature and humidity distribution in a cross-section of the surrounding uniform sand, provides an estimation of the heat and mass transport in that cross-section and the resulting condensation rate in the pipe. Experiments and validations of theoretical models are at present being conducted at LTU.

Pilot plants of Condensation Irrigation systems have been constructed in Tunisia and Algeria. Measurements from these plants will in future research be used for evaluating the feasibility of Condensation Irrigation. A second test plant will be constructed in Tunisia inside a greenhouse during 2006 in order to improve the accuracy of the measurements (Figure 5).

Figure 5: Pilot plant at the INRGREF in Tunisia. Ambient air is heated and humidified using solar collectors. The soil temperature and humidity are measured in the ground around drainage pipes.

4 Conclusion

Condensation Irrigation (CI) is a combined system for solar desalination and irrigation, in which solar stills are used for humidifying ambient air. The warm and humid air is led from the still into an underground pipe system where it is cooled and vapour precipitates as freshwater on the pipe walls. If drainage pipes are used the water and some of humid air percolate through the pipe perforations and irrigates and aerates the ground.

Mass and heat transfer in the soil around the buried pipes has been modelled in Matlab for a subsurface irrigation system. From the theoretical models it was concluded that CI could be used for irrigation at relatively low operational costs. The simulations of the subsurface irrigation resulted in a diurnal steady state condensation rate of 3.1 kg/m/d and a mean irrigation yield of 2.3 mm/d.

The CI system has attracted attention from several North African countries. Pilot plants are now in operation in Tunisia and Algeria where LTU is collaborating with the Tunisian Institute for Research on Rural Engineering, Water and Forestry and the University of Tlemcen in Algeria. LTU is also collaborating with Al Fatah University and the International Energy Foundation in Tripoli, Libya. Ongoing work aims at developing a design tool and monitoring program for the CI system to be used in the design and operation of a demonstration plant in Libya.

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Theoretical and experimental analysis on the thermal fluid dynamics of water droplets in irrigation

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Abstract

A complete thermal fluid dynamics analysis of a sprinkler droplet following its path from the sprinkler nozzle to the ground is made difficult by the high non-linearity of the differential equations describing the phenomenon. This fact, caused by a great inter-dependence between the parameters that play a role in the process, is partially overcome in this paper by representing the process in terms of force balance to which a few simplifying hypotheses are applied. The goal of this approach is to make the description entirely analytical thus avoiding any empiricisms that could limit the generality of the study. The model realised is able to provide reliable kinematic data, which prove to match significantly with data available in literature, especially for higher Reynolds numbers. The paper also shows an application of the model to the computation of the aerial evaporation of a water droplet: quantitatively, this part of the study is able to provide an upper limit of the friction-induced phenomenon only, however qualitatively the consequent analysis of the results opens a new window on the full understanding of the aerial evaporation of sprinkler water, highlighting the possible role played by certain environmental parameters, such as air friction and air temperature. This latter analysis also involved careful experimental activity, which is also presented herein.

Keywords: thermal fluid dynamics, mathematical model, sprinkler irrigation, water droplet, travel distance, time of flight, evaporation.

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1 Introduction

It is a widely reported fact that in industrialised countries more than half of the freshwater available is used for agricultural purposes and for crop irrigation in particular. This implies that the important challenge of achieving a more sustainable management of water, called for by the increasingly worrying over-exploitation of this resource, necessarily entails more efficient agricultural practices especially with regard to irrigation in general and sprinkler irrigation in particular, which is the key issue of this paper. From a technical physics point of view, the need to save water in sprinkler irrigation requires efforts in understanding and fully describing the whole phenomenon of a water droplet exiting a sprinkler nozzle, following its path and finally reaching the soil.

The general problem, characterised by the many interacting factors in determining the trajectory and evaporation of an airborne water droplet, can be summarised as follows:

- Experimentally [1–3], it is difficult to compute the effect of each single environmental parameter on aerial droplet dynamics, by distinguishing its effect from those of the other affecting parameters. In particular, when experimentally investigating aerial evaporation of a droplet, the results are often expressed by small numbers or percentages, the reliability of which depend on the typical error of measurement limits, which are sometimes of the same order of magnitude as the computed values.
- Analytically [4–6], a mutual interaction of the affecting parameters means that a complete description of the phenomenon and of the inter-dependences between parameters requires a non-linear partial differential equation to be solved: it is very unlikely that this will lead to a final solution, unless the procedure resorts significantly to case-dependent empiricisms, however, this option adds very little information to the general comprehension of the phenomenon.

The potential solutions to these problems, which are examined in this paper, imply:

- Experimentally, it would be necessary to perform single-parametric research on the process, that is evaluating the effect on spray dynamics of each affecting parameter independently of all the others and thus minimising the effect of all variables except that investigated. This is the approach adopted in this paper, for the affect of air temperature, with meticulous test management and data collection.
- Analytically, great efforts would be required to simplify the modelling of sprinkler water droplet dynamics, realising models of general (that is entirely analytical) and easy (that is considering a limited range of variables) applicability, but that also provide a reliable description of the actual phenomena: to this ends, in our research, we applied a mathematical model, based on a simplified force balance, that describes the aerial path of the process examined providing results that match satisfactorily with other authors' data.

The main goals of this paper are:

- Experimentally, to show a method, applied in this case to the analysis of the effect of air temperature, which, when suitably expanded, could be a potent technique for determining each single parametrical contribution to the global phenomenon.
- Analytically, to provide a fully analytical (in the hypotheses formulated) tool that can describe in-field events with a good degree of match to actual data and which is significantly easier (in the sense explained above) than the approaches available in literature and quoted in this work.

The results obtained seem to encourage an attempt to re-write the physics of the whole process under examination, also regarding the computation of the aerial evaporation, phenomenon for which some computed and experimental results (in the sense explained below) are also presented.

2 Materials, methods and results

2.1 Kynematics

A new simplified approach to the kinematic modelling of water droplet flow in sprinkler irrigation is that provided by Lorenzini [7], who describes the flow of a single sprinkler droplet based on the force balance: $\vec{F} = m\vec{a}$, where $\vec{F}$ is the total force acting on the droplet and equal to the vectorial sum of the weight of the droplet of mass *m* diminished by its buoyancy force and of the friction force acting during the flight on the droplet of acceleration $\vec{a}$. The friction factor *f* used in the model is that according to Fanning's definition [8]. The hypotheses formulated are that:

- Each droplet is generated exactly at the nozzle outlet
- The forces applied to the system are weight, buoyancy and friction
- The droplet has a spherical shape for the whole trajectory
- The volume of the droplet does not vary during the flight
- Friction has the same direction as droplet velocity but opposite sense for the whole path
- There is no wind disturbing the flight.

The parameters, depending on the practical case considered, to be introduced for the computation of the results are:

- The nozzle height *h* from ground level
- The droplet exit (from the nozzle) velocity v_0 and the angle α, in relation to the horizontal direction, at which the jet is initially inclined.

If *n* is the weight of the droplet accounting for its buoyancy component, $k = \frac{f\rho A}{2}$ (where ρ is air density, which is dependent on temperature, and *A* is the cross section of the droplet) is the coefficient that defines the action of the friction force and *g* is the acceleration of gravity, then the balance in final form is:

$$\left(-k\dot{x}^{2}, -k\dot{y}^{2} - ng\right) = m\left(\ddot{x}, \ddot{y}\right) \tag{1}$$

which, in the horizontal and vertical directions, respectively, gives:

$$m\ddot{x} = -k\dot{x}^{2} \tag{2}$$

$$m\ddot{y} = -k\dot{y}^{2} - ng \tag{3}$$

where $\dot{x}$, $\dot{y}$, $\ddot{x}$, $\ddot{y}$ are velocities and accelerations in the horizontal and vertical direction, respectively. The initial conditions defined are $x(t=0)=0$ and $\dot{x}(t=0)=v_{0x}$ for the first equation, whereas $y(t=0)=h$ and $\dot{y}(t=0)=v_{0y}$ for the second. Where: t is time; v_{0x}, v_{0y} are the horizontal and vertical velocity components, respectively, at the exit of the nozzle. Integrating the system of differential equations gives the full analytical solution of the problem in the form of parametric equations of position (*x(t), y(t)*), velocity ($\dot{x}$ *(t),* $\dot{y}$ *(t)*) and time of flight τ. This model, by providing an exact solution, applies to many cases but in the hypotheses formulated only. It should be pointed out that the parameter *k* has to be managed carefully according to the flow state considered: in fact it may be that a droplet starts its path in a certain flow state, modifying it along the way, thus requiring a different form of *k* (as explained above) to be introduced into the model. The validation of the model proposed needs a quantitative approach to determine how reliable the predictions are: this can be achieved by introducing other authors' data into the model. The research work chosen for comparative purposes is that of Edling [5] and Thompson et al. [3]: among the cases studied by these authors, only those involving a no-wind condition were considered. Results are shown in Figs. 1 to 10 in terms of travel distance and time of flight. In Figs. 4 to 9, it clearly a shows very good agreement in most cases. This does not hold true in Figs. 1, 2 and 3 for a droplet diameter of 0.5×10^{-3}m: in these cases, in any case, Edling's [5] data could not be entirely reliable being numerically too close together regardless of parameter variations. Figures 10 and table 1 show the comparative analysis on the basis of Thompson et al.'s [3] data in terms of travel distance and time of flight, respectively. A difference can be noted for the results for droplet diameter of 0.3×10^{-3}m: this is related to the flow description adopted in [3] for smaller droplets, which was not shared in the present approach. The other data, particularly those referring to intermediate droplet diameters in the range, show reasonable agreement both in the values obtained and in the trends determined. These comparisons show that the model defined here proves to be kinematically reliable in its predictions even from a quantitative point of view. This result is particularly relevant as its construction excluded most of the complicated parameters typically introduced in other models to describe the same phenomenon and to obtain similar results.

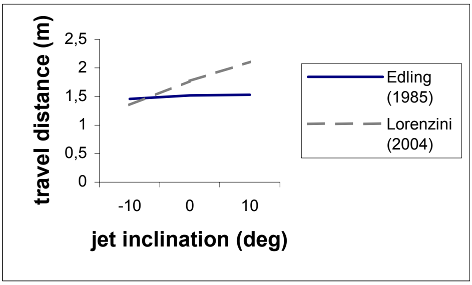

Figure 1: Travel distance of sprinkler droplets: Edling's [5] data compared to Lorenzini's [7]: flow rate = $1.4\cdot10^{-4}m^3\cdot s^{-1}$; nozzle diameter $3.96\cdot10^{-3}m$; air temperature 29.4°C; nozzle height = 1.22m; droplet diameter = $0.5\cdot10^{-3}m$. ($R^2 = 0.946$).

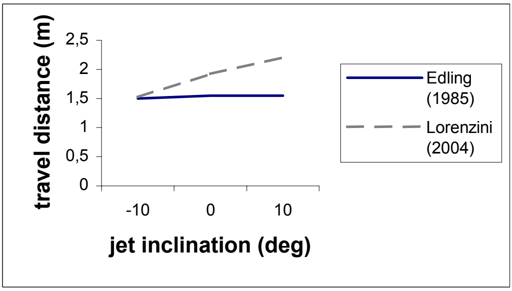

Figure 2: Travel distance of sprinkler droplets: Edling's [5] data compared to Lorenzini's [7]: flow rate = $1.4\cdot10^{-4}m^3\cdot s^{-1}$; nozzle diameter $3.96\cdot10^{-3}m$; air temperature 29.4°C; nozzle height = 2.44m; droplet diameter = $0.5\cdot10^{-3}m$. ($R^2 = 0.912$).

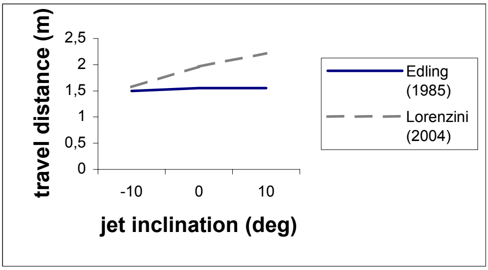

Figure 3: Travel distance of sprinkler droplets: Edling's [5] data compared to Lorenzini's [7]: flow rate = $1.4\cdot10^{-4}m^3\cdot s^{-1}$; nozzle diameter $3.96\cdot10^{-3}m$; air temperature 29.4°C; nozzle height = 3.66m; droplet diameter = $0.5\cdot10^{-3}m$. ($R^2 = 0.918$).

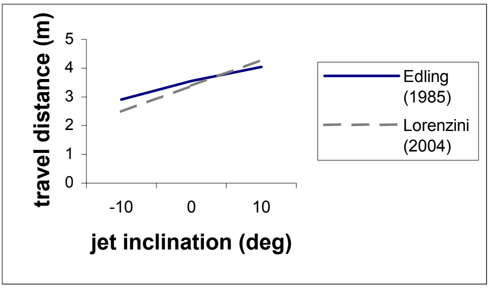

Figure 4: Travel distance of sprinkler droplets: Edling's [5] data compared to Lorenzini's [7]: flow rate = $1.4 \cdot 10^{-4} m^3 \cdot s^{-1}$; nozzle diameter $3.96 \cdot 10^{-3}$m; air temperature 29.4°C; nozzle height = 1.22m; droplet diameter = $1.5 \cdot 10^{-3}$m. ($R^2 = 0.997$).

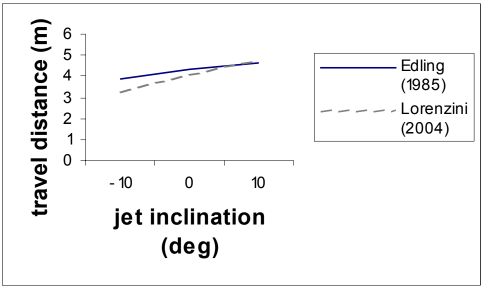

Figure 5: Travel distance of sprinkler droplets: Edling's [5] data compared to Lorenzini's [7]: flow rate = $1.4 \cdot 10^{-4} m^3 \cdot s^{-1}$; nozzle diameter $3.96 \cdot 10^{-3}$m; air temperature 29.4°C; nozzle height = 2.44m; droplet diameter = $1.5 \cdot 10^{-3}$m. ($R^2 = 0.997$).

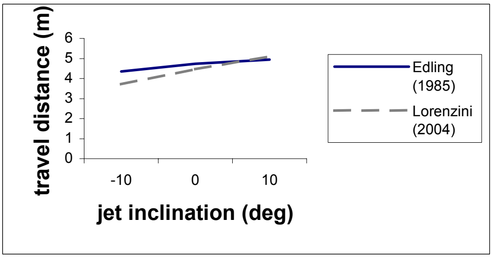

Figure 6: Travel distance of sprinkler droplets: Edling's [5] data compared to Lorenzini's [7]: flow rate = $1.4 \cdot 10^{-4} m^3 \cdot s^{-1}$; nozzle diameter $3.96 \cdot 10^{-3}$m; air temperature 29.4°C; nozzle height = 3.66m; droplet diameter = $1.5 \cdot 10^{-3}$m. ($R^2 = 0.995$).

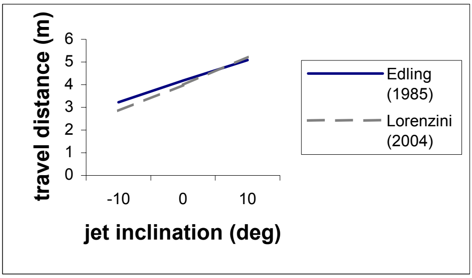

Figure 7: Travel distance of sprinkler droplets: Edling's [5] data compared to Lorenzini's [7]: flow rate = $1.4 \cdot 10^{-4} m^3 \cdot s^{-1}$; nozzle diameter $3.96 \cdot 10^{-3}$m; air temperature 29.4°C; nozzle height = 1.22m; droplet diameter = $2.5 \cdot 10^{-3}$m. ($R^2 = 0.999$).

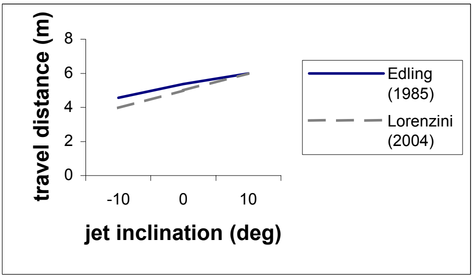

Figure 8: Travel distance of sprinkler droplets: Edling's [5] data compared to Lorenzini's [7]: flow rate = $1.4 \cdot 10^{-4} m^3 \cdot s^{-1}$; nozzle diameter $3.96 \cdot 10^{-3}$m; air temperature 29.4°C; nozzle height = 2.44m; droplet diameter = $2.5 \cdot 10^{-3}$m. ($R^2 = 0.998$).

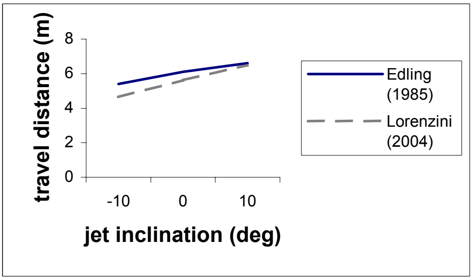

Figure 9: Travel distance of sprinkler droplets: Edling's [5] data compared to Lorenzini's [7]: flow rate = $1.4 \cdot 10^{-4} m^3 \cdot s^{-1}$; nozzle diameter $3.96 \cdot 10^{-3}$m; air temperature 29.4°C; nozzle height = 3.66m; droplet diameter = $2.5 \cdot 10^{-3}$m. ($R^2 = 0.998$)

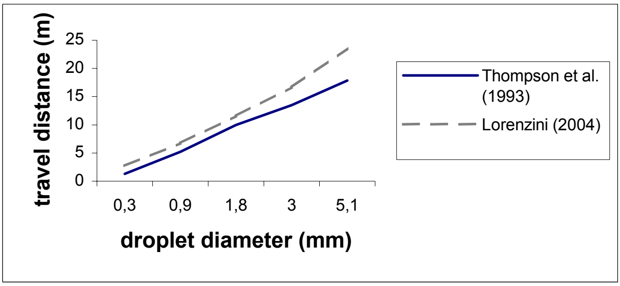

Figure 10: Travel distance of sprinkler droplets: Thompson et al.'s [3] data compared to Lorenzini's [7]: flow rate = $5.5 \cdot 10^{-4} m^3 \cdot s^{-1}$; nozzle diameter = $4.76 \cdot 10^{-3}$m; air temperature = 38°C; jet inclination = 25°; nozzle height = 4.5m. ($R^2 = 0.994$).

Table 1: Time of flight of sprinkler droplets: Thompson et al.'s [3] data compared to that of Lorenzini [7]: flow rate = $5.5 \cdot 10^{-4} m^3 \cdot s^{-1}$; nozzle diameter = $4.76 \cdot 10^{-3}$m; air temperature = 38°C; jet inclination = 25°; nozzle height = 4.5m.

		Droplet diameter (mm)				
		0.3	0.9	1.8	3.0	5.1
Time of flight (s)	*Thompson et al. (1993)*	2.63	1.54	1.63	1.75	1.84
	Lorenzini (2004)	0.84	1.35	1.73	2.00	2.26

2.2 Computed and experimental droplet evaporation

A new approach is suggested here for modelling spray evaporation in sprinkler irrigation. Once again, it is based on the analytical model in Lorenzini [7]. In accordance with this model, this section focuses on the effect that air friction has on the aerial evaporation of the droplet and excludes all other contributions, due to the many other parameters, which could have even a strong influence on the process, such as air humidity. This preliminary consideration shows the limit of this particular as a general description of the phenomenon, but highlights the role played by air friction, which has so far not been considered in literature [9]. A few more conditions are added to compute spray evaporation: evaporation is obtained by the total work of the resultant force that is converted into thermal energy; total droplet evaporation occurs at the end of the flight of the droplet and is schematically displayed as a material point. These assumptions determine a restriction to the validity of the results achieved in this section: the final kinetic energy of the droplet is calculated by its initial mass thus allowing an over-estimation of the evaporative process. The results obtained are "upper limits" of the real process, aimed at showing the relevance of air friction in spray evaporation for sprinkler irrigation. The model [7, 9] was used again on the data of Edling [5] and Thompson et al. [3]. In contrast to the approach adopted in our research, these works consider a range of parameters. Therefore, qualitative comparisons only can be made. Edling's [5] experiment was conducted in many different combinations of conditions, including: flow rate of $1.4\times10^{-4}m^3\cdot s^{-1}$, nozzle diameter of 7.14×10^{-3}m, jet inclination of 0°, nozzle height of 3.66m, air temperature of 21.11°C, relative humidity equal to 20% and no wind. Those of Thompson et al. [3] were: flow rate of $5.5\times10^{-4}m^3\cdot s^{-1}$, nozzle diameter of 4.76×10^{-3}m, jet inclination of 25°, nozzle height of 4.5m, air temperature of 38°C, relative humidity equal to 20% and no wind. The comparative results are quoted in Figs. 11 and 12 for a few small-diameter cases.

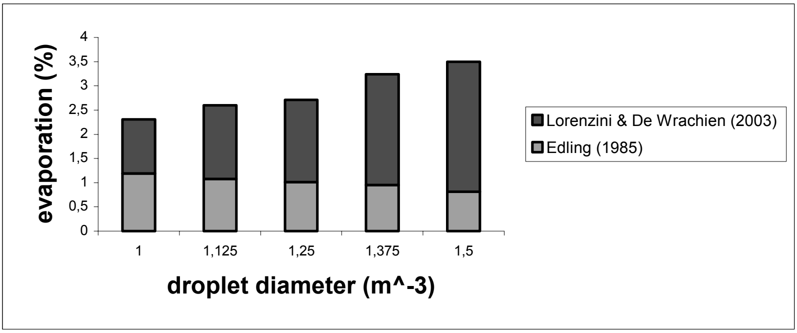

Figure 11: Spray evaporation results: Edling's results [5] compared to those of Lorenzini and De Wrachien [9].

The trends are different because of the over-estimation of the effect of air friction. However, the results obtained by the model and presented are qualitatively correct as they do not show the whole evaporative phenomenon but merely that part of it caused by air friction. In fact, as the friction force depends on the cross sectional area of the droplet, it is reasonable to say that larger droplets undergo larger frictional effects, even if they are not described, apart from with regard to their trends (which are correct), by the data of Figs. 11 and 12, which are to be considered upper limits, as previously mentioned. It is therefore possible to say that a new window has now been opened in this field, too as until now, air friction may have been unsuitably neglected. From an experimental point of view, of the main research performed in recent decades concerning experimental tests on sprinkler droplet evaporation, the research results published by Zanon and Testezlaf [10], Zanon et al. [11], Molle and Le Gat [12,13], Solomon [14], Tarjuelo et al. [1] were considered in a recent paper by Lorenzini [15]. Less recently, Frost and Schwalen [16] developed a nomograph to estimate evaporation empirically. All these works, characterised by different purposes yet related to the same topic, share the awareness of the difficulty in obtaining a clear result in the process of spray evaporation in sprinkler irrigation, because of the very many parameters mutually affecting one another in obtaining the final result. It is therefore unclear which effect is to be attributed to which parameter. In his paper, Lorenzini [15] proposed an experimental study in which all parameters, except air temperature, were neglected and opportunely set as constant. The problem of minimising experimental error was then faced by a statistical setting of the experimental activity itself, obtained by a repetition of each test at least 12 times and by the treatment of the data set by statistic means. Moreover, instead of the usual catch can collection performed by other researchers, it was decided to use a fully circular path of the sprinkler to avoid asymmetric losses in the inversion movements of the device [15]. The results, obtained in a reduced temperature interval varying between 21.0 and 27°C, for a constant relative air humidity of 94% and for a water temperature of 15.0°C, showed an evaporation rate of between 4.15 and 7.73%.

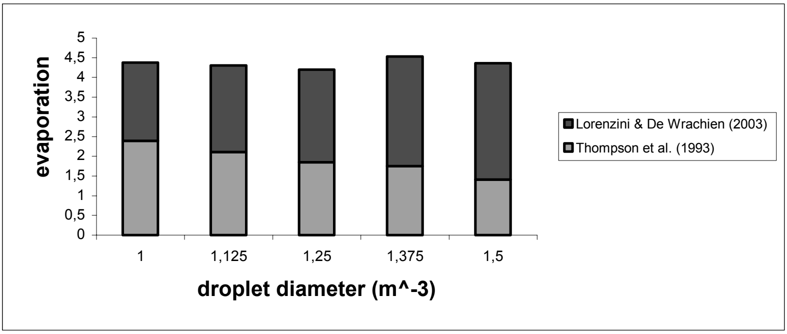

Figure 12: Spray evaporation results: Thompson et al.'s [3] results compared to those of Lorenzini and De Wrachien [9].

Each irrigation test was performed with sprinklers working in steady-state for a time interval of 360s and the flow rate delivered by the sprinkler was always equal to 3.025×10^{-4} $m^3 \cdot s^{-1}$. These results are significantly higher than those in Thompson et al. [17], but it should be noted that the climatic conditions of the experimental tests in Lorenzini [15] are far more homogeneous and hence more suitable for singling out each parametrical contribution than those considered in the abovementioned paper. In fact, in Thompson et al. [17], the evaporation measurements, each of which was conducted for a whole day, were obviously affected by usual daily thermal rushes and therefore difficult to interpret. It has to be highlighted that aerial evaporation of irrigation water in sprinkler systems has been very rarely tackled in literature, as most researchers prefer to focus on other phenomena, that are more easily determinable and to which they also attribute the effect actually due to aerial droplet evaporation. This experimental activity, which introduces the novelty of a single-parametric analysis of this problem, proved that the effect of air temperature on sprinkler spray evaporation, previously neglected by most researchers who considered it a less important parameter, in actual fact has an importance that further studies will have to prove in a wider range of air temperature and climatic, cinematic and geometric conditions.

3 Conclusions

The present work shows, both theoretically and experimentally, that the thermal fluid dynamics characterisation of water droplets in sprinkler irrigation is a complicated topic, due primarily to the many mutual interactions linking the parameters to one another. This difficulty implied, in the approaches available in literature, that the problem could not be fully solved, as excessively complicated systems of equations would be required to obtain a close solution (theoretically) and as the experimental error could not be entirely avoided (experimentally). However, the introduction of some new hypotheses, which are proposed herein, can help in determining a new approach to the problem. This was performed through the:

- introduction of a new and simple analytical method to study the kinematics of the process;
- use of the method to hypothesise a new way of computing sprinkler spray evaporation;
- definition and realisation of a single-parametric experimental test, applied in this case to determine the effect of air temperature on aerial droplet evaporation, to verify whether this direction could be followed to determine the relevance of each parameter to the whole phenomenon.

The research presented in this paper represents a first step from an applicative standpoint, however, from a descriptive point of view it pinpoints an investigative technique that proves to be efficacious in analysing practical situations related to irrigation. This method also entails important consequences for example, on the fundamental question of water waste in agriculture that, as recalled at the start of the paper, becomes increasingly delicate from an ecological standpoint. This is ultimately the most ambitious threshold overcome by this research: to consider water waste in agriculture, in this case with regard to sprinkler irrigation, through the use of a very simple, general (and therefore not connected to case-dependent empirical formulae) method that is applicable in a practical field by farmers with the choice of just a few fundamental environmental parameters, such as the data exiting the sprinkler, and basic weather conditions. The future must of course, develop the technique by expanding the field of the environmental variables considered, however the descriptive capacity of the approach, which has shown good results thus far, already makes it an interesting tool, that must, however, improve the match of the conditions applied to those technically realistic.

Notation

$\vec{a}$ = acceleration of the droplet, $m \cdot s^{-2}$
A = cross sectional area of the droplet, m^2
f = friction factor according to Fanning
$\vec{F}$ = total force acting on the system, N
g = acceleration of gravity, $m \cdot s^{-2}$
h = nozzle height from ground level, m
k = friction parameter, $kg \cdot m^{-1}$
m = mass of the droplet, kg
n = actual mass of the droplet, kg
t = time, s
v_{0x} v_{0y}, = initial velocities, $m \cdot s^{-1}$
v_0 = velocity vector of the droplet exiting the nozzle, $m \cdot s^{-1}$
$\dot{x}$, $\ddot{x}$, $\dot{y}$, $\ddot{y}$ = velocities and accelerations (horizontal and vertical direction), $m \cdot s^{-1}$, $m \cdot s^{-2}$
α = exit trajectory of droplet, °

ρ = air density, kg·m^{-3}
τ = droplet time of flight, s
0 (subscript) = initial value

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Section 4
Irrigation management

Social and irrigation water management issues in some water user's associations of the Low Segura River Valley (Alicante, Spain)

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Abstract

In the region of the Low Segura River Valley, in the southern area of the Alicante province, the reduction in irrigation water availability and the political debate draw a difficult situation for agriculture. During recent years, as a result of the application of the National Irrigation Plan, irrigated areas are being modernised, improving their irrigation network infrastructure. But, for modernisation to go beyond isolated or point measures, it should spread through all procedures that allow the Water User's Associations comprehensive management and control of irrigation water. The work presented here aims at analysing and quantifying the problems and needs perceived by some WUAs about irrigation. A survey was made by a 76 items questionnaire structured in four main topics: i) WUA identification and general information; ii) aspects related to decision making and management processes; iii) services for members provided by the WUA, and iv) future perspectives and improvement possibilities.

Keywords: WUA, water use, survey, irrigated agriculture, water availability.

1 Introduction

The Southern area of the province of Alicante, in which this work was made, corresponds to the region of the Low Segura River Valley that gathers 27

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municipalities with a total surface of 957 km^2, and approximately 16% of the total area of the province [1].

The area cultivated in the region represents 24% of the total of the province's cultivated land taking into account both dry-land and irrigated cultures, though the irrigated surface means 40% of the total irrigated land of the province of Alicante [2]. Citrus is the main crop (24,317 ha) that represents 69% of the total of citrus cultivated in the province. Horticultural crops (6,584 ha) come in second place, 63% of the province's area of horticultural crops, and in third place are other fruit trees (5,495 ha), that comprise, 13% of the province's total surface of other fruit trees [2]. In spite of the mild climate, the good quality of the soil and the suitable commercialization of agricultural products, Juárez [3] indicates that the limitation to the agricultural development of the area is a consequence of water shortages.

In this region, the irrigation water is administered by Water User's Associations (WUAs) some of which had their origins in the Middle Ages. A distinction among them, based on their origin and source of the irrigation water, is set up: the traditional WUAs take the irrigation water through a network of channels from the Segura river and all of them were established before 1933; the Water Transfer WUAs take the irrigation water from the Tagus-Segura water transfer and were settled down in the 70' and up till the end of the 90' of the 20th century. The WUA constitutes a group that self-manages freely, and that, as far as regards trusteeship, generally does not receive much support from the Public Administration. A fundamental aspect for a good operational management of the WUA is obtaining information relative to water management [4].

The problems of the WUAs are those of irrigated agriculture. The modernization of irrigation is mainly understood as the improvement of its infrastructures, and although it consists mainly in pressurizing water supplies up to the plot intake and other services, it is not only that. The modernization concept must extend, in agreement with Sanz and Ursua [5], the frame of isolated or point improvements, including all the achievements that allow the WUAs a management and integral control of the water in their irrigated areas. In the particular case of the WUA "Riegos de Levante" (Alicante) and according to Llanes [6] the modernization of irrigation infrastructures aims not only at the installation of a pressurized irrigation network that could allow drip irrigation, but "at improving the management of the irrigated land, at optimizing the distribution and use of water, helping its saving and the adaptation of the crops to the new technologies" aim that perhaps is more related to water management on the part of the WUA and, finally of the members. Other aspects must be taken into account in the analysis of the function of the WUAs as the influence of the land urbanization and the changes of rural society [7], the changes in the land uses and the reorientation of crops on a rent basis.

If agricultural farms are undergoing significant changes related to generational replacement, reduction in the number of farms and consequently increase of their average size, reorientation of crops, etc., the WUA must be prepared for these changes, and the technical training of the farmers is going to play a very important role to get adapted to the new scenario. The irrigation advisory services facilitate this adaptation as long as they support the farmer and give irrigation recommendations that help to carrying out a sounder use of water.

In recent years, there is a great debate in this region, as a result of the alternatives given to the National Hydrological Plan and drought conditions that have significantly reduced the irrigation water availability of the WUAs. In this framework, this work has the aim of analysing and quantitatively describing the problems and requirements about irrigation perceived by the WUAs of the region of the Low Segura River Valley (Alicante).

2 Methodology

The survey is a method to collect ideas, opinions, and expectations, normally answering a questionnaire or by means of an interview, and is suitable when the information must come directly from the concerned people. In the evaluation of social and technical aspects relative to irrigated land operations, the survey to farmers has successfully been used in our country by Alvarez *et al.* [8], Neira *et al.* [9] and Cuesta *et al.* [10]. Also Tanaka and Sato [7] analyze the behaviour in irrigation water management of Japanese WUAs by means of surveys to presidents and personnel of the WUAs.

Table 1: Number of hectares for each irrigation type and water-transfer zone.

Type	Zone	Total number of WUAs	Number of surveyed WUAs	% of surveyed WUAs	Total irrigated area (ha)	Irrigated area of the surveyed WUAs (ha)	% of irrigated area surveyed
Traditional		14	8	57.1%		(*)	
Traditional	Riegos Levante R.M.	1	1	100%	3,993	3,993	100%
Water Transfer	Riegos Levante L.M.	15	7	46.7%	36,751	35,448	96.5%
Water Transfer	Saladares de Alicante	1			1,500	1,500	
Water Transfer	Pedrera Zone	14	9	64.3%	11,565	8,603	74.5%
		45	25		53,809	49,544	92%

(*) Without data.

Surveys were administered to each WUA, interviewing personally the president, secretary or the person designated by them, during the period of July to September 2005. Altogether 25 surveys have been made out of 45 possible ones. One first classification of the WUAs has been established (table 1) based on their belonging to the traditional irrigated land (9 of the surveyed ones) or irrigating from the Tagus-Segura water transfer (14), and also taking care of the irrigated area, establishing four zones: "Riegos de Levante Margen Derecha" (Right margin, RM), "Riegos de Levante Margen Izquierda" (Left Margin, LM), "Saladares de Alicante" (Alicante's salty marshes) and the "Pedrera" Zone. The importance of the surveyed WUAs can be seen in table 1 since the percentage of surveyed WUAs represents more than half of the total number, and it includes 92% of the total surface irrigated by the water transfer in the region.

The previous design of the questionnaire and passes to test WUAs took place in June 2005. The definitive questionnaire contains a total of 76 questions structured in four main blocks. The first one (7 questions) asks for the identification of the WUA, as well as general information about it, in aspects related to the settlement year, kind of services available to the farmers, etc. In the second one questions are posed on the decision making process and management related aspect (17 questions). The third block is related to the WUAs's services to the partners, and especially about access to training courses (5 questions); the fourth block deals with future perspectives (8 questions) and improvement possibilities (39 questions).

3 Results and discussion

3.1 Block I: WUA's general information

The survey began with the identification of the surveyed WUA, the year of settlement was asked emphasizing the distinction between the traditional ones like the oldest Water Court of Orihuela dating from 1275. One dated from the 15th century, another one the 16th century, two of the 18th and two from the 19th centuries. In some cases there is a reference to the date of the decrees, but for those older ones it has not been possible to determine exactly their age. About the WUAs that irrigate from the water transfer, the oldest ones were established in 1930 General Water User's Association "Riegos de Levante Margen Izquierda" (Left Margin) and the youngest one in 1998 (Water User's Association of Albatera), stemming from the previous one.

The interviewed people have declared almost unanimously (96%), that the service that the WUA renders to its partners is providing irrigation water, and only one out of the 25 provides also water for urban supply. Regarding the type of water concession, all of them have superficial water and 4% have an additional concession of regenerated waste-water.

Regarding the establishment of charges, the WUAs that irrigate from the water transfer, (16 of the WUAs interviewed), the majority (44%), establish their rates on a volume basis, 4 WUAs that represent 25% of the surveyed ones, establish the rate according to the irrigation surface, and 3.2%, according to the irrigation time, two WUAs chose other types of charging: in one of them all pay the same amount and the second one does not answer. Nevertheless in traditional WUAs (9 of the WUAs interviewed), none of the surveyed ones establishes their rates on a volume or irrigation time basis, 3 have responded that according to the irrigated surface, and the other 6 chose other types: three of them responded that there is no rate, two of them pay quotas for channel maintenance and another one that they irrigate when water is running in the channel.

It is very important for the normal operation of the WUA that the partners feel integrated into it and that they have facilities in order to have their meetings. 23 Communities have social centre (92%), and 18 of them (72%) have their own premises where to meet, 6 Associations do not have their own premises and one of the surveyed ones did not respond to the question. Those Associations that do not have their own premises were asked if having them could influence positively the management and benefit the services to the partners. Half of them answered no, two said it would and to another one it was indifferent.

3.2 Block II: management and decision making

This block of questions dealt with aspects relative to the regularity of the assemblies, renovation of the Board of directors, age of the president, number and age of the partners, etc. As far as the frequency whereupon they meet in assembly a majority (60%), have only one general assembly per year, the percentage being greater in those WUAs that irrigate from the water transfer (68.8%). 20%, 5 associations, meet twice a year, and two associations, one traditional one and another one irrigating from the water transfer, have monthly meetings. It is remarkable the disparity among the associations that responded “other”, all of them of traditional irrigation, from one assembly each three years to another one with two meetings weekly which means more than 100 per year, this one corresponds to the Water Court of Orihuela, one of the greater ones; although in this case the assemblies are probably made grouped in secondary channels.

The question about the age of the president reveals an already little participation of the young people devoted to management tasks in the WUAs, this being a common characteristic of Spanish agriculture. Therefore, out of the validated answers (one association did not answer), 75% of the presidents are above the age of 50 years, most of these (40%) surpass 65 years of age, and only two communities have a younger president (40 years or less). Regarding the time the president dedicates to the management of the association’s activity, it is usually more than 4 hours a week, while in associations that irrigate from the water transfer it is mainly between 4 and 10 hours (10 WUAs out of 16 chose this answer), and in those of traditional associations affirm that they dedicate some more than 10 hours a week (3 WUAs out of 7 validated answers).

The Board of directors, integrated by the president and other members of the society, meets regularly to deliberate and to coordinate aspects of interest in the functioning of the WUA. These periodical meetings usually take place once a month or less in the WUAs that irrigate from the water transfer, being very uncommon the WUAs that have two or three meetings a month and only one claims to meet more than four times. In the traditional WUAs two groups are observed, those that have one meeting a month or less and those that state that they meet 2 or 3 times a month (even two of them meet more than four times). This second group agrees with the WUAs which claimed a greater time of dedication of the president to the management tasks.

Some resistance to change is observed regarding the renovation of the Board of directors' members. In most of the WUAs the position is appointed for at least 4 years, and this is so mainly in those that irrigate from the water transfer, almost 70%. On the contrary, in traditional WUAs the renovation of the Board usually takes place every two or three years. In these associations it is frequent to have a partial renovation of members, so that every year or at least every other year there are elections, but only to elect half of its members. This way gives some continuity to the association's projects and there is also an adaptation period that does not interrupt the on-going management.

All the traditional WUAs surveyed (9) have more than 200 members. Four of them (44.4%), oscillate between 200 and 1,000 and five (55.6%) have more than 1,000 members, the biggest one having 9,000 members. In those WUAs that irrigate from the water transfer (16), the number of members is smaller since only half of them have more than 200 members, of which six (37.5%) have between 200 and 1,000, and the rest more than 1,000 (one has 1,300 and the greater one than is "Riegos de Levante" LM that has 20,000).

It is interesting to know the degree of dedication of these members to the agricultural activity, mainly if this dedication is full-time or part-time. Part-time farmers complement the agricultural income with another activity and in some cases the main income of the familiar unit does not even come from the agricultural activity. For traditional WUAs, the part-time percentage of partners is 84%, whereas in those that irrigate from the water transfer is 64.5%, indicating that the water transfer farmers tend to have agriculture as their main business.

Asking about the average age of the members revealed that the majority (68%) of members are in the age interval of 40 to 60 years, being this percentage higher in WUAs that irrigate from the water transfer (81.3%). In traditional WUAs, out of 7 valid answers (2 associations did not answer) the majority (57%) are between 40 and 60 years old. No WUA chose the option less than 40 years.

A problem showed by Spanish agriculture is population aging. WUAs were asked if there were partners that could be eligible as "young farmers" (Law 19/95, of July 4th, of Modernization of agricultural farms), 92% of the cases (22 WUAs) answered yes, one WUA responded no and another one did not answer. Although the existence of young farmers is remarkable, they do not represent a generational replacement since only 18.2% of the WUAs that responded affirmatively indicated that in their associations there were more than 10 "young farmers".

A significant detail on the social distribution is the fact that although in most of the WUAs women take part as partners, (22 WUAs (88%) answered yes, one (4%) answered no, and two WUAs did not answer to the question about having women among the WUAs members) its representativeness in management is much reduced. Only 4 WUAs (18% of the affirmative answers to the previous question) indicated that they have a woman as a member of the Board of directors (two women in one WUA and one woman in the other three), which confirms the low feminine participation in management and representation in these societies. Differences between the traditional WUAs and those that irrigate from the water transfer have not been appraised on this issue.

3.3 Block III: Training and services to members

With regard to the interest and the importance allowed to training, overall most of the WUAs consider the training of members to be important or very important (76%). Training is more appreciated by the WUAs that irrigate from the water transfer, since 75% of these consider training to be quite important and 12.5% very important (though the only WUA that affirmed that training was not important at all belongs also to this group). Traditional irrigation WUAs were more cautious: one did not answer while for one of the eight WUAs that answered the question (11.1%) training was very important, four of them (50%) claimed it to be quite important and three of them (38%), indicated that it was barely important.

In order to deepen in the aspects related to training, WUAs were asked on the number of training courses that they had organized in last two years, since this would be an actual indicator of the degree of importance given to training. So we observed (table 2) that only five WUAs have organized at least one course. These five correspond in two cases with those which stated that training was very important, in other two with those which thought that it was quite important and finally with the WUA which did not show its opinion about its importance.

The contents of these courses have dealt on agricultural subjects, pesticides management and modernization in irrigation. As far as the short term forecast for the organization of courses, those WUAs that have already organized courses (four) are going to continue and have programmed some others for the next years, whereas the rest have not planned the organization of any course. A course on prevention of labour risks is proposed for the next years, in addition to those about pesticides and other agricultural subjects.

Table 2: Organization of training courses.

Importance of training	Courses organized	Traditional	%	Water Transfer	%	Total	%
Very important	No		0%	1	6.25%	1	4%
	Yes	1	11.1%	1	6.25%	2	8%
Quite important	No	2	22.2%	10	62.5%	12	48%
	Yes	1	11.1%	1	6.25%	2	8%
	Blank	1	11.1%	1	6.25%	2	8%
Unimportant	No	3	33.3%	1	6.25%	4	16%
Not important	No		0%	1	6.25%	1	4%
No answer	Yes	1	11.1%		0%	1	4%

In view of the results in table 2, most (67%) of the WUAs that claimed training being very important have acted accordingly organizing some training courses, while only 13% two of the ones which considered that it was quite important did organize any course. As it could be expected, none of the WUAs giving little or no importance to training has scheduled any course in the last two years.

3.4 Block IV: Future perspectives and improvement possibilities

In the block of future perspectives, WUAs were asked about their opinion on the functioning of the association, level of satisfaction and how they envisage the future.

When asked about how they foresee the future of the WUA, the majority (84%) answered “uncertain”, only one sees it “good” (4%), whereas another one sees it “difficult” (4%). No one responded “promising”. One WUA did not answer, another one responded “others”, indicating that the tourism will reduce the importance of the WUAs’ problems.

The level of satisfaction with the functioning of the WUA is high, since six of the 25 surveyed WUAs responded that they are very satisfied (24%), 17 are satisfied (68%), whereas two did not answer (8%). Concerning the aspects that could be improved, the questionnaire presented the option to answer among several alternatives: management, information, services to the partners and others, being it possible to mark more than one option. The results of the 25 WUAs (table 3), reveal that five of them did not answer and the rest thinks that mainly the information system must improve (4 WUAs), the services to the partners (3 WUAs), the quality of the water or its amount (3 WUAs), the management (2 WUAs), the management and the services to the members (1 WUA), the infrastructures (2 WUAs) (dams, irrigation systems), the increase of prices for the growers (1 WUA) and 4 WUAs said that everything should be improved.

Almost all the surveyed WUAs (96%) agree in pointing at water availability or quality as the most important problem of the WUA, and only one aims at the city-planning or urban development problem.

Table 3: Issues to be improved in the WUA.

Issues to improve	WUAs	%
Management	2	8%
Services to the partners	3	12%
Management and services to the members	1	4%
Information	4	16%
Infrastructures	2	8%
Water amount and quality	3	12%
All the former	4	16%
Others: Increase of prices to the growers	1	4%
No answer	5	20%
Total WUAs	25	100%

Among the solutions to improve the availability of water they emphasize water transfers with 17 answers (68%), followed by the sewage treatment plants with five (20%), whereas three WUAs did not respond (12%). Those that point out the sewage treatment plants as the best alternative think that the water transfer causes a great environmental impact (this was the answer of a traditional irrigation WUA), and that the water desalination plants are expensive (this was the opinion of water transfer WUAs), although also they show that the three alternatives are valid if water availability increases, or when political tendencies and reasons advise against other options. The WUAs that chose water transfers point out water quality and its price: the water from water transfer is cheaper and of better quality, the cost of the desalination plants is very high. The WUAs that did not show preference for any option think that a combination of the three options would be the best solution.

The Water Framework Directive (Directive 2000/60/EC, of October 23rd) appeals for full cost recovery, thus WUAs were asked about the price that the partners could pay for the water coming from a water transfer or from desalination plants. Most of them did not answer, and only five traditional WUAs pointed out that the water should have no cost for the growers or have a very low political price. As for the WUAs that irrigate from the water transfer, the participation was higher, ten WUAs answered, and they mainly pleaded the maintenance of current prices or that water should have a political price.

4 Conclusions

The WUAs surveyed indicate that their work is dedicated mainly to the management of irrigation water. The greater concern is detected on the quality of irrigation water and its availability. The problem of water shortages has been pointed out by all the people interviewed. Also a rather high satisfaction level with the functioning of the WUAs has been expressed. A reduced generational replacement has been detected, since although there are young farmers in the associations, their percentage on the total number of members is very low. The reduced presence of women as members and sometimes as members of the management boards has also been pointed out. It emphasizes the small relevance allowed to the training of farmers since there are very few WUAs that provide training courses, being this one a basic tool to improve the on-farm management of irrigation water. Regarding the alternatives to increase available water, farmers are more interested in water transfers than in desalinating plants, although in both cases they would not assume the real cost of water, but a political price.

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Towards sustainable irrigation in Western Australia

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Abstract

This paper summarises the results and implications from two research trials, both undertaken in the Harvey Irrigation Area (HIA) in South Western Australia. The first trial assessed the sustainability of irrigation in the HIA at the regional, or irrigation scheme, scale. The second assessed a number of irrigation Best Management Practices (BMPs) at the farm-scale and then applied these results to their potential system-scale implications.

The single most important point in terms of the sustainability of irrigated farming in the south west of Western Australia is likely to be the real (or more importantly, perceived) issue of nutrient export to regional waterways.

Nutrient losses from irrigated agricultural land were found to be associated more with winter rain-driven processes than with irrigation activities. Also, significant water and nutrient savings were observed to have been made when switching from traditional surface (flood) irrigation systems to more efficient, centre pivot systems.

However, these trials have shown that there are important nutrient assimilation and loss processes confounding apparently simple trial results. This is an important issue in determining how to appropriately assess the "sustainability" of irrigation practices.

Keywords: sustainability, Best Management Practice, irrigation, water use efficiency, eutrophication, runoff, catchment.

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1 Introduction

Although Australia is the world's driest inhabited continent, Australians are the highest water users per capita in the world with the agricultural sector (largely irrigation) accounting for about 70% of total water use (Commonwealth of Australia [1], Australian Bureau of Statistics [2]).

In total, the irrigation industry in Western Australia is the single largest water use group in the State accounting for about 36% (940 Gigalitres / year) of all licensed surface water and groundwater allocation. The Australian average of about 70% of water resources diverted for irrigation indicates considerably greater production in the Eastern States of the country.

Despite the relatively small scale in Western Australia, irrigation is a high value industry. From a total area of about 83,000 hectares, or 3% of the total WA land area, returns to WA are more than $650 million dollars a year. This value per hectare equates to more than three times the national average (Australian Academy of Technical Sciences and Engineering [3]).

Licensed groundwater allocations for irrigation in WA total about 490 Gigalitres / year and are used to irrigate about 61,000 hectares (McCrea and Balakumar [4]). This represents approximately 55% of the total water licensed for irrigation use. In comparison, about 450 Gigalitres / year are diverted from surface water resources and used to irrigate approximately 22,000 hectares. About 90% of the surface water used is supplied through four main irrigation schemes – the Ord, Carnarvon, Harvey, and Preston Valley schemes.

1.1 Trial background

The Harvey Irrigation Area (HIA) is Western Australia's prime irrigated dairying area supplying Perth and the south west of WA with more than 40 per cent of its milk. Irrigated agriculture commenced in Harvey with the establishment of a weir in 1916 and since that time pastures have been watered through surface irrigation of paddocks, which over time have been levelled and divided into individual irrigation bays.

The HIA currently has around 10,000 ha of land under permanent irrigation for dairy farming, beef grazing and horticulture, with a total irrigable area of approximately 30,000 ha. The region is presently experiencing some soil salinity problems common to other areas subject to irrigation, as well as producing nutrient-enriched drainage water that runs to environmentally sensitive estuarine receiving bodies including RAMSAR-listed wetlands, some of which have a long history of eutrophication and subsequent algal blooms.

2 Regional surface water quality in the Harvey Irrigation Area: implications for regional environmental sustainability

The need for an objective study examining the sustainability of irrigated agriculture in the HIA was identified by regional Natural Resource Management (NRM) partners as the quality of the water used for and following agricultural irrigation purposes in the area had not been well quantified. The popular view, however, in the broader community, and to some extent within the WA NRM community, appeared to be that irrigation farming in the region was a major contributor to surface water pollution lower in the catchment.

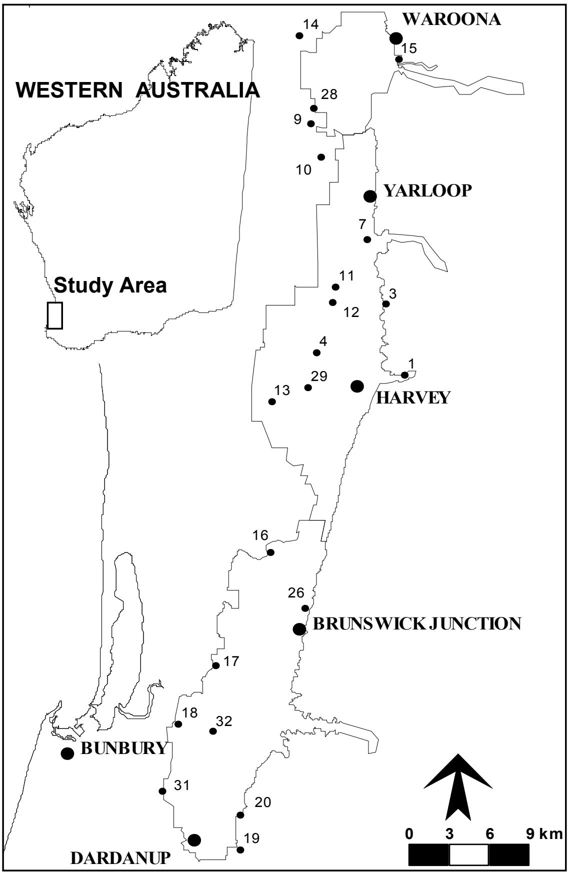

Figure 1: Location of sampling points within the Harvey Irrigation Area.

2.1 Methods

A suite of 21 monitoring sites was selected to reflect the quality of drainage water within the HIA and below the HIA in catchment terms. As well as being selected to provide an adequate coverage of channels and drains located higher and lower in the catchment, sites were selected to provide an adequate coverage of the three irrigation districts within the HIA – Waroona, Harvey and Collie – to determine if any district-specific differences could be observed. The location of these points can be seen in Figure 1.

Water samples were collected fortnightly during winter when irrigation water was not being released, and weekly during the summer months following the commencement of the irrigation season. Water samples were analysed in-situ or at the offices of the Department of Agriculture and Food for pH, turbidity and EC using hand held metering systems, and were transported to Murdoch University for nutrient analysis.

2.2 Discussion

pH and turbidity levels monitored throughout the channel and drain points generally fell within the acceptable guidelines while exhibiting fluctuations which are commonly measured in water bodies of this type.

Two significant points were apparent from the EC data:

EC levels in water sourced from the Wellington Dam and distributed throughout the Collie irrigation district generally exceeded the MRL for irrigation supply water by more than 100%. They also, generally, exceed the MRL for the protection of freshwater aquatic ecosystems. The average EC levels in this district increased annually for all three years of the monitoring programme.

2.2.1 Summary of macro nutrient concentration variations and patterns

Generally, nutrient concentrations in the waters of the distribution channels were below the maximum recommendations (ANZECC, [5]) while water within the drains was at about the ANZECC level most of the time, with short periods during which the ANZECC levels were exceeded.

Nitrogen concentrations in drainage water were found to be statistically higher during periods of dryland farming (outside of the irrigation periods) when compared with concentrations measured during irrigation periods. The median values during the dryland farming period were 1.4 mg/L compared with 0.95 mg/L during irrigation. This means that, in terms of measured nutrient concentrations, water flowing during irrigation has nitrogen levels 32% lower than those measured during winter. Or, water measured in winter holds 1.5 times the nitrogen held during irrigation.

Phosphorus concentrations between periods of irrigation and non-irrigation were not statistically different.

Increased nutrient concentrations in winter may reflect a number of issues: the dominant influence of rainfall over irrigation on the transport of water-borne nutrients in the south west WA environment; the effectively larger available catchment for rainfall during winter compared with irrigation “catchments” during summer; the influence of winter waterlogging on the release of nutrients under anoxic soil conditions, and; the influence of bare or non-productive areas outside of irrigation bays (where nutrients are not being utilised by plant growth) on the overall water quality.

Further analyses have been undertaken which examine the nutrient loadings based on measured flow rates. On average, while 79% of water travels through the irrigation system during winter, this water carries 88% of the phosphorus and 86% of the nitrogen exported annually. Irrigation water, while accounting for 21% of the water measured during the monitoring programme, carried 12% of the total phosphorus measured and 14% of the nitrogen.

Average nutrient loads per unit area are 6.0 kg/ha/yr (phosphorus) and 69.62 kg/ha/yr (nitrogen) during winter when the irrigation system is collecting dryland farming drainage water, and 0.89 kg/ha/yr (phosphorus) and 14.56 kg/ha/yr (nitrogen) during the summer irrigation period. The summer (irrigation) nutrient loads are observably lower than winter (non-irrigation) loads. This is especially significant as the irrigation season catchments are generally much smaller than the winter catchments. Given these variations in catchment size the larger (winter) catchments might in fact be expected to produce lower loads per unit area because of dilution factors.

However, when these figures are considered in comparison with other parts of the Swan Coastal Plain of similar size, it is clear that the irrigation area discharges significantly more nutrients than adjacent dryland farming areas of lighter, sandier soil. It appears, though, that the contribution to this from the irrigation season is relatively minor. For example, the total annual amount of phosphorus exported from the (estimated) 11,457 ha monitored as part of this programme is 58 tonnes. As a comparison, this equates to almost 40% of the total phosphorus export of the Peel-Harvey Catchment from only 6% of the area. This association has been made before (Birch, [6]). This study found that increasing phosphorus export rates within the Peel-Harvey catchment were closely associated with three factors: heavy soils, phosphorus application rates and dairying as a land use. It has also been noted (Attwater, [7]) that up to 80% of heavy soils within the southern portion of the Swan Coastal Plain already contain optimum or excess levels of phosphorus. Further phosphorus applied to these soils is generally lost to runoff and leaching.

Within the HIA, none of these factors can be viewed in isolation. The heavier soils have a naturally higher ability to retain phosphorus, and therefore require more phosphorus to provide plants with sufficient levels for growth. Also, the predominant dairying landuse exists within these regions, as they are the most productive.

High nutrient loads from the HIA are associated with the regional soils, predominant land use and associated high production levels, but are not due to irrigation per se.

3 On-farm assessment of WA irrigation practices and proposed BMPs

In addition to the system-scale assessment discussed above, work was also undertaken on an irrigated dairy located within the HIA and near the town of Harvey (see Figure 2).

Automatic water sampling equipment was installed to examine the amount of runoff and the quality of water leaving surface irrigation areas under different management regimes. It compared this with any losses from centre-pivot irrigated areas. Groundwater samples were also taken and any changes to groundwater levels or quality under the different systems recorded. Pasture quantity and quality was also measured by a consultant agronomist and soil moisture monitoring was used to manage the irrigation scheduling of the surface and centre pivot both systems.

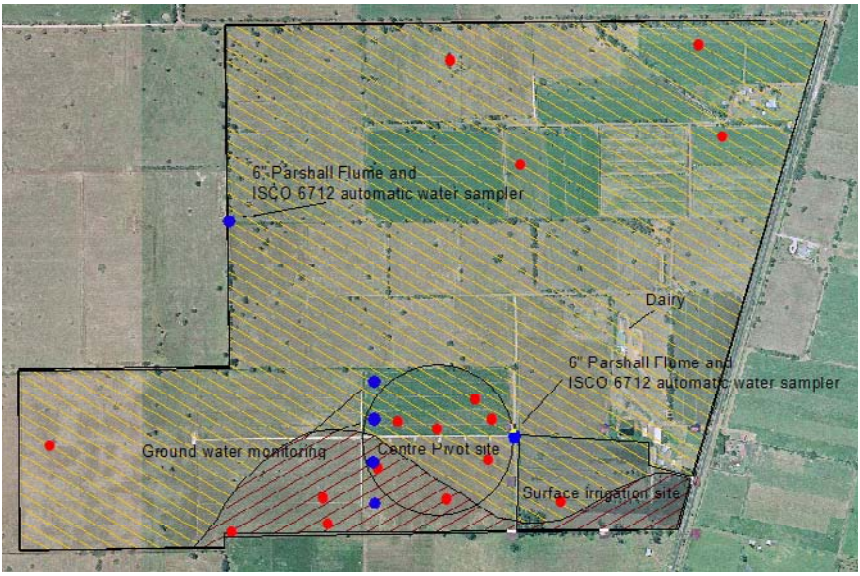

Figure 2: Layout of Harvey irrigation farm study area.

Table 1: Water use measures, irrigation seasons 2003-04 and 2004-05.

	Surface		**Centre Pivot**		
	Total (ML)	per hectare	Total (ML)	per hectare	*CP vs. Surface*
2003/2004	109	18	67	8	56%
2004/2005	71	11	68	8	28%
03/04 vs. 04/05		39%		0	

3.1 Water use efficiency

The results for the respective sites for the 2003-04 and 2004-05 irrigation seasons are shown in Table 1.

The results show the superior performance of the centre pivot in delivering the amount of water required for pasture production. With the centre pivot, 56% less water was applied in year 1 compared with the surface bay and 28% less in year 2. For the pivot itself, water use was essentially unchanged. For the surface bay, 39% less water was applied in year 2.

The centre pivot results can be largely attributed to improved scheduling and management that resulted from the increased experience and confidence of the land manager. In the case of the surface site, research staff attended the site for most of each irrigation event in the second season to open and close gates at optimum times. This allowed quicker movement of water across the bay, resulting in less water being applied in 2004-05 compared with 2003-04.

3.2 Groundwater quality

Groundwater quality in terms of both nitrogen and phosphorus was not of concern and were within the recommended maximum levels.

3.3 Water losses to runoff

Losses to runoff from the surface irrigation site for the 2003/04 irrigation season were very high (approximately 65%). These figures were reported for a six hectare, three bay, surface irrigation trial site, (see Figure 2).

Following a review of the monitoring design and protocols, an additional flow control structure and automatic water sampler were installed at the tail drain of the first, individual irrigation bay. This site is referred to as 'Bay 1'. The runoff figures for the 2004/05 irrigation season, expressed as a percentage of applied water are shown in Table 2 below.

Table 2: Runoff losses from individual and combined surface irrigation bays.

	Average (%)	Range (%)
Bay 1	12	7 – 19
3 combined bays	20	7 - 35

These figures are significantly better than the 65% measured during the 2003/04 irrigation season for the 3 combined bays. However, this would be expected given the reduction in water use and the ability to better manage the surface irrigation at the site during this season as discussed earlier.

It is also interesting to note the reduction in 'efficiency' between the individual bay scale and the 3-bay scale. This illustrates the cumulative effect of runoff from a series of irrigation bays irrigated together, and is also likely to be due to the less timely closing of gates in bays 2 and 3 because of less intensive monitoring and management of these bays.

3.4 Nutrient concentrations in runoff water

Nutrient concentrations measured in water samples taken during the irrigation seasons followed relatively predictable patterns at various scales. Highest concentrations of nutrients were measured in water flowing overland during irrigation events and, within events, concentrations were highest at the bottom of the irrigation bays. This would be the point when the water has had the maximum exposure to available nutrients on the soil surface and in the shallow subsurface. Levels of up to 44 mg/L and 66 mg/L for phosphorus and nitrogen respectively were measured in irrigation water flowing over the soil surface.

However, maximum concentrations of nutrients measured at the tail drain of Bay 1 had reduced to 6.4 mg/L and 23.4 mg/L for phosphorus and nitrogen respectively. Nutrient concentrations at this scale again followed predictable patterns with the maximum values occurring at the commencement of runoff flow through the drain.

Maximum nutrient concentrations in water samples from the automatic sampler collecting water from the three combined irrigation bays, however, had increased concentrations. This may again show the importance of good irrigation management discussed above in terms of water losses.

Figure 3 further develops this relationship between phosphorus concentration in water samples and catchment scale. This data shows the strong relationships between both total phosphorus and soluble phosphorus and catchment size (R^2 of 0.98 and 0.96 respectively).

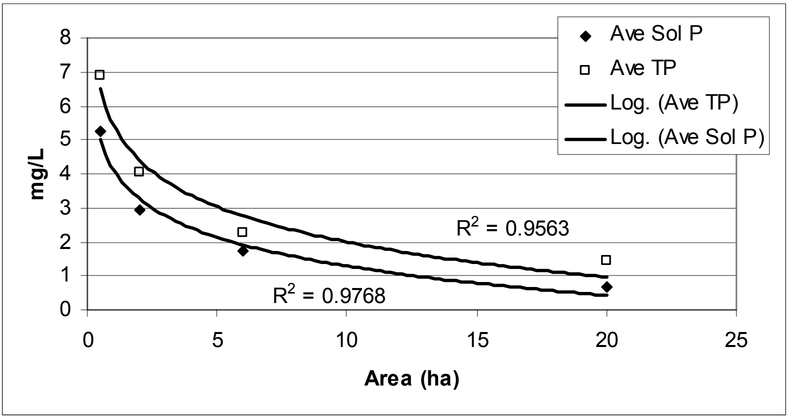

Figure 3: Phosphorus concentrations at increasing catchment areas.

This is a very important point, as the same land management practices are in place throughout the catchment scales from the irrigation bay scale to that of a large portion of the farm. It illustrates the fact that monitoring of land management practices at any scales larger than that at which the practices are implemented (in this case the scale of an irrigation bay) is unlikely to yield meaningful information because of the diluting influences of those parts of the catchment (farm) which do not contribute nutrients. It also illustrates the fact that phosphorus export reduction practices also need to be targetted at the appropriate, small scale at the nutrient source.

3.5 Productivity

Pasture productivity results demonstrate the outstanding potential of centre pivot irrigation to increase both the amount and quality of pasture needed for greater milk production as well as to reduce water and nutrient losses.

In 2003/04, the centre pivot site produced 54% more pasture than the surface irrigated site (same management regime) and during 2004/05 it produced almost double the pasture. Pasture palatability was also better under the centre pivot system.

The estimated increase in milk production under the centre pivot system for 2003/04 is 8,500 litres more milk per hectare than the surface irrigated site. This was achieved using far less water.

4 Conclusion

In summary, the following conclusions can be drawn from the research that was carried out across the farm and catchment-scale trials:

4.1 Harvey Irrigation Area Project

Problems with the high salinity levels of the water sourced from the Wellington Dam have been clearly shown. The exceedence of the recommended maximum limit for irrigation water for the entire irrigation season shows the limitations that this poor quality water will be inflicting on both regional agricultural productivity and regional, downstream water quality. This would have a marked effect on the real value of this irrigation water in terms of its ability to contribute to profitable and sustainable farming.

The nutrient concentrations in water collected during the irrigation season are similar to or lower than those collected in the same drains during winter. Irrigation nitrogen concentrations are of the order of 70% of those measured during winter.

Nutrient load calculations support the conclusions drawn from analyses of nutrient concentration data. That is, while 79% of water travels through the irrigation system during winter, this water carries 88% of the phosphorus and 86% of the nitrogen exported annually. Irrigation water, while accounting for 21% of the water measured during the monitoring programme, carried only 12% of the total phosphorus measured and 14% of the nitrogen.

However, the total nutrient export rates from the HIA are significantly higher than those from other regional catchments. This is likely to be associated with heavier soils in the irrigation districts, and more intensive farm practices

4.2 Irrigation practice assessment

Significant reductions in run-off loss from the surface irrigation site occurred in the second season due to closer management of this system. This has significant implications for automation of irrigation bay gates and suggests that this may be one of the more effective BMPs to pursue in this area. No runoff was observed at all from the centre pivot system.

Phosphorus concentrations are scale related; i.e., concentrations coming off individual bays are higher than combined bays for the same events. Phosphorus concentrations in tail drains and larger farm drains are similar to phosphorus concentrations in drains on non-irrigated properties.

Phosphorus concentrations at ‘end of farm’ monitoring points approached background levels, but were still above recommended maxima for ecosystem protection. Around 90% of phosphorus in run-off is the soluble and more ecologically active form.

The single most important point in terms of the sustainability of irrigated farming in the south west of Western Australia is likely to be the (perhaps perceived) issue of nutrient export to regional waterways. State regulators already have the ability to prosecute landowners for ‘environmental harm’ if those landowners cannot show that they are farming sustainably. It has been suggested that ‘sustainability’ may be measured in this context by the collection of water samples and their analysis for nutrient concentrations. The data presented here shows a very clear relationship between catchment size and nutrient concentration in runoff water.

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“Custodians” or “Investors”: classifying irrigators in Australia’s Namoi Valley

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Abstract

This paper examines groundwater irrigators’ perceptions of the community processes of developing water-sharing plans (WSP) within the Namoi Valley of New South Wales. The groundwater resource is over-allocated, and in some areas, over-extracted. It is a complex situation that has not necessarily been effectively managed by any party, government or licence holders. The result is that the government is now attempting to rectify the over-allocation of water entitlements through the WSP that have been jointly developed by irrigators, community members and government representatives. The WSPs in some instances will result in significant reductions to water entitlements. A mail-out questionnaire was sent to irrigators followed by personal interviews with irrigators and other stakeholders. Licence holders are dissatisfied with the process; they strongly believe that the process has been seriously flawed. The survey indicates that licence holders are planning to make a number of management responses to cope with the impact of the WSP, many of which are driven by considerations other than economic or financial. These findings should help policy makers to more accurately target farmers when planning significant changes.
Keywords: groundwater, water sharing plans, Namoi Valley, farmer typology.

1 Introduction

This paper explores some of the issues involved in the journey towards sustainability for a group of irrigators who are reliant on one of Australia’s most stressed aquifers. The aim of the research is to explore the reasons why farmers behave in the way that they do; what influences them when they make decisions

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and why the decisions that they make may not necessarily be driven only by financial and economic factors.

By extension, it is also of interest to consider why some organisations dealing with farmers appear to have failed to identify any diversity of behaviour assuming farmers respond as a homogenous whole.

This research began with an exploratory survey of groundwater licence holders, which was designed to uncover their understanding of the situation regarding reductions to water entitlements, the effect that this is having on them, the responses that they are making to the reductions, and the influences that have led them to make these responses. Follow-up personal interviews were undertaken with licence holders to explore and expand on the findings from the survey.

Qualitative questions in the survey, gave licence holders an opportunity to express a range of feelings including frustration, confusion and uncertainty (Kuehne and Bjornlund [1]). These responses show that the issue is laden with emotion and that the research needs to be approached with tact and discretion.

Questions arising from the initial survey were –

- Why do irrigators gain their information about the water reductions from sources other than the responsible department?
- Why has the department been so strongly criticised by licence holders?
- Why are licence holders not making economically rational decisions? Why are they not selling or leasing their water when it might be the most economically advantageous option?
- Is it possible to divide farmers into groups to better predict their behaviour?

2 The study area

Irrigation has been carried out in the Namoi Valley of Northern New South Wales (NSW) in a substantive way for about forty years (see table 1), and has developed concurrently with Australia’s modern cotton industry. Irrigation in this valley covers an area of 119,040 hectares (Powell *et al.* [2]), of which approximately 40,000 hectares are irrigated using groundwater, varying with seasonal conditions. Even with such a short history adjustments now need to be made to ensure future sustainability.

Averaged across the more than 700 groundwater licences in the valley, the extraction is about 233 ML per licence. Using the same per licence average, the estimated annual aquifer recharge is 281 ML. The real significance of the problem facing these licence holders comes from the fact that each of these licences entitles the holder on average to extract 600 ML from the aquifer (NGT [3]). The implication of this over allocation is that if all licence holders activate their licence and withdraw what they are legally entitled to use, they would be using more than double the sustainable yield. While the valley as a whole, currently, is not using more than the sustainable yield, there are problem areas.

The valley is divided into thirteen hydrogeologically distinct zones and four of these are currently being used unsustainably (Namoi groundwater management committee [4]).

The reasons for the over allocation are: 1) a lack of scientific research quantifying the available recharge; 2) the responsible State Government department sought to encourage the use of water up until the 1970s; 3) it was thought that the resource could be "mined" for a period of time, and then recharge would occur when wet years returned; and 4) water, at least initially, was not highly valued which meant that some of the licences granted were expected to remain inactive (Kuehne and Bjornlund [1]).

Table 1: Key events leading to the development of sustainability issues.

Date	Event
1961	Keepit Dam completed to moderate and conserve the Namoi River. The department encouraged irrigation development to use the resource.
1961-62	Cotton successfully grown using water supplied by Keepit Dam, leading to rapid development of the irrigation industry.
1964	Keepit Dam runs dry because of drought. Surface water users look to groundwater as an alternative.
1983	Irrigators start to warn of the over issuing of groundwater entitlements.
1992-95	Drought leads to nearly double the sustainable aquifer extraction in the Namoi Valley as a whole.

After many delays, and a divisive and conflict ridden development period (Kuehne and Bjornlund [1]) and after four deferrals in three years the NSW government will on July 1st 2006 start implementing the final WSP. The NSW Government in conjunction with irrigators developed the WSP to specify the changes needed to water use and to map the way forward to sustainability. The study area was chosen because of these impending changes to water access. Some of the more over allocated zones will need to make cuts to entitlements of up to 87%. Some licence holders (9%) will have no cuts, 47% will have a cut of about 40%, 35% will have a cut from 50% to 75% and 8% will be cut 75% or more. These cuts to entitlement will have most pronounced and immediate effect on license holders who are using a substantial proportion of their entitlement (high history of use). The impact on license holders traditionally using a small proportion of their entitlement (low history of use) and license holders who have never developed their properties to use their entitlement (inactive irrigators) will be less pronounced and immediate and mainly relate to the future potential and value of their property.

The advent of the WSP is a pivotal event for many of the licence holders and will require a management response of some sort from most of them (see table 3). Nearly 90% of the high use group (those needing to make reductions in their actual water use), almost 50% of the low use group (those not needing to make any reductions in their actual water use) and almost 25% of the inactive group report that they will be making some sort of management changes.

3 Literature review

Some authors suggest that it is erroneously thought by many, that farmers only make management decisions to maximize their financial benefits (Salamon [5], Vandermersch and Mathijs [6]). Other authors suggest that it is recognized that this is not the sole motivation for farmers decisions (Austin *et al.* [7], Gasson [8]), and that other goals and values are important. Maybery *et al.* [9] talks of "a failure to appreciate the diversity and complexity of triggers that motivate decisions in agriculture". They go on to suggest that it is the "within person intricacies and processes" that are important for an understanding of landholder behaviour. As farmers from developing countries appear to make decisions based more on economic returns (Solano *et al.* [10]), it could be that the same might apply in Australia; but that a hierarchy exists where non economic factors still play an important role in the decision making as long as economic imperatives have been met. Some authors have referred to a mistake made by authorities when they assume that farmers are an undifferentiated homogenous group (Whatmore *et al.* [11] and Perrett [12]), and do not recognize the diversity within the group, Thompson [13].

Using Weber's [14] typology of "ideal types" it has been suggested by Salamon [15] that farmers can be divided into "Yeoman" and "Entrepreneurs". Others caution against this approach suggesting they are meaningful constructs but not mutually exclusive (Austin *et al.* [7]). It is recognised that these results may only apply to the actual groups studied. Salamon conducted a large number of in-depth personal interviews with Midwestern US farmers, while Austin worked with survey data that was originally gathered in-person for a study into Scottish farm pluriactivity.

Weber explains his concept of "ideal types" (Weber [14]) as being a representation of how someone would behave in a "rational purposive way". By describing this idealized situation he argues that we are better able to see how the actual irrational behaviour deviates from this ideal type. It's a methodological tool that does not imply that any one actually does belong to this rationally behaved group.

4 The hypothesis

The hypothesis is that farmers can be classified by how they might fall on a continuum with "Investor" and the "Custodian" as the opposite poles (see table 2), and that this will help to predict or explain their decision-making behaviour. While this classification has similarities with Salamon's ideal types of "Yeoman" and "Entrepreneur" (Salamon [15]), they differ importantly in the sense that the "Yeoman" category is strongly influenced by ethnicity.

The object of the research is to explore the validity of the classification variables used to build the types. The hypothesis will then be refined and tested in the final stages of the research.

The proposed typology and classification variables have been developed from the literature (Salamon [15]), the analysis of the mail-out survey and the first author's lived experience.

Table 2: Proposed typology and classification variables.

Classification variables	Investors	Custodian
Goals /Motivation	Focus on return on investment. Forward looking.	Replicate the farm, with sons all owning farms. Being recognised as a good farmer. Pride in the product. Looking forward but aware of the past.
Family Focus	Not focused or dependent on family. Family labour unlikely to be used. Succession is a business decision; with a good education their children can probably do better elsewhere.	Family-centric. Family replicates the culture. Family labour often used. There is a desire for sons (or daughters) to continue farming.
Business commitment	Money needs to “work” and will be shifted into other areas and opportunities when necessary.	Long term and committed to farming as an occupation and way of life.
Business history	Recent entrants & may be new to agriculture and the community.	Family based, possibly multi-generational business.
Attitude to Change	Prepared to respond to a changing environment.	Resistant to change. Emotional / family issues are associated with change even when voluntary.
Approach to debt	Recognition that large debts can be necessary to ensure business growth	Prefer to avoid exposure to large business debts.
Ownership of water	Resource to be bought and sold. Seen as having a capital and a productive value.	Both a right and a responsibility. A resource to be used efficiently. Not likely to be sold because it could be useful in the future
Ownership of land	Resource that is tradable. Farms will be bought and sold. More land gives more power, and the ability to generate more wealth.	Desire to leave the land in better condition for future generations. Strong connection to a property.

5 Methodology

The database of all the 730 groundwater licence holders in the Namoi Valley was provided by the department. After removing duplicate names 650 licence holders were sent survey forms. The purpose of the questionnaire was to gain an understanding of licence holders’ behaviour by investigating 1) how they felt about the WSP, 2) how they plan to respond to the WSP, and 3) demographic information about them. The findings in tables 3 and 4 are based on open-ended questions coded by the researchers. Each respondent could give more than one management response or influence on major decisions. The columns in the tables reflect all the answers given and therefore add up to more than 100%. The questionnaire was piloted in a neighbouring region facing similar issues.

The survey followed much of the Dillman method and was conducted in Aug – Sep 05 (Dillman [16]). Semi-structured personal interviews were conducted in September of 2005. The hour-long interviews were conducted at the premises of the interviewee, usually either in a kitchen or an office.

Computer analysis of the survey responses and the personal interviews was undertaken using QSR's program N6 for qualitative data analyses and SPSS for the quantitative analyses. Simple frequencies and descriptive statistics were used.

Table 3: Licence holder responses.

	High (n=44)	Low (n=53)	Inactive (n=19)
Buy extra water	41%	13%	21%
Sell or lease out water		9%	10%
Sell or lease out land			10%
Reduce irrigated area or water use	23%		
Change crop types to use less water	18%		
Change irrigation technology	30%	19%	
Water use efficiency improvements	36%		
Infrastructure improvements		24%	
Diversify away from irrigation		9%	
No action	9%	26%	32%
Don't know	2%	24%	47%

6 Results

A response was received from 36% of all license holders. Removing those that did not want to be involved in the research project reduced the useable response rate to 20%. Using Chi-squared tests proved that the survey respondents do not differ significantly from the non-respondents. However, active users of water are over represented reflecting that these license holders are going to be most affected by the WSP.

Turton describes three phases that irrigators pass through when dealing with reductions in access to water: (1) getting more water; (2) using water more efficiently; and (3) allocating water more equitably (Turton [17]). While some license holders proposed supply side solutions in the form of government investments in infrastructure to provide access to more water, most proposed management responses reflect Turton's three categories (table 3): (1) 13% to 41% expect to buy more water; (2) a significant number of high users are looking at improving their water use efficiency or changing their crop type; and (3) relatively few respondents expect to respond by selling their water. None of the high water use group and only 9-10% of the other groups contemplate selling their water. During the interviews some indicated the need to reallocate water away from cotton suggesting that this was no longer an appropriate crop to grow due to its high water requirements while many was opposed water trading preferring that water remains tied to land, thereby effectively rejecting Turton's third phase.

The survey shows that even irrigators who have regularly used most of their annual entitlements (and consequently now face the largest cuts) are motivated by factors other than financial reward. They identify a range of factors that can be grouped into distinct categories (see table 4).

Table 4: Factors influencing significant decisions.

Influence	High N=76	Low N=82	Inactive N=27
I am a farmer, it's what I do	4.8%	15.9%	6.7%
Lifestyle	38.1%	43.2%	40.0%
Financial	40.5%	27.3%	33.3%
Resource quality, e.g. good soil	26.2%	25.0%	73.3%
Fit with existing way of doing things	9.5%	20.5%	6.7%
Community	9.5%	0.0%	0.0%
Family	52.4%	54.5%	20.0%

When asked about their sources of information for responding to the WSP licence holders suggested that it was much more likely that they would gain information from friends, neighbours or other farmers than they would get it from the responsible department. This is both surprising and concerning. The department has the mandate to implement the reductions to entitlements and has the knowledge necessary to inform the affected parties. The respondents criticized the government and the department for many things, including not sharing information.

During the personal interviews license holders expressed negative opinions of, and in some cases a real disdain for, the department. It could probably have been expected that the relationship would be difficult, as it is the department which have determined the level of reductions, and it is their task to implement the changes associated with the WSP.

It also appears that licence holders require someone to blame for their predicament. It does seem warranted that the department should accept some of the blame for the situation, because the over allocation of entitlements largely is a result of the department issuing more licences than what is sustainable. Many of the survey responses reinforce this belief and it appears as though licence holders would gain some satisfaction from the department admitting that they were responsible to at least some degree.

Some of the responses to the survey and the comments made during the personal interviews highlighted the irrigators' perception that the department has been difficult to deal with. They complained that the department did not provide accurate and timely information. They didn't return phone calls or make staff available. This could be a clash of cultures, but whatever the reason, it is obvious that the goal of resource sustainability would be more readily achieved if the relationship were less troubled.

The expected effect of the WSP on the community is substantial and widely recognised (Powell *et al.* [2], Wolfenden and van der Lee [18]). When fully implemented the effect will be the loss of from 190 to 400 jobs and the reduction of the valley's annual gross value of agricultural production by A$18m to A$42m. The survey respondents, when commenting on the impact of the WSP, identify both the impact that they expect on their own business as well as the impact that it will have on the community as a whole.

7 Personal interview results

Some quotations from the transcribed interviews which illustrate the different approaches between "Custodian" and "Investors" are listed below. These are some early findings that form the basis for the next stage of the research – the electronic discussion groups and the telephone interviews.

Caring for the land is important to the "Custodian"; one said, *"we can keep going ... and really improve the soil over the next ten years ... Another ten years and this place is going to be in really good shape".*

An "Investor" described a contrasting approach to the land, *"we're using the land as one of our tools to make a dollar, no-one will deny that".*

"Custodians" have pride in the length of time that their family have been farming, and the length of time that their property has belonged to their family; one said, *"I was born here, and my father had this place so the family has been around since the late 1800's".*

Another "Custodian" made it quite clear, stating that *"our attachment to this country is far greater than they could ever imagine ... so you're [we're] not about to give it up easily if you [we] can ... the perception is that we're a bunch of ... wealthy, large cotton farmers ... but most of us are just ordinary people, just trying to ... educate our kids and keep our heads above water".*

Talking about the arrival of the more entrepreneurial American cotton growers a "Custodian" said *"my experience with Americans is that it's got to be done quickly, they don't buggerize around, and that's a good thing".*

One "Custodian", who had been a grazier before becoming an irrigator, spoke about the difficulty associated with adopting new ideas when he said *"you can imagine all the emotional part of the argument. Family being around here for 2 or 3 generations, being graziers and I was the one who was moving away from it".*

Another "Custodian" echoed similar sentiments by stating that *"dad wasn't into irrigation at all, other than as a back-up ... for the cattle and when things got tough ... so there's been a little bit of a change of focus ... my view is that you've got to try and make farming pay".*

For the "Custodian" water is more than a resource to be bought and sold. Talking about the possibility of selling water one said *"it wouldn't enter our head. We said to the bureaucrats and the politicians ... We don't want the money. We want the water ... We're here for the long haul. I'm second generation ... our son is third. And he's put his name on a bit of land".*

But the "Investor" sees water differently; one stated *"I said to my wife ... that's our super ... In another 15 or 20 years when I want to retire to the Gold Coast ... that water licence alone is going to be worth a hell of a lot"*.

It seems as though some "Custodians" also see water as a responsibility when he stated that *"the government has allocated you ... so many megalitres, it's your duty to make as much production as possible from each of those megalitres, I think it's your public duty, and I don't think people would argue too much about that"*.

An "Investor" described his approach to business this way, *"our imperative is one of business, and I never use the word lifestyle. It doesn't appeal to me at all when people describe themselves as having a great lifestyle when they're living in poverty"*.

Another "Investor" describes his approach to business growth this way, *"you've just got to get more and more and more land. You know irrigation is very important to us, it's king, it's king of the castle as far as we're concerned"*.

The "Custodian's" business goals are about more than just profits, one said *"we want to stay on the land, we want to remain growing crops, to do it we've got to be sustainable, and we've got to be able to do it a lot better than what were doing now"*.

The "Custodians" recognise that the "Investors" have different motivations than they have, one said that *"it's that bloke that has come in, I suppose a different type of farmer, more the type of farmer ... the business farmer ... looking at rate of return ... it was that farmer that came into these areas"*.

An "Investor" describes his entrepreneurial philosophy this way, *"if they want economic development, if they want the nation to be a stronger place, then the sort of people that are prepared to expand are people with a capitalistic type nature about them, and of course they're always going to bite off a little more than they can chew"*.

"Custodians" also feel a responsibility for the community; one said *"our little towns really need us to generate economic activity. My main driver is the little town that I live near, that my great great grandfather came to. It's dear to us all..."*.

8 Discussion and conclusions

The results from the mail-out survey show that the process of developing the water sharing plans and the quest for achieving sustainable levels of groundwater extraction has been difficult. The research suggests cultural differences between licence holders and the government. The irrigators believe that the department behaved poorly throughout the process and did not provide information willingly. Some of this criticism is about the way information was presented, even to the level of document layout and design.

Some of their responses seen in the light of Turtons' model suggest that they are at varying stages in their response to the WSP. This may lead to further conflict and explain their current dissatisfaction. These differences lead to license holders wanting to blame the department, and wanting it to acknowledge its role in causing the problem. Licence holders do not only show concern for their own financial situation, they are concerned about the impact on the community as a whole.

The results from the personal interviews show that ideal types of “Investor” and “Custodian” could offer a useful way of looking at farmers’ behaviour. The “Custodians” do demonstrate a different attitude to their land and water. They value length of tenure, and indicate difficulty with adapting to change. Their goals are broader than profit and include a desire to care for the land, use water cautiously, and to contribute to the community for the sake of the community.

On the other hand “Investors” are more focused on using their land and their water as a resource to generate income and to grow their business. It appears as though their concern for the community is seen in terms of what it can offer them.

Some of the farmers that could be described by these classifications appear outwardly similar, for example in their criticisms of the department, and only differ when their motivations are explored more deeply. Initial results suggest that it is worthwhile continuing to develop a typology of farmers based on the “Investor” and “Custodian” categories. It could be expected that the outcome of this research would be useful for those formulating and implementing policy when dealing with farmers, especially as in this case, when there is a need for cooperation over a contentious issue.

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Irrigation management: the optimization perspective

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Abstract

Irrigation management deals with many different decisions: the selection of economically viable cropping patterns, allocation of land per crop, allocation of water resources per crop, irrigation scheduling, management of irrigation deficit, etc. Plants need appropriate amounts of water, and its distribution during the full growing cycle has a tremendous influence on the final crop yield. This means that managing the soil water content is crucial to obtain an optimal allocation of water resources, supposing that the other production factors are adequate. The use of decision models to help irrigation management appears to be an interesting approach, as they are capable of handling different facets of such problems (economic, physiological, environmental, etc.) all together. This paper presents a synthetic state-of-the-art literature review of the optimization models for these purposes. The different agricultural production functions and their inclusion in the decision models are discussed.

Keywords: irrigation management, agricultural production functions, optimization models.

1 Introduction

Water is a scarce good in many regions of the world, and simultaneously it is the most important factor in some production processes, like agriculture. Supposing that the other production factors are at an adequate level, managing the soil water content is crucial to obtaining an optimal allocation of water resources. Irrigation supplements rainfall and can help to overcome the main risks associated with the uncertainty of hydrological events. In arid and semi-arid regions irrigation is intrinsically related to the availability of water resources, and thus deficit irrigation can occur. A benefit-cost analysis of irrigation systems should take

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into account the considerable investments (installation, operation and maintenance costs) needed to design and to operate a proper irrigation system, and the corresponding benefits in terms of crop yield improvement. Decision-aid models can be very helpful in finding the best decisions for irrigation management. In fact these models can incorporate the many of the different facets of such problems (economic, environmental, physiological, etc.).

This paper presents a synthetic state-of-the-art review of the optimization models found in the literature in this field. The different agricultural production functions are discussed, as well as their inclusion in the decision models.

2 Irrigation management problems

Many different situations can arise where irrigation management methodologies have to be used. As water is the principal factor in agricultural production, two cases can be considered: when the availability of water is adequate, and when it is not adequate. If there is enough water then irrigation can be timed to define the critical level. In this case the decision will be about the optimal allocation of the area to different crops in order to maximize the yield. Following the classification of Smout and Gorantiwar [32] we are dealing with area allocation models (Matanga and Marino [22], Maji and Heady [18], Afshar *et al.* [1], Onta *et al.* [24])

If water availability is inadequate, water deficits will occur. The way these deficits are distributed through the vegetative life cycle will have a tremendous influence on the final yield, consequently in benefits of the crop production. Therefore, in this kind of problem the best way to distribute the deficits has to be optimized. Two problems can be analysed here: ones where the cropping pattern is previously defined, and others where the cropping patterns are to be defined. The first situation gives rise to the water allocation models (Rao *et al.* [28], Hiessl and Plate [11], Paudyal and Manguerra [25], Vedula and Mujumbar [36], Wardlaw and Barnes [37], Kipkorir *et al.* [14]), and the second situation gives rise to the land and water allocation models (Matanga and Mariño [23], Kumar and Khepar [17], Yaron and Dinar [38], Rao *et al.* [27], Manocchi and Mecarelli [19], Sahoo *et al.* [30], Marques *et al.* [21], Smout and Gorantiwar [32], Gorantiwar and Smout [8]).

To solve any of the stated problems, information on the relations between crop yield and water applied is needed. These relations can be established for the entire growing season or for individual irrigation periods (when decisions are about intraseasonal allocation of water). Therefore it is important to establish agricultural production functions, incorporating the processes involved in crop development and the corresponding yield.

3 Agricultural production functions

The production of a given plant depends on many different factors, particularly on the amount of water available and its distribution during the vegetative life cycle.

Two types of production functions are reported in the literature: seasonal crop-water production functions and dated crop-water production functions.

The first considers the effect of water availability in aggregated terms over the entire season. Equation (1) is an example of a production function of this type (Haxem and Heady [9]):

$$Y_k - Y_{0k} = \left(Y_{\max k} - Y_{0k}\right)\exp\left[\frac{-coef_k\left(X_{mk} - X_k\right)}{X_k}\right] \tag{1}$$

Y_k= seasonal relative yield for crop k corresponding to X_k depth of water applied; Y_{0k}= relative yield corresponding to zero irrigation allocation; $Y_{max\mathrm{k}}$= maximum relative yield obtainable for the initial soil and climatic conditions; X_{mk}= minimum depth of water required to give potential relative yield $Y_{max\mathrm{k}}$; $coef_k$= coefficient for a particular crop.

Regarding dated crop-water production functions, it is important to point out that the final production depends on the allocation of the available water in the different periods of the life cycle. The final yield is sensitive to the period where there is a water deficit. Some periods in the vegetative life cycle are more critical than others, and the way this can influence the final yield is modelled using two approaches. A first approach that considers additive effects of the water deficits (Jensen [13]) and the second considers multiplicative effects.

The latter appears to be more realistic since it determines the development in each period, accounting for the conditions observed in the previous periods. An example of this type of model is given by Bowen and Young [2]:

$$\frac{Ya}{Ym} = \prod_{i=1}^{N}\left(\frac{Ya_i}{Ym_i}\right) \tag{2}$$

Y_a= actual production; Y_m= maximal production (when no factor limits production); N: total number of periods; i= period index, Y_{ai}= actual production in period i; Y_{mi}= maximal production (when no factor limits production) in period i.

Another important aspect for the construction of the production functions is the way yield is related to water consumption. There are models that use a physiological approach, where the development results from a complex interaction between various physiological aspects (stomatic behaviour, photosynthesis, etc.), related to the amount of water available for irrigation. Usually they are not well systematized and are built for specific case studies. Hsiao *et al.* [12] emphasizes the difficulty of building a model of this type, when all the aspects contributing to plant development have to be considered. The most widespread models, like that devised by Doorenbos and Kassan [6], employ evapotranspiration for such purposes (here for dated production):

$$\left(1 - \frac{Ya_i}{Ym_i}\right) = Ky_i\left(1 - \frac{ETa_i}{ETm_i}\right) \tag{3}$$

Ky_i= yield response coefficient in period *i*; ETa_i= actual evapotranspiration in period *i*; ETm_i= maximal evapotranspiration in period *i* (if there is no irrigation deficit).

Evapotranspiration can also be used for the seasonal crop-water production function (Carvallo *et al.* [4]):

$$Y_a = \left[AC + BC\left(\frac{ETa}{ETm}\right)^{\alpha} - CC\left(\frac{ETa}{ETm}\right)^{\beta} \right] Y_m \tag{4}$$

AC, *BC*, *CC*, α, β= experimentally obtained coefficients.

To apply these models to real-world situations, the actual evapotranspiration should be expressed as a function of water availability in the soil. Soil moisture depletion is a complex process and the actual evapotranspiration depends on the moisture level between field capacity and the permanent wilting point. For operational purposes, theses processes are often simplified. Three examples taken from the literature will be described. The first one is proposed by Wardlaw and Barnes [37] and also used by Kumar *et al.* [16], and establishes that the ratio of actual evapotranspiration to maximal evapotranspiration is the same as the ratio of irrigation supply to irrigation demand:

$$\frac{ETa}{ETm} = \frac{I}{DI} \tag{5}$$

I= irrigation supply; *DI*= irrigation demand.

The second example, by Cunha *et al.* [5], proposed a model where the actual evapotranspiration is determined as a function of the soil water index ASI_i, that represents the fraction of the period where Eta_i=Etm_i and depends on the water available in the soil:

$$ETa_i = \left(ca_i + cb_i ASI_i\right) nd_i \tag{6}$$

ca_i, cb_i = coefficients of the linear regression model; *ndi*= number of days of period *i*.

The hypotheses used to built this model imply that its validity is limited to the following situations:

$$0 \le ASI_i \le 1 \tag{7}$$

$$0.5ETm_i \le ETa_i \le ETm_i \tag{8}$$

The third one is given by Paul *et al.* [26]:

$$ET_a = \left\{ \begin{array}{c} 0;\ SM = WP \\ \\ \dfrac{ET_m(SM - WP))}{(1-p)(FC - WP)};\ WP \le SM \le (1-p)(FC - WP) \\ \\ ET_m;\ SM \ge (1-p)(FC - WP) \\ \\ \end{array} \right\} \quad (9)$$

SM= soil moisture content; *WP*= wilting point; *FC*= field capacity; *p*= crop water depletion factor.

Quite recently Schmitz *et al.* [31] presented an innovative work for establishing water application parameters to create an optimal soil moisture profile using an artificial neural network approach.

The incorporation of the different agricultural production functions into decision processes will lead to decision-aid models that differ in terms of their mathematical characteristics.

4 Decision-aid models

In the last twenty years the literature has reported a number of decision-aid models to solve irrigation management problems. Linear programming, non-linear programming and dynamic programming techniques and, quite recently, genetic algorithms are among the most popular methods employed to solve irrigation management problems. Irrigation management models can become more complex if the decisions are simultaneously about the hydraulic infrastructures needed for storage and / or to supply water (reservoirs, canals, wells in an aquifer, etc.). The inclusion of uncertainty issues is also challenging when it comes to solving large scale irrigation management problems.

Three different representative objective functions will be described. The first aims to optimize the water allocation among various crops (Kumar *et al.* [16])

$$Max \sum_{c=1}^{NC} \left\{ 1 - \sum_{g=1}^{NGS} Ky_g^c \left(1 - \frac{\sum_{i \in g} ETa_t^c}{\sum_{i \in g} ETm_t^c} \right)_g \right\} \quad (10)$$

NC= number of crops; *c*= crop index; *NGS*= number of growth stages; Ky^c_g= yield response coefficient for the growth stage *g* of the crop *c*; ETa^c_t= actual evapotranspiration for period *t* for crop *c*; and ETm^c_t= maximal evapotranspiration for period *t* for crop *c*.

This objective function was used for water allocation when determining the operating policy for an irrigation reservoir. Constraints on reservoir water balance were considered. The decision-model was solved by a genetic algorithm.

The second objective function was built for the optimal allocation of irrigation water supplies in real time (Wardlaw and Barnes [37]):

$$Min \sum_{s=1}^{NSC} \frac{1}{Ym_s} \left(Ym_s - Ya_s \right)^2 \tag{11}$$

NSC= number of different irrigation schemes; s= irrigation scheme index

This model was considered for the management of a run-of-river with a complex distribution network. Non-linear programming (quadratic programming) was the method chosen to solve the decision model.

Another nonlinear objective function is presented in Carvallo *et al.* [4] for maximizing the profit of irrigation under water availability constraints:

$$Max \sum_{l=1}^{NS} \sum_{c=1}^{NC} \left(P_j A_{lj} Ya_{lj} - C_{lj} A_{lj} \right) \tag{12}$$

NS= number of soil types; l= soil type index; NC= number of crops; P= price received for crop j; A_{lj}= area cultivated of soil l and crop c; C_{lj}= production cost per unit are of soil l and crop c.

The decision-aid model includes soil, water and labour availability constraints, as well as crop rotation and market limitations on the area to be cultivated for each crop.

Cunha *et al.* [5] presented a nonlinear objective function for maximizing the net benefits of an irrigated area of a given crop, with the water supplied by an aquifer:

$$Max\ P_y Y_{\max} \prod_{i=1}^{N} \frac{Y_{a_i}}{Y_{\max_i}} - \sum_{i=1}^{N} C_{ek} \sum_{k=1}^{M} \left(HS_k + R_{k,i} \right) Q_{k,i} \tag{13}$$

N= number of periods; P_y= price received for the crop; C_{ek}= energy cost per unit of flow and elevation head in well k; M= number of wells; HS_k= static level in the well k; $R_{k,i}$= drawdown in well k, as a function of pumping in the well k and in all other wells until period i; $Q_{k,i=}$ flow pumped in well k in period i.

The decision model incorporates a groundwater flow model for drawdown calculations as a consequence of the flows pumped for irrigation purposes.

Linear decision models (Tintner [34]) are very limited in terms of representing real world problems (Hazell and Norton [10]). But the software and hardware capabilities available have, for some years, made it difficult to use more sophisticated approaches.

Dynamic programming models have been widely used in the context of irrigation management (Dudley *et al.* [7], Matanga and Mariño [23], Knapp *et al.* [15]). Even with relatively small case studies, dimensional problems can arise and an intractable computational situation can result. Combining linear programming and dynamic programming could help to avoid some of these limitations (Yaron and Dinar [38], Vedula and Nagesh Kumar [35]). Recently, Mannocchi and Todisco [20] built a three-step model for the optimal weekly intraseasonal operation of a multipurpose reservoir. A parametric dynamic programming model was used to avoid the "curse of dimensionality". Paul *et al.* [26] have developed a multilevel approach for determining optimal seasonal water allocation and optimal cropping pattern, based on coupling deterministic dynamic programming and stochastic dynamic programming.

Stochastic aspects characterizing the evapotranspiration demands (or the variable linked to the evapotranspiration representing the crop water requirements) were included in the dynamic programming models for single crop situation by Rhenals and Bras [29], and Bras and Cordova [3]. Multicrop situations were dealt with by Sunantara and Ramirez [33] in an optimal seasonal irrigation water allocation and an optimal stochastic intraseasonal (daily) irrigation scheduling model, by Vedula and Nagesh Kumar [35] in the context of a single purpose irrigation reservoir, and by Rao *et al.* [28] that used heuristically derived seasonal crop-water production functions. Marques *et al.* [21] have described a two-stage stochastic quadratic programming technique for taking decisions on perennial and annual crops, water use, irrigation technologies and economic performance.

5 Conclusions

A synthetic review of irrigation management models has been presented. Many diverse issues can be incorporated into these models, giving more or less complex models. Considering water the principal factor in agricultural production, the relation between crop yield and the corresponding water requirements is analysed. New developments in mathematical programming and in hardware capabilities are allowing large size problems to be tackled, more closely representing real world irrigation management problems.

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Decision support systems for efficient irrigated agriculture

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Abstract

Water is the lifeblood of the American West and the foundation of its economy, but it remains its scarcest resource. The explosive population growth in western urban areas, the emerging need for water for environmental and recreational uses, and the national importance of the domestic food production from western farms are driving major conflicts between these competing water uses (US Department of Interior, 2003). Irrigated agriculture in particular is by far the largest water user – 80% countrywide and 90% in the Western U.S – and since it is perceived to be a comparatively inefficient user, it is frequently asked to decrease its water consumption. Irrigated agriculture in the Middle Rio Grande diverts large quantities of river water, which is believed to leave insufficient water to meet other societal needs such as urban and wildlife requirements. This paper will present our research on options to make irrigation system operations more efficient. Most irrigation systems can meet their users' needs with decreased river diversions by adopting operational procedures, which are based on real-time knowledge of available water supplies and crop water requirements. The paper will describe our on-going research in the Middle Rio Grande Valley, to develop a Decision-Support System (DSS) that can assist water managers to closely match water deliveries to crop water requirements, thereby reducing river diversions. The DSS uses linear programming logic with an objective function to find an optimum water delivery schedule for the service areas in an irrigation system. Water delivery using the DSS is accomplished using three modules: a water demand module, a supply network module and an irrigation scheduling module. Limited field validation shows that the DSS is indeed able to correctly model the irrigation delivery system, and recommend water delivery schedules that are reasonable. Future plans include more intensive field validation and implementation in the Middle Rio Grande irrigation service area.

Keywords: irrigated agriculture, decision support systems, competing water uses, operational procedures, ecology, wildlife habitat, rotational water delivery.

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1 Introduction

Irrigated agriculture in the Western United States has traditionally been the backbone of the rural economy. The climate in the American West with average annual rainfall of 20-38 cm is such that dry land farming is not an option in most areas. Topography in the West is characterized by the Rocky Mountains which accumulate significant snowfall every year. Snowmelt in the Rockies results in considerable surface water, of which irrigated agriculture uses roughly 80 to 90%. Along with water quantity issues, irrigated agriculture causes water quality degradation through surface runoff and return flow laden with sediment, agricultural fertilizers, and pesticides. Managing salinity in irrigation districts in the West is a poignant concern due to the fact that 17% of the world's arable land has been lost to salinization. Along with degradation in water quality, wildlife concerns need to be addressed. The combined demands of agriculture, urban, and industrial sectors leave little water for fish and wildlife. Flows in many western rivers have become so minimal that rivers actually go dry from diversions and fish and wildlife become threatened. Since irrigated agriculture uses roughly 80 to 90% of surface water in the West it is often targeted to decrease diversions. Due to wildlife concerns and demands from an ever growing urban population, the pressure for flow reductions on irrigated agriculture increases every year. In order to sustain itself and deal with outside pressure for reduced river diversions irrigated agriculture has to become more efficient in overall water consumption. This paper focuses on research regarding improving water delivery operations in the Middle Rio Grande irrigation system through the use of a decision support system.

1.1 Middle Rio Grande Valley

The Middle Rio Grande (MRG) Valley runs north to south through central New Mexico from Cochiti Reservoir to the headwaters of Elephant Butte Reservoir, a distance of approximately 175 miles. The valley is narrow, with the majority of water use occurring within five miles on either side of the river. The *bosque*, or riverside forest of cottonwood and salt cedar, is supported by waters of the Rio Grande. Surrounding the bosque is widespread irrigated farming. The City of Albuquerque and several smaller communities are located in and adjacent to the MRG Valley. Although the valley receives less than 10 inches of rainfall annually, it supports a rich and diverse ecosystem of fish and wildlife and is a common resource for communities in the region.

Water supply available for use in the MRG Valley includes: native flow of the Rio Grande and its tributaries, allocated according to the Rio Grande Compact of 1938; San Juan-Chama (SJC) project water, obtained via a trans-mountain diversion from the Colorado River system; and groundwater. Water is fully appropriated in the MRG Valley and its utilization is limited by the Rio Grande Compact. The Compact sets forth a schedule of deliveries of native Rio Grande water from Colorado to New Mexico and from New Mexico to Texas.

Figure 1.

Water demand in the MRG Valley includes irrigated agriculture in the MRGCD (Middle Rio Grande Conservancy District) and Indian Lands, and municipal and industrial consumption. In addition to these demands, there are significant consumptive uses associated with riparian vegetation, and wetland, river, and reservoir evaporation. Superimposed on these demands are river flow targets associated with two federally-listed endangered species, the silvery minnow (*hybognathus amarus*), and the southwestern willow fly catcher (*Empidonax traillii extimus)*.

1.2 Middle Rio Grande Conservancy District

The MRGCD was formed in 1925 in response to flooding and the deterioration of irrigation works. Water diverted by the MRGCD originates as native flow of the Rio Grande and its tributaries, including the Rio Chama. The MRGCD services irrigators from Cochiti Reservoir to the northern boundary of the Bosque del Apache National Wildlife Refuge. Irrigation facilities managed by the MRGCD divert water from the river to service agricultural lands, which include small urban parcels and large tracts that produce alfalfa, pasture, corn and vegetable crops. The diversity of users includes: six Indian pueblos, large farm parcels, community ditch associations, independent *acequia* communities and urban landscape irrigators. The MRGCD supplies water to its four divisions -- Cochiti, Albuquerque, Belen and Socorro -- through Cochiti Dam and Angostura, Isleta and San Acacia diversion weirs, respectively. In addition to direct diversions at these weirs, all divisions except Cochiti receive return flow via drains from divisions upstream. Water is conveyed in the MRGCD by gravity flow through primarily earthen ditches. Water is delivered to users in a hierarchical manner: it is typically diverted from the river into a main canal, to secondary canal or lateral, and eventually into the farm ditch. After water is conveyed through laterals, it is delivered to the farm through a turnout structure, often with a check structure in the lateral canal. On-farm water management is entirely the responsibility of water users. The method of application is typically surface (flood) irrigation, either basin or furrow.

The MRGCD does not meter individual farm turnouts; rather, ditch-riders estimate water delivery on the basis of time required for irrigation. Prior to the recent drought, to provide flexible and reliable water delivery to users on a continuous basis, MRGCD operated the main canals and laterals near full capacity, so water supply was always greater than perceived demand. However, the practice resulted in large water diversions from the river. During the recent drought years, the MRGCD has taken a proactive approach to be a more efficient water user and service its irrigators with reduced river diversions. Towards this end, the division managers and ditch-riders are increasingly practicing rotational water delivery, which is an effective way to fulfill demand with reduced available water.

Rotational Water Delivery (RWD) is used in irrigation systems worldwide to improve water delivery and to support water conservation. In RWD, lateral canals receive water from the main canal by turns, allowing water use in some laterals while others are closed. In addition to this water rotation *among laterals*, there can be rotation *within laterals* whereby water use is distributed in turns among farm turnouts or check structures along a lateral. By distributing water among users in a systematic rotational fashion, an irrigation district can decrease water diversions and still meet crop water use requirements. A well-managed program of rotational water delivery is able to fulfill seasonal crop water requirements in a timely manner, but requires less water than continuous water delivery.

2 Decision support modelling of irrigation systems

The New Mexico Interstate Stream Commission and the MRGCD have sponsored a research project with Colorado State University to develop a DSS, to model and assist implementation of rotational water delivery in the MRGCD's service area. A DSS combines intellectual resources of individuals with capabilities of computers to improve the quality of decision-making. It is a logical arrangement of information including engineering models, field data, GIS and graphical user interfaces, and is used by managers to make informed decisions. In irrigation systems, a DSS can organize information about water demand in the service area and then schedule available water supplies to efficiently fulfill the demand.

The conceptual problem addressed by a DSS for an irrigation system, then, is: how best to route water supply in a main canal to its laterals so that the required water diversion is minimized. The desirable solution to this problem should be "demand-driven", in the sense that it should be based on a realistic estimation of water demand. The water demand in a lateral canal service area, or for an irrigated parcel, can be predicted throughout the season through analysis of information on the irrigated area, crop type and soil characteristics. The important demand concepts are: *When* is water supply needed to meet crop demand (Irrigation Timing), *How long* is the water supply needed during an irrigation event (Irrigation Duration), and *How often* must irrigation events occur for given service area (Frequency of Irrigation).

Decision support systems have found implementation throughout the American West and are mostly used to regulate river flow. Decision support systems on the river level are linked to gauging stations and are used to administer water rights at diversions points. Although decision support systems have proved their worth in river management, few have been implemented for modeling irrigation canals and laterals. The research presented in this paper has focused on developing, calibrating, validating and eventually implementing a decision support system capable of modeling flow on a canal and lateral level, with the overall goal of efficient irrigation water delivery.

3 Formulation of decision support system for the Middle Rio Grande

The DSS was formulated using linear programming with the use of an objective function. Overall model structure consists of three modules that function in tandem to calculate the most efficient irrigation water delivery.

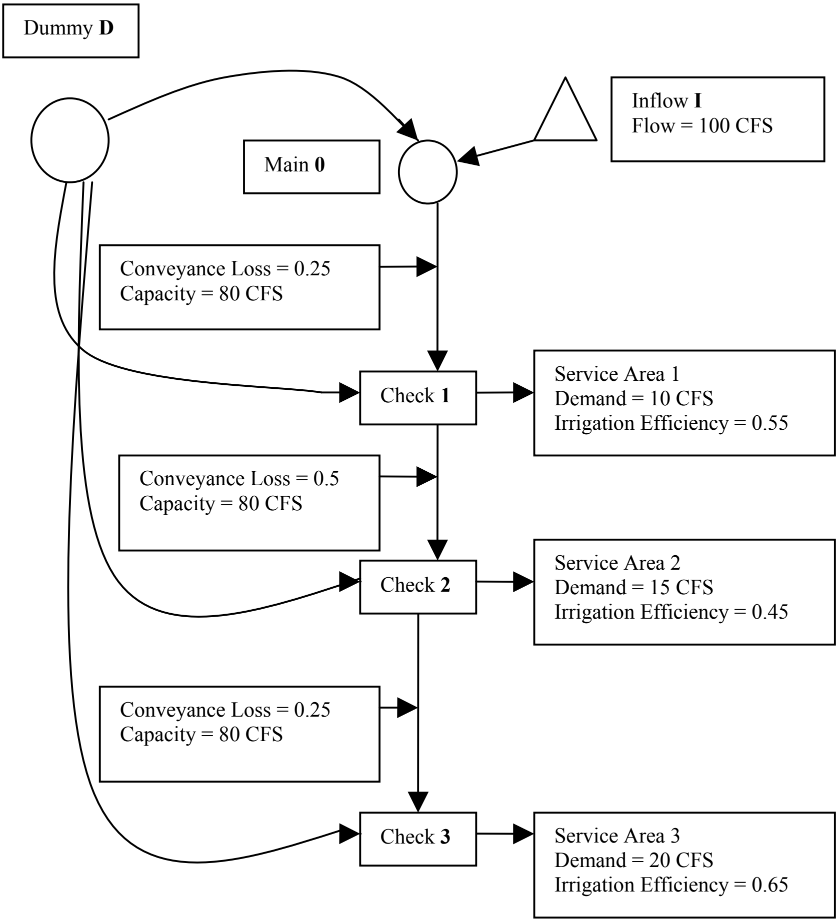

Figure 2.

3.1 Model programming

Programming in the model was developed using an objective function to schedule water deliveries to lateral service areas. Constraints on variables within the objective function are specified and must be satisfied in determining the optimum solution. This process achieves the result that water delivery to laterals with more immediate water needs is favored, and delivery to laterals that have sufficient water in a given time step is minimized.

$$\text{Minimize } Z = MP_{D\text{-}0}\, X_{D\text{-}0} + MP_{D\text{-}1}\, X_{D\text{-}1} + MP_{D\text{-}2}\, X_{D\text{-}2} + MP_{D\text{-}3}\, X_{D\text{-}3}$$

where Z is the sum of a modified priority (MP) multiplied by amount of supply (X) from the dummy supply to each demand node. The subscripts refer to the nodal points between which flow occurs, i.e., X_{D-1} refers to flow from the Dummy supply to Check 1, and MP_{D-1} refers to the modified priority of demand to be satisfied at Check 1 from the Dummy supply node. The MP value reflects the need-based ranking system where demand nodes with lower available soil moisture are favored for irrigation. The objective function is solved in conjunction with a system of mass balance equations representing the actual water (and dummy water) delivered to demand nodes, along with other physically-based constraints.

3.2 Model structure

The DSS consists of three elements; a water demand module, a supply network, and a scheduling program. A Graphical User Interface (GUI) provides a means for linking the three elements of the DSS. This GUI constitutes a framework for the DSS that provides the user with the ability to access data and output for the system. The three DSS model components are termed *modules*. The project GIS and databases are used to develop input for both the *water demand* and the *supply network* modules. Some of the input is directly linked through the GUI and some is handled externally in this DSS version.

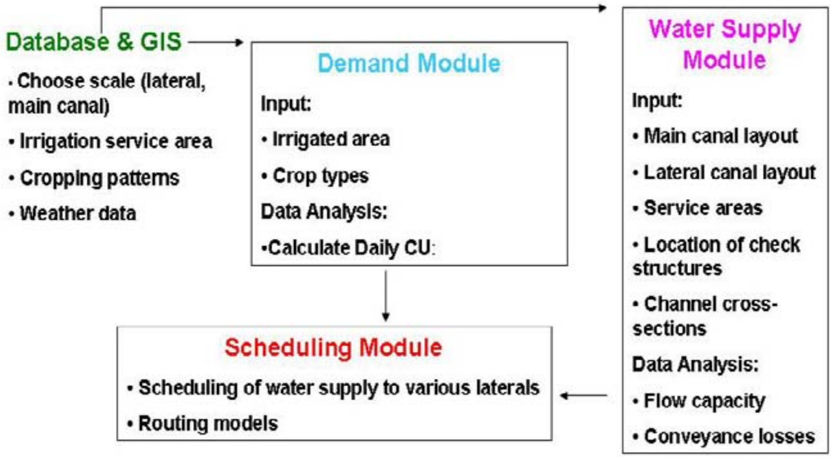

Figure 3.

3.3 Water demand module

The water demand module of the MRGCD DSS is implemented through the Integrated Decision Support Consumptive Use, or IDSCU model, a model developed over a period of years by Colorado State University. The IDSCU model consists of a Graphical User Interface (GUI) written in Visual C++ and program calculations implemented with FORTRAN. The IDSCU model offers numerous features and options and calculates the following; crop consumptive use (CU), crop irrigation requirement (CIR), and readily available moisture (RAM), as a capacity. The latter two variables, CIR and RAM (as a capacity), are subsequently used in the supply network module. Crop consumptive use is calculated using the Penman-Montieth Method. The reference ET is calculated using weather data from the MRGCD. Crop coefficients using growing degree days are applied to the Penman-based ET to obtain a consumptive use for each crop type throughout the growing season. The water demand module performs these calculations to obtain a spatially-averaged consumptive use at the lateral service area level, using the distribution of crop types within each service area. The crop irrigation requirement (CIR) is calculated by accounting for the effective precipitation using the Soil Conservation Service Method (USDA, [8]). The crop irrigation requirement is calculated on a daily basis, corresponding to the water needed to directly satisfy crop needs for all acres in the service area. The crop irrigation requirement for the service area is subsequently passed to the supply network module, where it is divided by an efficiency factor to obtain a lateral service area delivery requirement (LDR).

Based on acreages, crop types and soil types within each lateral service area, a RAM is calculated. The RAM calculated in this context represents a storage capacity to be filled and depleted over several irrigation cycles during the course of the irrigation season. During each irrigation, it is expected that an amount of water equal to the RAM will be stored in soils. Then, as crops utilize water, the RAM will become depleted.

3.4 Supply network module

The *supply network* module represents the layout of the conveyance system, its physical properties, supply to the conveyance network, and the relative location of diversions from the network to the lateral service area. The layout of the conveyance system is specified through a user-designed link-node network. Through the DSS GUI, a user can drag and drop different types of nodes such as inflows, demands and return flow nodes. The link-node network represents the connections between canals or laterals and demands for water at each service area.

3.5 Irrigation scheduling module

The *irrigation scheduling* module can be used to plan water deliveries to meet crop demand at the lateral and at the main canal level. The module calculates and displays a rotational schedule for the laterals on a given main canal. This schedule indicates how many laterals can be run at a time, how long each lateral should run and how often. The module is currently set up to run on a daily time step. This module calculates the daily irrigation schedule using mass balance equations and the linear programming solver. The approach is based on the consideration that the farm soil root-zone is a reservoir for water storage, for which irrigation applications are inflows and CIR is an outflow.

4 Field testing and validation

Field testing and validation of the MRGCD DSS was conducted during the summer of 2005. Initial calibration was performed and examined the irrigated acreages and crop distribution represented by the model. The acreages used by the model were adjusted to match GIS coverages of irrigated acreage and crop type. System infrastructure data was also collected during 2005 to insure accurate representation of the distribution network. Canal capacity measurements were made to represent actual canal carrying capacities in the DSS. To calibrate the model, a sensitivity analysis was performed on the main input variables. Sensitivity analysis consisted of varying one single variable while keeping all other variables constant. Using the sensitivity analysis the model input parameters were calibrated.

To validate and field test the rotation set forth by the DSS, the DSS rotation was compared to the rotational procedure implemented by MRGCD ditch-riders for a small portion of the MRGCD. Field testing of the irrigation rotation, using the input parameters determined during the calibration, was done on two laterals. The average required irrigation flow, average irrigation duration, and average irrigation frequency from the model were compared to data collected in the field. Average irrigation flows, as well as average irrigation duration, were modeled well and little discrepancy between the model and actual practice exists. Model values for irrigation frequency were slightly higher than the values from actual practice. The reason for this could be that during actual practice, irrigation events occur before the RAM is significantly depleted. It was observed on several occasions during the summer of 2005 that alfalfa fields were irrigated every ten days. Irrigation of alfalfa every ten days is excessive and would account for the shorter irrigation frequency recorded from the field data. Overall, the irrigation frequency developed by the model is reasonable within the limits set forth by the MRGCD.

When comparing the required irrigation flow, irrigation duration, and frequency of irrigation, the results from the model compare well with the actual data. Overall the schedule developed by the DSS is reasonable and accurately matches conditions in the field.

5 Conclusions and further research

A decision support system for the Middle Rio Grande Conservancy District was developed that models canal network systems and can compute water delivery options for optimum water use. Using three modules the model represents water demands, the irrigation network, and water scheduling aspects of irrigation. The model is fully capable of developing schedules for rotational water delivery in the MRGCD and evaluation has shown that model recommendations are realistic and represent ditch-rider rotational practice.

Future work on the DSS will entail an in depth field investigation of model adequacy and eventually the full implementation of the model. Model adequacy will be tested by closely monitoring fluctuations in RAM during a period where the rotational schedule from the model is used exclusively. By determining whether the model effectively manages the moisture in the root zone, revisions and improvements to the model can be made. Once field investigations are complete the finalized model can be implemented for rotational scheduling throughout the entire MRGCD. By implementing the DSS for rotational scheduling the MRCGD will reduce river diversions and can continue to sustain irrigated agriculture in the Middle Rio Grande Valley.

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Irrigation with low quality water: model approach

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Abstract

Limited availability of good quality water increases the need for a strategy for the use of wastewater and other low quality waters for various purposes. Irrigation with low quality water may affect crop quality, crop production and the environment.

In the EU-project "SAFIR" (www.safir4eu.org) the "open modelling interface" (openMI-protocol) for model interaction is being used to integrate modelling tools handling all issues within irrigation management on a farm level, i.e. water sources, water purification, soil-plant-atmosphere processes, irrigation and fertigation strategy, risk assessment, crop quality and economy. The integrated modelling system will be used as the core of a decision support system to select water sources for irrigation and define purification requirements, based on the demands to crop quality and yield as well as economic issues. Short term and long term effects on concentrations of pollutants affecting crop quality are thoroughly analysed to propose improved practices and determine critical concentration levels. The accumulation of pollutants within a single crop cycle and the long term deterioration and degradation of the root zone of the soil will also be addressed.

The integrated modelling system will be tested on data from a comprehensive field investigation programme in Denmark, Italy, Greece, Romania and China.
Keywords: irrigation, low quality water, decision support system, modelling.

1 Introduction

A huge amount of the fresh water resources of the world are used to irrigate crops. However, in many places around the world, clean water is a scarce resource, and waste water, treated or untreated, is used as water source for

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irrigation. The result may be contamination of the crop and/or the soil, or risks to farm workers working with the dirty water.

Different strategies may be employed to reduce the problem. First of all, water saving methods of irrigation, such as e.g. partial root drying (PRD), may be used to minimize the water use. Secondly, the dirty water may be used for irrigation only during crop stages, where it does not cause problems or it may be diluted with water from a better source during critical growing periods to ensure that any contamination is kept below critical levels.

Tools for such analyses have been developed for different purposes, e.g. to describe the solute fluxes between the water source (river or well) and applied irrigation water at field level, to describe plant growth as a function of water and nutrient availability or to describe plant uptake of pollutants. However, new irrigation techniques and the relationships between water quality and crop quality, require further development of tools and descriptions.

The decision support system planned must help the irrigation manager on a farm determine which water source and irrigation method to use, taking into account the water quality, water purification possibilities, and water quantity available, as well as the quality of the final produce. It is the vision of the system planned that the project manager is able to compare irrigation methods, water use, water sources and purification techniques with respect to economic return (taking into account crop quality) as well as risks to farm workers, consumers and soil and groundwater resources. With the tool is should be possible to prevent that acceptable limits are exceeded.

The immediate target group of the system is well educated farmers and agricultural extensionists. For specific sites with a given water quality, it may be possible to extract simpler rules from model runs.

The system is planned to work on “a number of fields with different crops”, but in the SAFIR project, all components will be developed only for tomatoes and potatoes.

2 The decision support system

The framework of the decision support system to be developed and tested in the SAFIR project is shown in fig. 1. More specifically, the system should be able to answer a number of specific questions, such as

For single fields (scenario mode):

a. Taking into account the present crop history, if we irrigate using this technique and with water from this source, what is the effect on yield, risks and economy, assuming that
    I. we continue with the same source until harvest, or
    II. continue with clean water until harvest, or
    III. do not irrigate further.
b. Taking into account the present crop history, what is the difference on crop quality, risks and economy if I use water from source A and source B for the rest of the season?

c. What will be projected water use and benefits/risk if I change to a different irrigation method?

For multiple fields (scenario mode):

d. With the existing constraints of water, how will my total water use be distributed for a given crop distribution, irrigation technology and set of crop prices?

Multiple fields (forecast mode):

e. With the existing constraints of water and the present selection of water, what is the proposed irrigation and fertigation strategy for the forecast period, e.g. 5 days?

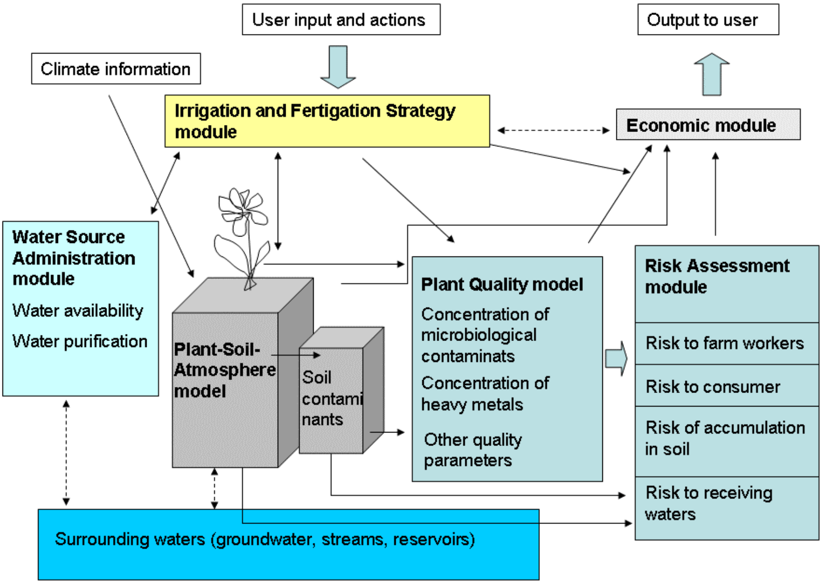

Figure 1: Overview of the models and modules in the management model.

In principle, there will be early stages of irrigation projects, where water quality simulations could help to choose the right irrigation system, filtering methods, disinfection, irrigation management etc. When an irrigation system is established and the growing season has begun, the actual number of realistic choices is much reduced.

The key elements in the irrigation management system are the Irrigation and Fertigation Strategy module and the Plant-Soil-Atmosphere model (PSA-model). The PSA-model calculates the irrigation water demand and the crop yield. It supplies key information for calculation of impact on the production system and quality of the final produce using the various quality waters as well as risks for the food chain (from field to fork). The PSA-model must be set up at the latest at the beginning of the growing season and the model is updated regularly during the growing season. To answer the questions above, it must be possible to run scenarios from the last endpoint, to choose a strategy and to update the simulation with the actually implemented strategy.

The irrigation and fertigation strategies are governed from the Irrigation and Fertigation Strategy module, which allows the user to specify irrigation criteria and rules for irrigation and fertigation. The module interacts with the PSA-model and other modules to determine a possible strategy to follow in a given situation.

As indicated the system consists of:

1) a Plant-Soil-Atmosphere model,
2) an Irrigation and Fertigation Strategy module,
3) a Water Source Administration module,
4) a Plant Quality model,
5) a Risk Assessment module, and
6) an Economic module.

Calculations related to soil contaminants may be collected in a specific module or be part of the plant quality and the risk assessment modules. The modules and models interact with climatic information and surrounding waters and receive input from the user of the system as well as give suggestions to the user.

The modules are expected to be communicating through OpenMI-interfaces, a system developed in an earlier in an EU-project (Gijsbers [1]). The OpenMI-technology is a very promising tool for linking of models originally conceived with different purposes (Westen *et al.* [2]). However, so far the experience with the technology is limited to rather few cases. An important point is therefore to tailor the OpenMI standard to field and farm scale modelling, to make a step-by-step procedure for implementation of the modelling interface and to test it on software relevant for irrigation management. The OpenMI-system supports models in .NET-languages and the advantage of using OpenMI is that all modules in the system can be exchanged with other modules performing the same task - as long as they are wrapped to exchange the same data. In the following a short description of the DSS modules and models is given.

2.1 The Plant-Soil-Atmosphere model

In the first version of the management model the Plant-Soil-Atmosphere model will be the Daisy model (Hansen *et al.* [3], Abrahamsen and Hansen [4]), which is a well-validated soil-plant-atmosphere system modelling framework that simulates all main components of the water and nitrogen cycle in 1D. A new water saving irrigation concept - partial root drying (PRD) – is tested in the project. Partial root drying means that different parts of the root zone are alternately wetted, causing an uneven moisture distribution in the root zone. Daisy is currently being developed to account for two-dimensional effects related to the PRD. Daisy requires basically a description of the soil (horizons, hydraulic properties, textural information, bulk density, organic content, C/N-relationship), a description of the climate (and already performed irrigation) from initialization of the simulation till present (precipitation, insolation, average temperature, wind speed, vapour pressure or alternatively reference evaporation), and management (crop, sowing time, tillage, fertilization).

Climate and weather time series will have to be administered through the user interface for the different types of runs. It is anticipated that three different options will be possible:

1) actual weather in the year to be simulated,
2) forecasts of e.g. 5 days, and
3) historical climatic series.

In relation to the management model Daisy will also handle concentrations of nitrate and ammonia, be able to describe the irrigation methods, and handle the lower boundary condition, such as groundwater level. The PSA-model works in close contact with the Irrigation and Fertigation Strategy module. When the PSA-model has developed a water and N-demand, the Irrigation and Fertigation Strategy module then governs the actions to be taken with respect to irrigation and fertigation based on the conditions in the soil and plant, and the water availability and quality. This information is transferred or iterated with other modules and models in the management model. In order to create an overview of the system, an input/output matrix is developed for each of the models and modules in the system. The draft input and output matrix for the Plant-Soil-Atmosphere model is shown in Table 1.

2.2 The Irrigation and Fertigation Strategy module

The PSA-model interacts closely with the Irrigation and Fertigation Strategy module that tells the plant/soil model about the irrigation conditions (date, depth, how much water and content of ammonia and nitrate).

This module will specify an irrigation strategy only if the PSA-model registers stress with respect to either water or N for at least one simulated field in a forecast period – or when running a historical weather series. The module will:

1) estimate whether irrigation is required for each field,
2) estimate whether fertigation is required for each field,
3) estimate whether the required amount and quality of water is available,
4) make some sort of economic assessment of whether irrigation is economically defendable,
5) and schedule the required irrigation, i.e. tell the PSA-model how much water is required for how long on which date and with which content of ammonia and nitrate,
6) calculate the input of other compounds with the irrigation water and list it in a tabular form.

Table 1: Draft input and output matrix for the PSA-model.

Input	**From**	**Unit**	**Data type**
Irrigation water: - quantity of water and - concentration of nitrate and ammonia	Irrigation and Fertigation Strategy module	$m^3\ m^{-2}s^{-1}$ $g\ m^{-3}$	Time series
Lower boundary condition, such as groundwater level and concentration if required	"Surrounding Waters*"	m	Time series
Output	**To**	**Unit**	**Data type**
Indicators of water demand and N-demand	Irrigation and Fertigation Strategy module	m^3	Time series
Percolation to groundwater: - quantity of water and - concentration of nitrate and ammonia	"Surrounding Waters*" module and Risk Assessment module	$m^3\ m^{-2}s^{-1}$ $g\ m^{-3}$	Time series
Drainwater losses: - quantity of water and - concentration of nitrate and ammonia	"Surrounding Waters*" and Risk Assessment module	$m^3\ s^{-1}$ $g\ m^{-3}$	Time series
Crop stage, development stage, crop type	Irrigation and Fertigation Strategy module and Plant Quality model	-	Time series
Harvested dry matter Harvested C Harvested N, (Uptake of xenobiotics)	Economic model Plant Quality model Plant Quality model Plant Quality model	Kg ha^{-1} Kg ha^{-1} Kg ha^{-1} ?	Time series
Water balance components (to be defined)	Plant Quality model	Pending	Time series
Concentration of nitrate, ammonia and additional compound in the soil	Risk Assessment module	$g\ m^{-3}$ or $g\ kg^{-1}$	Values at different depths

* "Surrounding waters" may be described by time series, by models or may in some cases not be accounted for.

The module has to operate differently depending on whether a scenario run is performed or whether it is a forecast.

In case of a scenario run, the PSA-models describing the different fields on the irrigated farm may develop a deficit of water and N, and the module has to respond with respect to water and fertigation on the basis of water ability and an economic indicator that gives preference for particular fields. The final plant quality and yield is not known at the time when the Irrigation and fertigation strategy module allocates the water.

In case of a forecast, the situation is different. The PSA-model can simulate the case with and without irrigation in the forecast period and a with a selected irrigation strategy for the following period until harvest. In this case simulated yield loss, quality parameters, risks and economy can be presented to the user together with proposed dates of irrigation that takes into account the actual water availability.

The Irrigation and Fertigation Strategy module mainly communicates with the PSA-model and the Water Sources Administration module but requires some economic information.

Important outputs of the module for a scenario run include:

1) a set of dates and irrigation amounts and irrigation depth for each field
2) an amount of fertigation with the irrigation water – fertigation is adjusted for inorganic N in the irrigation water,
3) a table of irrigation dates, method, water quantity, nutrient content and critical compounds added with irrigation water, to be used by other modules for further calculations.

Important outputs of the module for a forecast run include:

4) a proposed set of dates and irrigation amounts for each field – specifically for the forecast period,
5) a proposed amount of fertigation with the irrigation water – fertigation is adjusted for inorganic N in the irrigation water,
6) together with the economics of the irrigation action based on simulations with the PSA-model and prices of the harvested crop, water and fertigation, and
7) a simple estimate of bacteriological risk (low, medium, high) for the specific application, based on the content in the irrigation water, the crop type, the DT50-value and the time till harvest may be included.

2.3 The Water Source Administration module

In the conceptual model, the water sources may be a river, a reservoir or a groundwater well. The system will be able to choose between at least two sources – that is to discard a source, if it turns out to be of too poor quality, or to dilute one, if the resulting quality becomes acceptable.

The water source may be described by a model or by a number of time series only. The content should, in case of a time series, be the maximum extractable amount of water and the quality of water defined by the concentration of $NO3^-$, $NH4^+$, organic matter and other compounds of relevance. In the most complex mode such a module could consists of a groundwater model, a river model and a model of an irrigation reservoir including interaction between the models regarding both water quantity and quality. However, this is not foreseen within the scope of this project.

A water purification plant may – or may not- be assigned to a water source. If there is no purification plant, the water amount and quality that goes on to the next step is unchanged. If there is a water purification plant, it is suggested that the purification process must be defined by the fraction of water passing through the plant and the fraction of each pollutant passing through the plant.

The module will, when the irrigation and fertigation strategy module demands it, return how much water is available from each source, what the water quality of each source is and what is the mixing ratio to fulfil particular criteria. In some areas, water is only available on certain dates, and that is of course included in the water source files mentioned above. The capacity of the equipment may be a limiting factor for the water availability calculation.

The module thus takes into account the water availability of each source, the capacity of the equipment, the priority of water sources, purification of water from one or both sources and losses in the distribution system, losses caused by the choice of purification system and possibly one or more quality parameters that must be fulfilled.

The Irrigation and Fertigation Strategy module returns the actual amount of water used from each source, making it possible to calculate the actual extraction required.

2.4 The Plant Quality module

The Plant Quality module assesses the crop quality as a function of the irrigation water quality. The content of xenobiotics and heavy metals in the fruit may be assessed as well as the microbiological contamination on the fruit. Other quality parameters may be a function of water content and nutrient uptake. In reality, it thus consists of several rather independent assessments:

1) Assessment of microbiological contamination of fruit
2) Assessment of xenobiotics and heavy metals in the fruit
3) Assessment of other quality parameters in the fruit.

The biological contamination depends on irrigation technology, water quality and timing of irrigation and the placement of the harvested part of the crop. Special focus will be on the transfer of toxic solutes (heavy metals and As) to the food products and on long term effects related to their accumulation in soil and their potential transfer to groundwater (Kass *et al.* [5]). Assessment of this will require information on the total amount of contamination as well as of water balance elements, sorption properties and plant uptake parameters. Whether it will be possible to assess differences in crop quality parameters such as nutrients and sugar due to differences related to irrigation practise remains to be seen from the experimental results of the project.

2.5 The Risk Assessment module

The Risk Assessment module consists of four different more or less independent sub-models, which are used to assess risk due to:

1) direct exposure of the farm worker during cropping,
2) exposure to consumer when the crop is eaten,

3) the risk for accumulation of unwanted compounds in the soil over one or more seasons, and
4) the risk of leaching of unwanted compounds to groundwater or via drain water to surface water.

The exposure of the farm worker mainly relates to biological contamination during cropping and harvest. The exposure to the consumer is mainly biological but could also be related to content of metals or organic contaminants.

The accumulation risk could be heavy metals or total ion content, while the leaching in addition can contain unwanted nutrients.

Some of the inputs to this module include irrigation method, irrigation water quality, amount of irrigation, concentration of microbiological contaminants on the crop at harvest, total uptake of xenobiotics and heavy metals as well as other quality parameters, concentrations of compounds in the soil and percolation to groundwater and drainage system. The result of the risk assessment is a table of risk indicators calculated with the different sub-models.

2.6 The Economic module

The Economic module will compare the cost of irrigation with the income from the harvested crop. The accumulated cost of water, purification and fertigation is calculated for each defined scenario, as well as the cost of other inputs. Crop yield is estimated with the given water quality and the price of the crop is determined based on crop quality.

3 Conclusions

The proposed management system is presently in the design phase. Partners of the different work packages of the SAFIR project co-operate to produce the final design, and the responsibility for building the different modules will be distributed to the relevant partners. The first prototype is expected in 2008 and will be tested on data from one of the field sites.

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Quarry plans in the management of water resources: case study of the River Serio

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Abstract

This work investigates the possibility of rehabilitating and using volumes made available by the creation of quarries of inert materials in watercourse flood plains for the regulation of floods and for the maintenance of supplies in times of water scarcity. Such activities offer technical and economic synergies between the need for production of inert materials and the benefits that such excavations, given appropriate expedients, can provide both in reducing the flood risk and in mitigating shortages. The work in question fully complies with the terms of the Catchment Area and Water Conservation Plan, demonstrating moreover that the required rehabilitation operations are of low impact and are fully sustainable. The case study concerns the last stretch of the River Serio in the province of Cremona.

Keywords: quarries, water scarcity, water supplies, sustainable management, conflicts, irrigation, flow duration curve.

1 Introduction

In the Lombardy region, in Italy, the water supplies are maintained by heterogeneous resources, such as natural lakes, artificial reservoirs mostly located in mountains, groundwater and natural springs widespread in the southern part of the region. Water resources have been traditionally utilized for human consumptions, hydropower and thermoelectric production and, above all, agricultural irrigation. In the most recent years an increased environmental sensibility asked for the respect of the minimum flows for aquatic life conservation. Despite the natural abundance of water in Lombardy, shortage of water in recent years and the increase of consumptions, have exasperated the conflict between the users. In the last emergencies for water scarcity, irrigation

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deficit has been calculated as 20% (1495 million m^3) with an equivalent economic damage of 230 million euro in Lombardy. In this situation new management rules and water resources are required taking into account the needs of all the stakeholders.

An interesting water resource which can help in complying with the requests in shortage period is the water stored into the quarries of inert material. A recent regional census has counted more than 700 quarry lakes in Lombardy (Regione Lombardia [6]), most located in watercourse flood plain where agriculture is the main human activity. These manmade reservoirs cover a surface of about 100 km^2 with an available water volume estimated in the range 350 – 700 million m^3. In front of these numbers, the volume of water that can be extracted from the quarries is comparable to the volume of traditional water resources, which are subject to an intensive exploitation. Quarry reservoirs may, then, become a strategic means for the mitigation of water scarcity.

The work presented in this paper investigates the possibility and the efficiency of using the water of the quarry lakes for the reduction of negative effects of water scarcity on environment and economy. In addition an evaluation of the positive effects of the quarries on the regulation of flood and consequently on the reduction of the hydraulic risk is made (not presented in this paper; for further details refer to Provincia di Cremona [5]).

2 The study area

The study area involves three quarries located in the north of the city of Crema, in proximity of the river Serio (fig. 1). The quarries today cover a surface of 314850 m^2 but in the near future an expansion of 258600 m^2 is planned (tab. 1).

The river Serio watershed covers an area of about 940 km^2 (711 km^2 at the section of the quarries). The river takes origin in the Barbellino Lakes at an elevation of 2100 m a.s.l. joining the river Adda after a distance of 124 km. The upstream part of the basin is characterized by high mountains with steep slopes. Downstream the section of Alzano Lombardo, the river flows down into the plain and the average slope decreases. When the river goes into the province of Cremona, in proximity of Mozzanica, the flow is regulated by the contribution of natural springs (“fontanili”) which are widespread in this area of the basin: Roggia Vidolasca, Roggia Babbiona, Roggia Menasciutto, Roggia Molinara, Roggia Cataletto, Canale Vacchelli, Roggia Rino Fontana, Roggia Cresmiero, Bocchello Oche, Fosso Fuga, Bocchello Ripalta, Roggia Acqua Rossa, Roggia Comuna, Roggia Malcontenta, Roggia Archetta, Roggia Borromea (Provincia di Cremona [4]).

2.1 Available data

Cartographic and time series data available for the study include: digital elevation model, lithologic atlas, land use map, long series discharge measurements at Ponte Cene station, discharge data for the station of Mozzanica and Montodine only for the most recent flood event, rainfall measurements, cross section survey of river Serio.

Table 1: Characteristics of the quarries.

	Actual state		Planned expansion	
Quarry code	Surface [m^2]	Depth [m]	Surface [m^2]	Depth [m]
ATE g2	51400	16	0	-
ATE g3	163250	15	160000	15
ATE g4	100200	15	98600	15
total	314850	-	258600	-

Figure 1: River Serio hydrographic basin (left) and a detail of ATE-g3 quarry and planned expansion (right).

3 Drought hydrology

The analysis of the available water in the river is based on the flow duration curve. Discharge measurements are not available for the section where quarries are located; in this case it is possible to use regional methods for the evaluation of an approximated natural flow duration curve (Bartolini *et al* [1]).

According to the adopted method, the flow duration curve can be written as:

$$D(q) = 365\lfloor 1 - F_q(q) \rfloor \tag{1}$$

where D denotes duration in days, q the discharge in m^3/s and F_q the cumulative frequency.

The adopted probability distribution function (PDF) is the lognormal distribution:

$$f(y) = \frac{1}{\sigma_y \sqrt{2\pi}} \exp\left\{ -\frac{1}{2} \left[\frac{y - \mu_y}{\sigma_y} \right]^2 \right\} \tag{2}$$

where $y = \ln(q)$ denotes the reduced variable and:

$$\sigma_y^2 = \ln\left[\left(\frac{\sigma_q}{\mu_q} \right)^2 + 1 \right] \tag{2.a}$$

$$\mu_y = \ln(\mu_q) - 0.5\sigma_y^2 \tag{2.b}$$

$$\mu_q = a_1 S^{b_1} H^{c_1} \tag{2.c}$$

$$\sigma_q = a_2 S^{b_2} H^{c_2} \tag{2.d}$$

where S denotes surface of the basin in km^2 and H denotes average annual rainfall depth in meter.

Evaluation of model parameters, a_1, b_1, c_1, a_2, b_2, c_2, (tab. 2), has been conducted by a trial and error approach matching flow duration curve of the Ponte Cene section where discharge data are available (§2.1). It is possible, then, to evaluate flow duration curve for the ungauged river sections. If the section drains a basin in which anthropic effects are important (e.g. withdrawals for irrigation or intakes from wastewater treatment plants) the flow duration curve is modified by adding or subtracting the average annual artificial contribution. The natural and anthropic flow duration curves for the section of quarries is shown in fig. 2. In that figure the minimum flow necessary for life (critical flow), evaluated as the 10% of the annual average natural discharge, according to the Regional Water Plan for Water Management, is reported. Its value is then fixed to 3.06 m^3/s. From the comparison of anthropic flow duration curve and minimum flow it is possible to note that river discharge is lower than the critical for about 24 days in a year. The deficit volume, highlighted in grey in fig. 2, sums up to 3700000 m^3.

Table 2: Parameters for evaluation of flow duration curve in ungauged section.

a_1	a_2	a_3	b_1	b_2	b_3
0.0216	0.99	1.43	0.023	0.924	1.148

4 Quarry management during water scarcity

In the river reach downstream the quarries, the Regional Water Plan for Water Management reports three withdrawals for agricultural use: Roggia Borromea (1.4 m^3/s), roggia Malcontenta (0.44 m^3/s) and a whole of little irrigation channels summing up to 0.42 m^3/s, with a total of 2.26 m^3/s. The sum of the aforementioned withdrawals and the minimum critical flow gives the river discharge that satisfies environmental quality and agricultural needs.

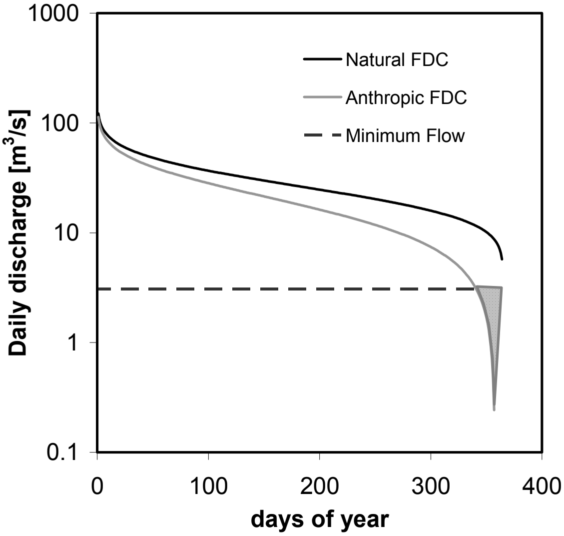

Figure 2: Evaluation of the flow duration curve (FDC) of the river Serio for ungauged section where quarries are located: natural FDC in black line, anthropic FDC in grey line and minimum critical flow in dashed black line. Grey area represents the deficit volume (3700000 m^3).

We suppose three scenarios for the employment of the volume of water contained in the quarries. The available water is calculated considering the future expansion plan (total surface covered is 573450 m^2). The three quarries are considered as an unique storage. The water inflow to the quarries coming from groundwater is considered negligible.

The first scenario gives priority to the environment conservation, guaranteeing the minimum flow in the river for natural life during all the year. This hypothesis is satisfied by a volume of water of 3700000 m^3 (fig. 2) that corresponds to a drawdown of the water surface level in the quarries of about 6.5 m.

The second scenario is intended to satisfy the irrigation needs adding to the river Serio a volume of water necessary to guarantee the three downstream withdrawals on the occurrence of water scarcity. With a drawdown of the water surface level in the quarries of 2 m, 4 m or 5.5 m, the extracted volume can maintain irrigation for, in order, 6, 12 and 16 days.

The third scenario is the ideal situation in which both environment conservation and agricultural needs are satisfied. In this hypothesis the discharge which must be preserved in the river Serio is 5.32 m^3/s, sum of minimum critical flow and the downstream water withdrawals. Unfortunately, the necessary volume (10000000 m^3) is greater than total water stored in the three quarries. It is , then impossible to put in action the ideal scenario.

5 Draining time and interaction with the river

It is interesting to evaluate the time needed for the draining of the quarries. The three quarries are considered as an unique system characterized by an initial water surface at 75 m a.s.l.. The aquifer is considered isotropic with an hydraulic conductivity K of $3 \cdot 10^{-5}$ m/s as reported in the Regional Water Plan for Water Management. The minimum water level in the lakes is fixed to 69.5 m a.s.l., which corresponds to a drawdown of 5.5 m. The dynamic of the water level and, consequently the draining of the storage, is modelled with mass balance equation:

$$\frac{\Delta W}{\Delta t} = Q_i - Q_o \tag{3}$$

where Q_o is the extracted discharge and Q_i is the inflow discharge coming from the aquifer given by (Citrini and Noseda [2]):

$$Q_i = \left(h_2^2 - H_q^2\right)\frac{K\,P}{2\,L} \tag{4}$$

where h_2 (m) is the undisturbed piezometric head at a distance L (m) from the quarry, H_q (m) is the level in the quarry, P (m) is the perimeter of the quarry and K is the hydraulic conductivity (m/s). The length of influence, L, is evaluated with the empiric equation:

$$L = 573\,(h - H)\,\sqrt{Kh} \tag{5}$$

valid for the steady state (tab. 3).

Table 3: Length of influence, L, evaluated by means of (5) considering two different values of hydraulic conductivity.

h-H (m)	K (m/s)	h (m)	L (m)
5.5	$3 \cdot 10^{-4}$	75	472
5.5	$3 \cdot 10^{-5}$	75	149

As the evaluation of hydraulic conductivity is, as well known, subject to great uncertainty, in this study three values are considered: the aforementioned $3 \cdot 10^{-5}$ m/s, $3 \cdot 10^{-9}$ and $3 \cdot 10^{-4}$ m/s. The draining time and the extracted volumes are evaluated considering, in the first case, Q_o = 2.26 m^3/s and, in the second case, Q_o = 3.06 m^3/s (§4). Results are reported in the fig. 3.

The draining times, reported in tab. 4, can be evaluated as the intersection of drawdown line and the horizontal dashed line which represents the maximum drawdown.

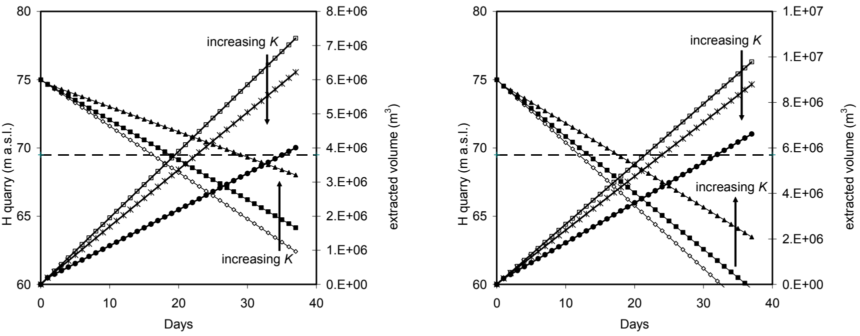

Figure 3: Evaluation of the drawdowns (decreasing lines) and extracted volume (increasing lines) for a pumping discharge of 2.26 m^3/s (left) and 3.06 m^3/s (right). Values of hydraulic conductivity are $3\cdot10^{-4}$ m/s, $3\cdot10^{-5}$ and $3\cdot10^{-9}$ m/s. The dashed horizontal line represents the maximum drawdown.

Table 4: Draining times as a function of the hydraulic conductivity, K, and pumping water, Q.

K (m/s)	Q (m3/s)	Draining time (days)
$3\cdot10^{-9}$	2.26	19
$3\cdot10^{-5}$	2.26	22
$3\cdot10^{-4}$	2.26	29
$3\cdot10^{-9}$	3.06	12
$3\cdot10^{-4}$	3.06	14
$3\cdot10^{-5}$	3.06	18

From eqn. (4) it is possible to calculate the piezometric head distribution when the drawdown has reached its maximum. For a given pumping discharge Q, and a given hydraulic conductivity K, the water table h_2 is calculated as a function of the distance from the quarry H according to eqn. (6). It is so possible to analyse interaction of quarry with river Serio and aquifer.

$$h_2 = \left(H^2 + \frac{2QL}{KP} \right)^{0.5} \tag{6}$$

The results are shown in fig. 4 in which a representative section involving ATE-g3 and ATE-g4 quarries and a cross section of the river Serio is reported. Analysis of piezometric head shows a possible interaction with the river Serio, but water exchange is negligible due to low hydraulic conductivity of river bed material.

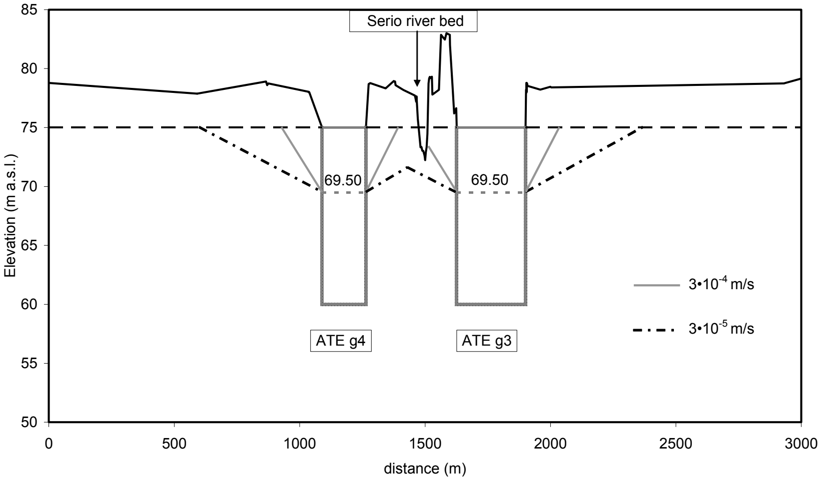

Figure 4: Representative cross section involving ATE-g3 and ATE-g4 quarries and Serio river bed. Water table for a drawdown of 5.5 m and two different values for hydraulic conductivity are displayed.

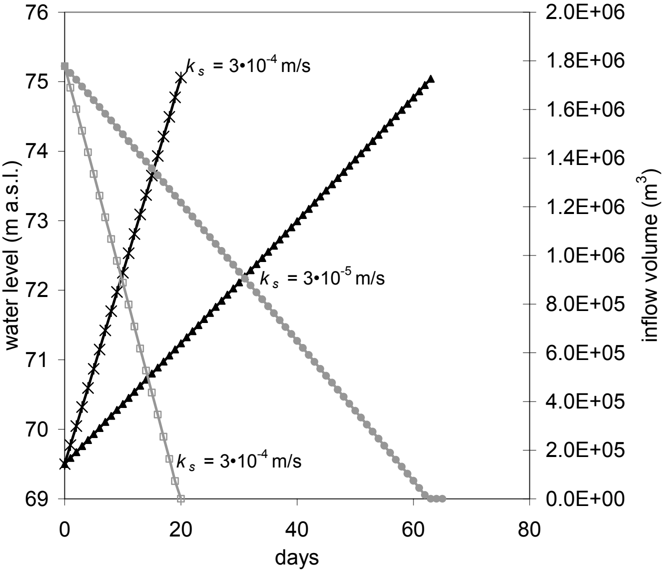

Figure 5: Water level in the quarry ATE-g3 during refilling (black lines) and inflow volume (grey lines). Value of hydraulic conductivity is displayed on the chart.

6 Refilling time

In a similar way to the evaluation of draining time, it is possible to calculate the refilling time, the time necessary to restore undisturbed water table level. In this calculation we made the hypothesis that natural and anthropic events (rainfall or irrigation) are negligible.

In fig. 5 we show the details for ATE-g3 quarry, as the others have similar behaviour. The necessary time for total refilling of the lake varies from 20 days for an aquifer hydraulic conductivity of $3 \cdot 10^{-4}$ m/s and 63 days for hydraulic conductivity of $3 \cdot 10^{-5}$ m/s.

7 Conclusions

In the present study we investigated the possibility of rehabilitating and using volumes made available by the creation of quarries of inert materials in watercourse flood plains for maintenance of supplies in times of water scarcity. The results show the great importance quarries may have in environment conservation and agricultural activities. With a drawdown of 5.5 m, in fact, it is possible to maintain in the river Serio the discharge necessary for the downstream water withdrawals for a 16 days period. Alternatively, by means of the same drawdown, it is possible to maintain the minimum flow in the river for natural life for a 12 days period. However, the available water volume is not enough to satisfy both environment conservation and agricultural needs.

The piezometric head depression induced by pumping may interact with the river Serio level itself, but the conductivity of river bed is very low so that exchange with the water table can be considered negligible.

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Strategic decision-making for water resource management in semi-arid metropolitan and rural areas

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Abstract

This paper explores natural resource management decision-making for sustainable long-term water resource management in semi-arid regions. The paper lobbies for reconsideration of current long-term natural resource management decision-making methodologies. It uses bulk-water resource management in semi-arid areas to illustrate shortcomings in current methodologies that could lead to unsustainable resource utilisation. Information asymmetry is put forward as the main reason for shortcomings in the current methodologies. The risk of ignorance concerning asymmetry is explained. The financial and political markets as management strategies for scarce resources are explained and revised, and shortcomings are identified.

The paper concludes by emphasizing the complexity of water management in semi-arid areas. A systems approach towards sustainable long-term water resource management in semi-arid areas is recommended and the process of multi-criteria decision-making is offered as a suitable decision-making aid, given that some refinements with regard to spatial, time and geographical dimensions of the methodology are developed.

Keywords: water policy development; strategic water management; bulk-water supply management; sustainable resource utilisation; multi-criteria decision analysis; seawater desalination.

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1 Introduction

Metropolitan areas like the City of Cape Town, situated in the semi-arid Western Cape Province of South Africa, are confronted with water scarcity problems. Domestic water use often exceeds own supply tempos and metropolitan areas like these therefore rely increasingly on adjacent rural areas for additional water supply. Various reasons could be put forward for this phenomenon, for which price-elasticity of demand and related arguments are often used. However, water resource decision-makers cannot be certain of the true total costs and benefits associated with these re-allocations of water. If addition supply expansion alternatives are extremely limited (such as in the case of most semi-arid metropolitan areas), a complex web of long-term impacts on both rural and urban areas comes to the fore. These long-term impacts (such as negative environmental impacts, structural changes in agriculture and population demographics) of re-allocations are neither yet fully understood nor quantifiable and cannot therefore be fully accounted for in long-term strategic water management considerations.

Furthermore, urban usage traditionally enjoys priority over rural usage and accordingly dominates the planning process in long-term water allocation management. As such, the strategic planning context is often narrowed in favour of urban areas. Such narrowing could be in terms of temporal and spatial dimensions, encouraging sub-optimal resource allocations within the broader regional context. This situation develops tension between urban and rural water user groups. In addition, efforts to reverse negative long-term externalities of sub-optimal allocations often prove more costly compared with avoiding such policies in the first place. These situations result from strategic water managers being unable to fully account for the long-term impacts of different water management strategies in their decision-making. This could be traced back to shortcomings in benefit-cost quantification methodologies where “softer” and less tangible impacts of water re-allocations cannot readily be defined in terms of monetary variables.

The above-mentioned situation illustrates both a failure in the market as resource allocation mechanism and a shortcoming in the political market, where water management authorities and government officials interpret their responsibilities in a narrow sense or measure optimality in terms of efficient water allocation exclusively to urban areas. Bulk water re-allocations from rural to urban areas have a negative socio-economic impact on rural societies, the natural environment and irrigated agriculture. These impacts are not readily accounted for in deciding whether or not to proceed with these re-allocation projects.

This dilemma has created an opportunity for research into the problem of sub-optimisation (“unsustainability”) within natural resource allocation management. The problem at hand indicates complexity within a resource scarcity context, and by adding the challenge of truly sustainable but equitable and efficient resource utilisation, the problem becomes even more complex. Better management of uncertainties regarding long-term implications of bulk water supply options is needed to facilitate a better comparison of different management options. Decision support tools like multi-criteria decision-making (MCDM), which is generally used to support water resource management, needs to be adapted to capture considerations of relevance in the broader decision-making environment. This paper attempts to engage in refinements to MCDM in terms of the spatial and temporal dimensions of the decision-making context.

The research implies a refined regional MCDM in the City of Cape Town area and the adjacent rural areas sharing water resources with the city. Refinements to the contexts of MCDM methodology were made in terms of spatial and temporal dimensions. A spatial expansion was attempted by broadening the physical context (boundaries) of the decision-making area for water resource management in the above-mentioned area. This expansion implied expansions in decision-making representation, which were canvassed via a public survey, an expert panel survey and an expanded representation of key decision-makers. The public survey needed to yield a satisfactorily response rate, be politically transparent and objective, and imply changes in information loads. Expansion of the temporal dimension was attempted via the development of two "development paths" that had to be objective, transparent and concise. This expansion also required an expansion of decision-making criteria.

2 Contextual and theoretical background

Water service authorities (such as governments) usually promote an efficient but equitable and sustainable allocation of water (Eberhard, [11]; Shand *et al.*, [31]; Thomas and Durham, [37]). Such an allocation is, for practical reasons, impossible to achieve, but it does serve as a management guideline. Given a budget constraint, decision-makers are challenged to opt for the management option that will find a balance between sustainable development, environmental conservation and social welfare maximisation. (Note that social welfare creation includes sustainable development and environmental conservation.) Figure 1 illustrates this phenomenon. Water managers need to decide whether to follow a market- or a command-and-control-dominated approach. Either a command-and-control- or a market-driven strategy will dominate the resource management strategy (usually a combination is used), and rarely will it be the case that a particular strategy could exclusively be defined as a command-and-control- or a market-driven strategy.

If water resource managers apply the principle of marginal benefit by turning to the market for bulk water resource management, the competitive market is utilised as a mechanism for allocating water use rights to more efficient uses in their management area (Eberhard, [10]; Pearce, [27]; Thrall, [38]). Market allocation theory states that an efficient and equitable allocation of water resources (water use rights) will be achieved if the suitable market structures are in place - i.e. the assumption of perfect competition (Mueller, [24]). This means that the market (assuming water managers facilitate the functioning of such a market) will allocate water use rights to users who will make the greatest contribution to social welfare. However, frequent market failures occur in cases with public goods, such as water, because of high transaction costs, externalities (unaccounted for impacts) and the faulty telescopic tendency of market participants (Blignaut and De Wit, [5]; Goodstein, [16]; Pearce, [27]; Pearce and Turner, [28]). The market also needs large numbers of independent sellers and buyers, which is not always the case with tradable water use rights in semi-arid areas (e.g. the greater City of Cape Town). In addition, to have an efficient and free market, the social cost of a transaction must correspond with its private cost. If not, society as a whole could be harmed because the drive to private gain may not simultaneously lead to an increase in social welfare (Arrow, [1]).

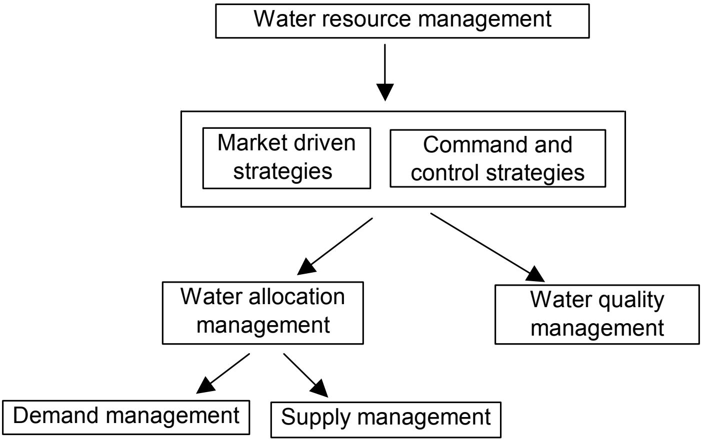

Figure 1: A contextual framework for bulk-water resource management.

The market is also criticised for of its inability to maximize social welfare in an objective way, because the market only accounts for a weighted sum of individual prices (Arrow, [2,3]). The social outcome of such an allocation has not been evaluated and may therefore be politically unpopular. Proof can be found where the re-allocation of water use rights from rural to urban use is approved because of higher effective urban demand. Water prices cannot therefore fully account for all trade-offs of rural to urban re-allocations (e.g. the contribution of agriculture to the economy, the relative value of rural areas in sustaining the rural population and the relative value of rural amenities for tourism). The market merely provides one of many allocations because of the inherent inability of welfare economics to present an objective method to achieve maximum social welfare via any given voting procedure (like the market) from an aggregation of individual welfare functions. The market for tradable water use rights could therefore not be seen as the ultimate allocation mechanism for society as a whole.

Indeed, some margin is created for government interference when the market for water use rights fails. This implies that public trust is placed in bureaucrats and politicians to compensate for market failures by making use of rules and regulations to allocate water use rights in such a way that they will contribute to social welfare maximisation. A functional bureaucratic system is used to motivate politicians to act in the best interests of the public (Buchanan and Tullock, [6]; Mueller, [24]). A principal-agent relationship can be found between water managers (agents) and the receivers of such services (public or principal). The problematic choice before the agent is whether, and to what extent, to involve the preferences of the principal in strategic water resource allocation decisions. By ignoring the principal's (public's) preferences, a somewhat paternalistic stand is adopted because the agent assumes, without consulting the principal, superior information and a recommended allocation of water use rights will be in the best interest of the principal. However, government intervention leads to the need for detailed monitoring and measurement because of problems regarding hidden incentives and different time-frames between principals and agents (Goodstein, [16]; Kleynhans, [20]). Also, strategic decision-making in bulk water supply management has a typical twenty-year planning horizon while a bureaucracy functions in four- to five-year terms. Long-term bulk water supply planning could therefore be hampered if politicians continually opt for short-term water supply solutions just to enhance their own political positions. Incentive-related problems, such as the aforementioned, occur because of the separation of power and responsibility (i.e. those having decision-making power in government agencies do not bear responsibility for their decisions, at least not to the same extent as profit-seeking entrepreneurs in a market setting do). There are also no signals in the collective decision-making process that are comparable to profits and losses in the market for water use rights. Therefore, no reliable way exists of judging efficiency where outputs are not produced and sold under competitive conditions.

Both market- and command-and-control-oriented approaches therefore show uncertainties and inefficiencies regarding water resource allocation, and some alternatives that make uncertainties more tangible are called for. MCDA presents a way of managing these uncertainties and subjectivities in order to make unknown factors more tangible (Stewart, [33]). One of the principles of the MCDA approach is to help decision-makers organise and synthesise relevant information to enhance decision-making (Heynes, [17]).

3 Decision-making in water resource management

Water in its natural form has no costs attached to it - as long as it is used in its natural form with no additional effort to enhance the usefulness (utility) derived from using the resource (Terreblanche, [36]; Turpie *et al.*, [39]). However, the moment the resource is manipulated and/or transformed to enhance the utility derived from using the resource, additional costs will emerge. Cost considerations are important determinants in bulk-water management, with the quantification of costs not necessarily being in monetary terms. Standard monetary terms ease the comparison of different bulk water projects because such terms are defined per se; however, they ignore the local context in which the costs occur, and the challenge is therefore to capture all costs in the decision-making process.

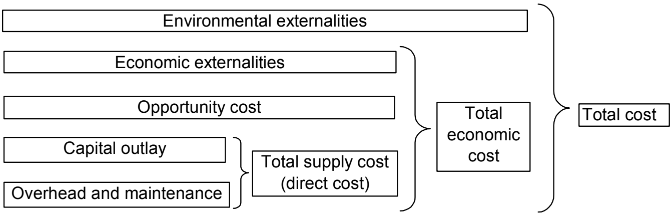

Figure 2: Cost components of management alternatives. Source: (Rogers *et al.*, [29]).

A wide range of estimating techniques is available to aid in such quantification. These efforts have achieved success in estimating total supply cost (direct cost) but have been less successful in estimating the total economic cost and total cost of alternatives. Direct costs are reasonably well covered and normally consist of an engineering approach, summating the capital outlay, operating and maintenance costs over the project lifetime. Some controversy may be found in the determination of a suitable discount rate for future direct cost, but in most cases an assumption can be made to overcome this problem (Gollier, [15]; Goodstein, [16]; Pearce, [27]). The estimation of total economic cost and total cost remains problematic. This implies that water management decision-makers are confronted with incomplete decision-making information. Also, different options often have different proportions of direct and indirect costs. Take, for example, two bulk water supply alternatives: a new dam site or a water production facility like a seawater desalination plant. Direct costs with both options could be accounted for with relative ease against an acceptable level of certainty, and it would probably be the case that the dam would have a lower direct cost per kilolitre of water compared to the desalination plant. However, it could be that the dam contains more unknown and unaccounted-for long-term externalities compared with the desalination plant. Such externalities are not taken into account to the same extent as the measurable (direct) costs of the two options. Decision-makers are therefore left with little choice but to focus more on the direct cost in making a choice between the two options. Such a dilemma implies that decision-makers assume the risk of making unsustainable long-term management decisions based on incomplete information. The irony of the situation is that, lamentably, future negative impacts become apparent only when it is too late to reverse the situation because of sunken costs. The danger for sustainable water management therefore lies in basing strategic decisions on incomplete information or even worse: being ignorant of a potentially large cost component Figure 2. It should be clear that strategic decision-making in bulk water management faces a classic case of decision-making in situations of incomplete cost information, with numerous uncertainties (Joubert *et al.*, [19]; Mander *et al.*, [22]; McDaniels *et al.*, [23]; Pavlikakis and Tsihrintzis, [26]; Shand *et al.*, [31]). One step forward in accommodating externalities is the development of decision support techniques that will at least manage uncertainties and intangible factors to structure the decision-making process.

4 Decision support for strategic water resource management

The existence of externalities in water management decision-making are due to numerous interrelationships between different factors, each playing a role in the benefits and costs associated with alternatives. To manage such a “messy” situation calls for an integrated approach to water resource management. Systems thinking is at the core of integrated resource management, and MCDA forms part of an integrated and trans-disciplinary approach to water resource planning (Figure 3) (City of Cape Town: Water Services, [8]; Thomas and Durham, [37]).

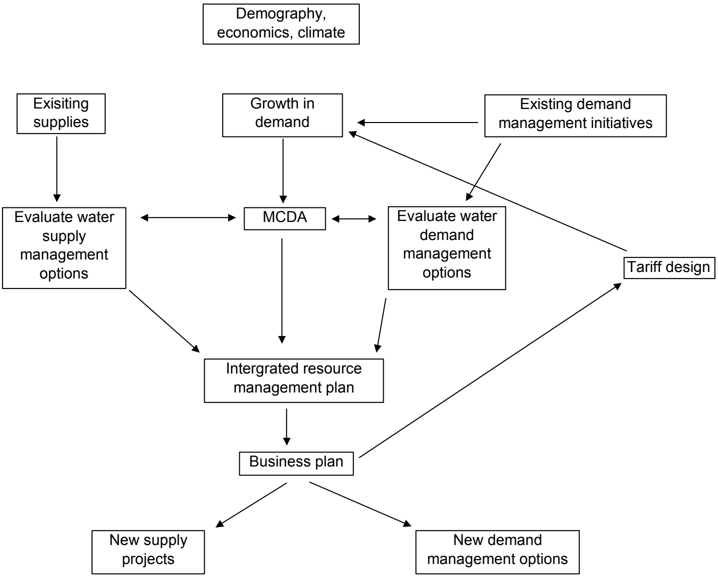

Figure 3: Integrated water resource planning. Source: (Eberhard and Joubert, [13]).

Integrated water resource management may be considered in at least three ways (Du Plessis *et al.*, [9]).

First, it can imply the systematic consideration of the various dimensions regarding the quality and quantity of water. Important here is the acceptance that water comprises an ecological system formed by a number of independent components. Each component (quantity and quality, surface and groundwater) may influence other components, and therefore, needs to be managed with regard to its interrelationships. At this level of integration, management’s attention is directed to joint consideration of aspects such as water supply, waste treatment and water quality.

Second, integrated water management can imply that, while water is a system, it is also a component that interacts with other systems. This points to interactions between water, land, and the environment, recognising that changes in any one may have consequences for the other. At this level, management's interest becomes focused on issues like floodplain management, erosion control, non-point pollution, agricultural drainage and recreational use of water.

A third, and broader interpretation is to approach integrated water management via the interrelationships between water and the social and economic environments. Here the concern is to determine the extent to which water is both an opportunity for and an obstacle to sustainable economic development. At this level, interest turns to the role of urban water use.

Integrated water resource management implies anticipation of the short- and long-term impacts of water management decisions (Belton and Stewart, [4]). Short-term impacts can be anticipated with an acceptable level of certainty; however, long-term impacts present a major challenge. Such issues are far too complex to be analysed by an individual decision- maker for their potential long-term consequences. The decision-maker is therefore dependent on decision support for making the best decision given the context (Carmichael *et al.*, 2001; Hobbs *et al.*, [18]; Laukkanen *et al.*, [21]; Oosthuizen *et al.*, [25]; Slinger, [32]; Stewart *et al.*, [34]; Van Zyl and Leiman, [40]; Wierzbicki, [41]).

Decision support and decision analysis will not solve a decision-making problem, nor are they intended to do so. Their purpose is to produce insight and to promote creativity to help decision-makers make better decisions (Stewart, [33]). Decision support is directly related to explaining decision-making behaviour and voting theory, which is related to utility theory because an expected utility maximising strategy exists in voting situations as well as in decision-making situations (Laukkanen *et al.*, [21]). In order to justify and explain behaviour, rational choice theory appeals to three distinct elements in the choice situation (Belton and Stewart, [4]; Eberhard and Joubert, [12,13]). First, there is the feasible set, which can be defined as a set of all actions (water management alternatives) that satisfy various logical, physical and socio-economic constraints (decision-making criteria). The second is the causal structure or the situation that determines which action will lead to which outcome (interrelatedness between actions and outcomes). The third is a subjective (normative) ranking of the feasible alternatives, usually derived from a ranking of expected outcomes. To act rationally then simply means to choose the highest ranked element in the feasible set (Belton and Stewart, [4]; Elster, [14]); however, it is important to stress the subjective nature of these decision-making environments as well as the limitations of an analytic-reductionistic mindset (Arrow, [1]; Sen, [30]).

MCDA appeals in strategic water management because it manages uncertainties and makes subjectivity more tangible. This does not imply that MCDA will eliminate subjectivity in decision-making - it only manages subjectivity since it and subjectivity will remain part of decision-making, particularly in choosing criteria on which to base the decision and in choosing what weight to allocate to each decision-making criterion. MCDA manages subjectivity by making the need for subjective choice explicit and the process of taking account of this subjectivity more transparent (Stewart, [33]). Such transparency is important since it promotes stakeholder participation, especially in cases where multiple stakeholders are involved, as is the case in water resource management.

MCDA is both a process and a methodology that provides a consistent approach to compare alternatives that have impacts on, or are relevant to, a number of different criteria. Essentially, the process comparing management alternatives from different points of view (criteria) and combines these comparisons (scores) to obtain an overall ranking of alternatives. Each criterion is evaluated from different disciplines.

The following statements describe the character of MCDA (Belton and Stewart, [4]):

- MCDA tries to take explicit account of the multiple conflicting criteria for decision-making.
- MCDA assists in structuring the problem of choice.
- All models used in MCDA provide a focus and a common language for discussion.
- MCDA facilitates decision-making by assisting the decision-maker to place the problem in context, to determine the stakeholder preferences and to present the information.
- MCDA acts as a sounding board against which ideas can be tested.
- MCDA improves the justification of decisions

It must be noted that MCDA does not claim to provide a "correct" or "true" system of weights or scores, as these are determined by the inputs of the stakeholders of the decision-making process (Hobbs *et al.*, [18]; Stewart *et al.*, [34,35]). The "correct" system reflects the trade-offs society is willing to make in any specific situation. The relative importance attached to each criterion and the correct treatment of their comparative importance is critical to implementation. However, the assessment and interpretation of importance weights is often a topic of controversy between decision-makers. In addition, the weights of criteria are based on normative grounds - economic theory is therefore less suitable to resolve controversy between decision-makers.

5 Conclusion

Despite the general acceptance of the concept of integrated water resource management, progress in its implementation has been slow and unsystematic. This is partly because of obstacles to integration. The slow pace of adoption also indicates that decision makers are learning as they proceed, with no obviously correct model to follow. As a result, individuals are usually cautious and follow an incremental strategy in which they move forward slowly. Key obstacles to integrated water management include decisions regarding what information is needed to assist in planning and management decisions as well as deciding how to incorporate the public into the management process.

Employing MCDA in the water management decision-making process is certainly a step in the right direction. However, the process should be further refined and expanded by comparing sequences of management alternatives over time instead of comparing alternatives at the same time. By doing this, new dimensions, such as spatial, temporal and geographical dimensions come to the fore. Defining MCDA as a process on a bigger spatial scale, will force decision-makers to think more broadly regarding the consequences of water management decisions. The time dimension will pre-empt consideration of the long-term implications of different sequences of management alternatives. The geographical broadening of MCDA would include aspects such as impacts on rural areas from where water is re-allocated to urban areas. If rural areas were to be included, rural communities would have to be included. The public needs to be consulted regarding preferences in terms of sequences of alternatives over time, and the challenge lies in communicating complex issues in a simple way to the public in order to obtain a meaningful answer. Within such refinement lies the difficult question regarding whether, and to what extent, public opinion should be questioned in long-term strategic decision-making. Questions regarding the rationale of simplifying complex problems, such as strategic water management, and presenting these questions to the public in order to identify public preferences remain.

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Increased participation in Australian water markets

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Abstract

This paper examines evidence of the factors affecting the adoption of water markets within Australia's largest irrigation district, the Goulburn-Murray Irrigation District in Northern Victoria. The district is unique for the purpose of this analysis for a number of reasons: 1) irrigators are supplied by two main systems with very different supply reliability; 2) parts of the district have a high proportion of land suffering from soil degradation and salinity with low value production while other areas have better soils and higher value production; 3) market restrictions have been eased over time and vary across the district; 4) the district has experienced severe drought over the last six years; and 5) there are two different types of irrigators within the district, those supplied by the district infrastructure and those pumping their own water directly from the rivers with slightly different entitlements. The paper uses the trading and entitlement registers to analyze the trading behavior of all farm businesses during the first 13 years of trading both in the market for water entitlements and water allocations. Originally markets were adopted most extensively in the area with the largest potential financial tradeoffs between high and low value water users and irrigators with poor and good soils, while in the other parts of the district the main drivers of market participation have been scarcity and policy changes.
Keywords: water markets, market adoption, market participation, Australia.

1 Introduction

Water markets have been promoted by economists as a preferred instrument to reallocate scarce water resources within a mature water economy since the 1960s and 1970s. It was not until the early 1990s, however, that policy makers began in

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earnest to promote markets as a preferred mechanism to reallocate water between competing users within arid and semi arid regions. Globally, water markets and other economic instruments were brought to the fore at the Earth Summit in 1992 and were embedded in the two key policy documents; the Rio Convention and Agenda 21. Since then, the use of market instruments has formed part of the water polices of international organizations such as in the World Bank as well as being promoted in by the OECD and FAO. Market instruments were part of a wider policy paradigm shift which included increased public participation in water planning and management, privatization of the water industry and a growing recognition of the environment as a legitimate water user.

Driven by significant environmental problems within its major water resource, the Murray-Darling Basin (the Basin), Australia has in many ways been at the forefront in implementing the new policy paradigm. In 1994, the Council of Australian Governments (CoAG) introduced a new Water Policy Reform Agenda embracing all elements of the new policy paradigm and in 2004 CoAG went further by launching a new National Water Initiative. Water markets are central in these and other associated documents related to the management of the Basin. Markets are seen as the main instrument by which water users can manage the process of reducing water extraction to provide adequate water for the environment and simultaneously secure a sustainable irrigation industry and thereby maintain a viable rural community. One of the main drivers of the new National Water Initiative was the need to provide improved market mechanisms to better achieve these objectives. Markets have therefore developed quite significantly in the three main states of the Basin since the early 1990s. Within Australia's largest irrigation district, the Goulburn-Murray Irrigation District (GMID), water markets have now formally been in operation for 14 years. It is therefore possible to make meaningful analyses of how this market has been adopted by irrigators, how the market participation rate of farm businesses has increased and identify the factors which have influenced this increase. These experiences should be valuable for policy makers and water managers in other parts of the world contemplating to introduce water markets. This paper is based on analyses of entitlement and trading registers of the GMID. The second part describes aspects of the GMID which are expected to determine the extent to which water markets are likely to be adopted. The third part provides an overview of the data sources used, while the remaining parts discuss the findings of the research.

2 Goulburn-Murray Irrigation District

There are three main factors which could be expected to influence farm businesses willingness to use water markets: 1) more productive and higher valued water users on more suitable soils buying water from less productive and lower value users are likely to present mutually beneficial tradeoffs; 2) as trading restrictions are eased and more potential buyers and sellers are capable of making mutually beneficial tradeoffs and therefore more trading should take place; and 3) as supply is restricted due to increased scarcity either created by drought or policy changes the need to use the market should increase as water users try to manage the impact of these changes. This section will discuss the extent to which these factors exist within the GMID.

The GMID consists of a number of districts, which are supplied by two main systems – the Goulburn and the Murray System (figure 1). Goulburn-Murray Water (GMW) administers the districts as well as the diversion licenses along the rivers within the district. The farm businesses fall within the following groups (figure 1):

- Almost 45% of farm businesses are within the eastern part of the Goulburn System which is dominated by dairy farms and some horticulture. This part has little soil degradation or salinity problems.
- About 5% of the farm businesses are located within the western part of the Goulburn System which is dominated by broad acre cropping, grazing and mixed farming. This part has large areas with poor and salt infected soils. Water entitlements within this area are much larger than within the other areas (table 1).

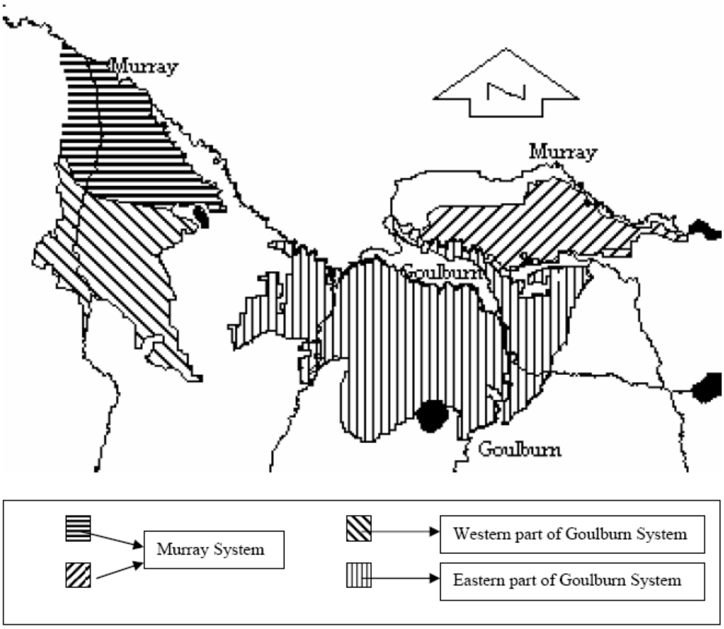

Figure 1: The Goulburn-Murray Irrigation District.

- 17.3% of all farm businesses base their irrigation on diversion licenses; that is they take water from the rivers using their own pumps and divert the water to their field using their own infrastructure. Traditionally these farm businesses have smaller entitlements (table 1) and less intensive irrigation and many had not developed their irrigation in full or part at the time trade between district irrigators and river diverters was introduced. There are also more non-commercial farmers in this category.

- Almost a third of the farm businesses are located within the Murray System. This system has two parts: a) the Murray Valley in the east, which is dominated by dairy production; and b) the western part, which have large sections in broad acre cropping and mixed grazing, with some areas having serious salinity problems. There are pockets with dairy production and new high value farms. The Murray System has in more recent history experienced considerably higher levels of seasonal allocations than the Goulburn System (table 2).

Table 1: Distribution size of entitlement.

	All farm business	Goulburn West	Goulburn East	Murray	Diverters
10 ML or less	12.60	3.60	13.00	10.30	18.80
11 to 50 ML	24.60	7.70	24.50	21.80	32.10
51 to 150 ML	24.40	12.40	25.90	22.70	26.60
151 to 300 ML	19.50	27.40	19.00	23.00	14.00
301 ML or more	18.90	48.90	17.60	22.30	8.50

The figures in the Table show the percentage of farm businesses within each category

Table 2: Allocation levels Goulburn and Murray Systems.

	Goulburn System		Murray System	
	Allocation	Opening allocation	Allocation	Opening allocations
1991/92	200	180	200	200
1992/93	200+	140	200+	180
1993/94	200+	200	200+	200
1994/95	200+	200	200+	200
1995/96	150	150	200	150
1996/97	200	200	200	200
1997/98	120	120	130	130
1998/99	100	40	200	95
1999/00	100	35	190	100
2000/01	100	48	200	200
2001/02	100	55	200	200
2002/03	57	34	129	129
2003/04	100	18	100	100

The development of market policies and the easing of trading restrictions have been incremental. Initially trading was restricted in order to alleviate community concern over the impact of trading. As irrigators became more familiar with the market and saw the potential benefits of trading, and as the need for trading increased due to reduced supply these restrictions were eased as follows:

- Trade both in entitlements and allocations were formally introduced by the Water Act 1989, while allocation trading was trialled within some districts in 1987.
- Trade in entitlements was not implemented until the regulations controlling this trade were introduced in 1991. Restrictions on trade were as follows: 1) no trade was allowed between district irrigators and river diverters; 2) only internal trade was allowed within the western part of the Murray System; 3) no trade was allowed within the eastern part of the Murray System; 4) within the western part of the Goulburn System internal trade was allowed and trade could take place from the western to the eastern part; and 5) water could, with only one limitation, be freely traded within the eastern part of the Goulburn System.
- In 1994 new regulations eased restrictions by allowing trading: 1) between district irrigators and river diverters; and 2) from the GMID and downstream into Sunraysia. This was expected to drive trade in that direction due to demand from horticulture and viticulture. The first transfers under this rule did not take place until 1997 when demand from new vineyards escalated.
- In 1995 restrictions were eased again allowing trade: 1) within the eastern part of the Murray System and from the eastern to the western part; 2) between the eastern and western parts of the Goulburn System; 3) from the Goulburn System to the Murray System; 4) in water allocations between states; and 5) in ‘sales’ water for district irrigators (Irrigators have two different entitlements. The entitlement itself is expected to be delivered in full 96 out of 100 years. In addition to their entitlement, users get additional water called ‘sales’ when reservoirs hold more water than what is needed for this and the following season.
- In 1997 restrictions were eased again by: 1) allowing interstate trading in entitlements; 2) restricting trade in ‘sales’ water to 30%; and 3) allowing trade from the Murray System upstream into the Goulburn System in substitution for downstream trade. This rule was implemented for the first time in January 2001;
- In 1998 the Northern Victoria Water Exchange was introduced providing fast, cheap and secure trading in allocations.

Two other policy issues combined with climatic conditions have also had an impact on water supply and supply risk within the GMID. In 1996 The Murray-Darling Basin Commission (MDBC) placed a cap on water extraction for consumptive use. According to this Cap no state can divert more water from the Basin in any given year than it would have done given the same climatic conditions at the 1993/94 level of development. Victoria’s main tool to stay within the Cap was to reduce ‘sales’. The introduction of the cap as well as an extended period of drought, has been contributing factors to lower allocations since 1997 (table 2). In 1998 GMW changed its allocation policy. Historically GMW announced allocations at the beginning of the season based on what was available in the reservoirs and expected inflows based on historical records. This provided certainty of supply for irrigators before planting and thereby committing to a certain level of water use. From 1998 GMW only incorporated minimum expectations to inflows during the seasons when announcing opening allocations. This has resulted in much lower opening allocations (table 2), thereby transferring the risk of supply uncertainty from GMW to the irrigators.

3 Data and methods

This paper is based on an analysis of the entitlement register as of 30 June 2004, as well as the trading registers for the first thirteen years of water trading within the GMID. Increases in water trading based on volume traded have previously been reported in papers such as [1, 2] but an analysis of the extend to which farm businesses have adopted water trading has not previously been carried out. To facilitate the most meaningful analysis, water entitlements were first consolidated into farm businesses. This was done by sorting the entitlement register by surname and address, and then consolidating all entitlements in the same ownership into one farm business. This process reduced the original number of 17,125 service numbers to 14,384 farm businesses. Next, farm businesses without a tradable water entitlement were eliminated reducing the number of farm businesses to 10,011. Trading registers were then merged with the entitlement register to analyze the trading pattern of each farm business for each of the thirteen years.

4 The uptake of trade over the last 13 years

This section analyses how big a proportion of farm businesses was active in water markets during each of the last 13 years. During the first three years only 3-4% of all farm businesses were selling or buying allocations (fig. 2). The use of the allocation market increased significantly to involve about 20% in 1994/95 when trade between district irrigators and river diverters, interstate trade in allocations and trade in ‘sales’ was introduced. The participation rate increased again in 1997/98 due to the low allocation that season and some further easing of trade restrictions (table 2). For the next three seasons, when allocations within the Goulburn System only reached 100% and opening allocations were very low, the participation rate remained steady at about 15%. During the following two seasons the participation rate increased sharply as the drought continued and the allocation in the Goulburn System was reduced to 57% and 129% in the Murray System in 2002/03 and to 100% in the Murray System in 2003/04. It can be noted that the new Water Exchange was in place from 1998/99, ready to deal with the substantial increase in trading activity.

Until 1998/99 approximately the same proportion of farm businesses participated in buying and selling allocations. Since then, more farm businesses have been involved in selling than buying allocations. During the most water scarce season of 2002/03 almost 45% of all farm businesses sold while only about 28% bought allocations. During 2003/04 the proportion selling fell back to 35% while the proportion buying continued to increase to 30%. The sharper increase in the proportion of selling farm businesses is caused by at least three factors: 1) the introduction of interstate trade in allocations; 2) the start of trading into Sunraysia; and 3) the change to allocation announcements introduced in 1998/99. The last change has caused some irrigators to buy water early in the season when opening allocations are low. If allocations then increased more than expected they ended up with excess allocations which they then sold. This trading pattern is also reflected in the increase in the number of farm businesses which have both bought and sold allocations during the season (note that the farm businesses which have both bought and sold allocations during the seasons are also included in the graphs for buying and selling).

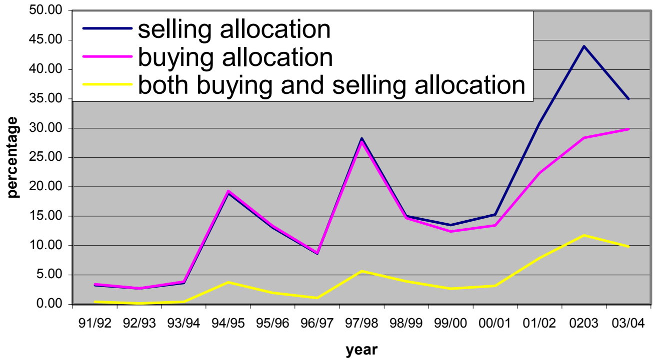

Figure 2: Percentage of farm businesses buying and selling allocations.

Figure 3 shows that the percentage of farm businesses in the market for entitlements increased from an initial 0.5% to between 1% and 1.5% buying and selling entitlements in 1994/95 when trade between river diverters and district irrigators were made possible and district irrigators purchased unused diversion entitlements at low prices [3]. Involvements in trade in entitlements increased further during 1996/97 and 1997/98 to just under 2% as a consequence of the easing of trade restrictions within both the Murray and the Goulburn Systems, the introduction of interstate trade in entitlements, and the commencement of downstream trade to the expanding wine industry. Since 1997/98 more farm businesses have been selling than buying, as a lot of water was sold to the Sunraysia region where the expansion in the wine industry was driving prices up (the buyers in this situation were located outside the GMID and therefore not included in figure 3). As the boom in the wine industry slowed, trade in entitlements declined again during the following years. As the drought intensified after 2000/01 the participation rate increased to 2.6% selling and fewer than 2% buying entitlements. This period also saw a substantial increase in allocation prices, many irrigators therefore felt that it was too uncertain and expensive to buy allocations and therefore increased their entitlement. At least part of the high level of selling has been caused by farm businesses within the GMID being more or less squeezed out of business due to increased water scarcity and high water prices as well as subsidies offered to exit the dairy industry.

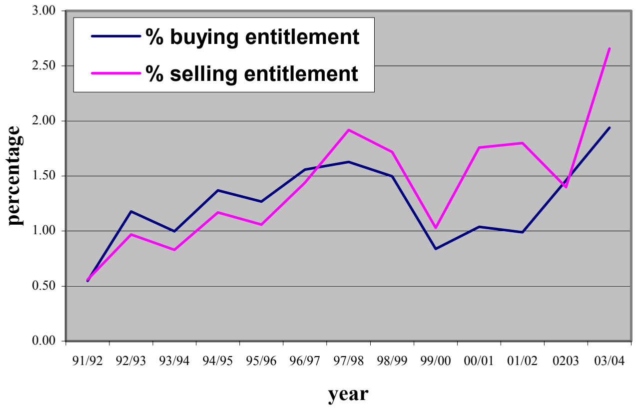

Figure 3: Percentage of farm businesses buying and selling entitlements.

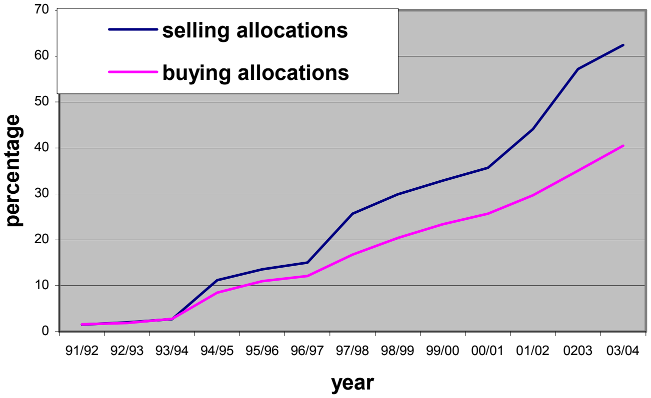

Figure 4: Accumulated percentage of farm businesses that have traded in allocations.

5 Market adoption within the GMID

This section analyses how new farm businesses have entered the market during the thirteen year period. Figure 4 shows the accumulated participation rate; that is, at the end of each season what percentage of farm businesses had then bought or sold allocations. The figure shows the same jumps in market participation in 1994/95, 1997/98 and 2002/03 as discussed above. It can be noted that the jumps are most significant among farm businesses entering the market to sell allocations and this gap has continued to grow since 1997/98. This pattern is likely to be caused by a number of factors including:

- An increasing number of smaller entitlement holders are selling to a few buyers using a number of small purchases to satisfy their needs. This is especially likely to be the case in 1994/95 when more private diverters entered the market, as they have smaller entitlements (table 1);
- very high allocation prices during 2002/03 made it worthwhile for smaller entitlement holders to sell their low volume of allocations;
- the start of downstream trade into Sunraysia in 1997/98 caused many farm businesses to sell water into this area. In such trades the buyers are outside the GMID and therefore not included in figure 4;
- The start of the Exchange in 1998/99 facilitating easy and cheap transfers encouraging smaller entitlement holder to trade; and,
- the change to allocations policy 1998 as previously discussed.

The increase in the participation rate in buying allocations has been consistently increasing as a result of a growing awareness of the benefits of buying and the increased need to buy water to keep the business going, during drought and policy induced scarcity.

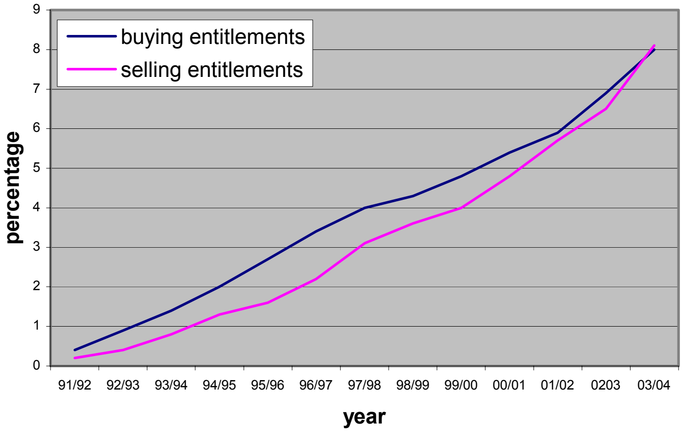

Figure 5: Accumulated percentage of farm businesses that have traded in entitlements.

Figure 5 shows the increase in the participation rate in the market for entitlements. The increase in farm businesses buying entitlements during the early years was higher than for selling entitlements. However by the end of the period the same proportion of 8% of farm businesses had bought and sold water entitlements. This development is caused by the fact that some early sellers of water entitlements sold all their water and therefore did not have any entitlement as of 30 June 2004 and therefore are not included in figure 4. That the market participation rate for selling entitlements by 2004 still approached 8%, as for buyers, is caused by the fact that many sellers since 1997 have sold water to the Sunraysia region.

6 Variation in market adoption

This section analysis the variation in adoption of water trading across the GMID. Figure 6 shows the proportion of farm businesses that participated in any kind of water trading each year within the different categories. The figure shows that until 2002/03 the participation rate was generally much higher within the Goulburn System than within the Murray System because of the higher level of allocations within the latter system (table 2). Figure 6 shows that:

- within the Goulburn System the participation rate was initially much higher within the western part with large segments of poor and saline soils as well as high levels of water use for grazing and mixed farming. This provided opportunities for mutually beneficial tradeoffs, when these farm businesses traded with higher value users on more productive soils predominantly within the eastern part; something that was made possible in 1995. The participation rate within the eastern part slowly reached the same level by 2000/01 driven by increased scarcity rather than potential tradeoffs;

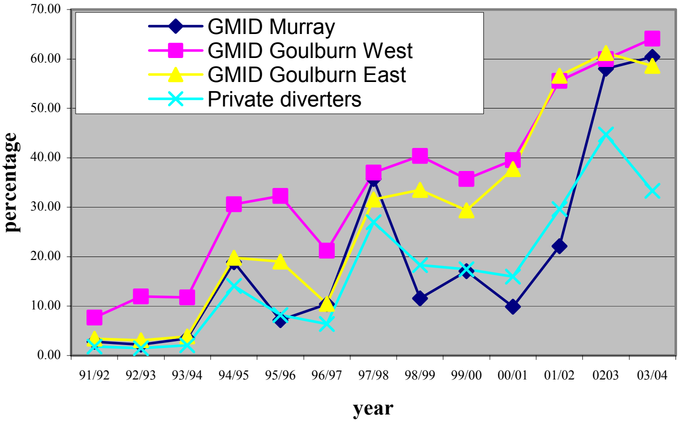

Figure 6: Percentage of farm businesses trading annually.

- the participation rate within the Murray System shows clear evidence of the impact of water scarcity. When allocations are at 200% or more, the level of market activity is markedly lower within this system. However, when the allocation drops down to 130% or 100% the activity level is similar to that within the Goulburn System. This is clearly evident during the seasons of 1997/98, 2002/03 and 2003/04 (table 2). It can also be noted that the participation rate during 2002/03 is almost the same within the two systems despite the fact that the allocation in the Goulburn System was 57% compared to 129% within the Murray System. This suggests that the preceding five year period of 100% allocations in the Goulburn System has caused some farm businesses to make long-term adjustments to reduce their need for seasonal trading while many farm businesses in the Murray System have not been forced to do so. Reflecting this, when allocations in the Murray System dropped to 100% for the first time during 2003/04 the participation rate within that system was higher than within the eastern part of the Goulburn System; and,

- private diverters trade far less than district irrigators but with peaks in 1994/95, 1997/98 and 2002/03. The removal of trading restrictions between district irrigators and river diverters caused the first peak, the start of downstream trade into the Sunraysia region and low allocations during 1997/98 caused the second peak, while the third peak was caused by very high water prices during 2002/03 encouraging the smaller entitlement holder to sell. The lower participation rate among river diverters is also likely to be caused by the smaller entitlements held by these irrigators (table 1) and therefore a lower potential gain from trade. Relating entitlement size to market participation show a direct relationship between entitlement size and market activity. During 2002/03, 80% of all farm businesses with more than 300 ML of entitlement traded compared to only 20% of those with 10 ML or less [4].

Figure 7 shows the accumulated participation rate – that is the proportion of farm businesses that had participated in any kind of water trading at the end of each irrigation season since 1991. It can be seen that:

- the initial increase in the uptake of trade was relatively slow, with very few new farm businesses entering the market during the second and third year except within the western part of the Goulburn System. During this period irrigators slowly became familiar with trading, and high allocation levels reduced the need for trading;
- there was a high number of new entrants into the market during 1994/95 despite continued high allocations, as river diverters sold unused water following the introduction of trade between river diverters and district irrigators in 1994;

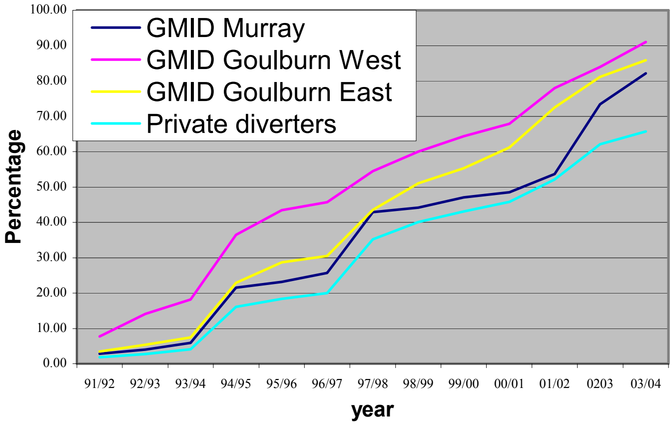

Figure 7: Accumulated % of farm businesses which have traded in water.

- the Goulburn System again saw a jump in new entrants in 1995/96 driven by a number of factors: 1) allocations dropped to 150%; 2) spatial restrictions on trade were eased; and 3) trade in sales water and interstate trade in allocations was introduced;
- the Murray System did not see many new farm businesses entering the market during the 1995 to 1997 period as allocations remained at 200% (table 2);
- all districts experienced a significant increase in new entrants during 1997/98 as allocation levels dropped to 120% and 130% respectively (table 2) and trade into Sunraysia started to take effect;
- within the Murray System the rate of new traders then slowed down again during the next four seasons as allocations returned to 200%;
- within both parts of the Goulburn System the rate of new entrants continued to increase as allocations declined to 100% and stayed there for the four seasons;
- the participation rate during this period increased sharply in the eastern part of the Goulburn System where new entrants were driven more by scarcity than the potential for beneficial tradeoffs, which caused early entrants in the western part;
- during this period the gap in the accumulated participation rate within the two parts narrowed; and,
- new entrants flooded into the market in the Murray System during 2002/03 and 2003/04 when allocations there declined to 129% and 100% respectively (table 2). The participation rate was then close to the levels within the Goulburn System with 82-92% of farm businesses having some market experience.

7 Conclusions

This paper has analyzed farm businesses use and adoption of water markets within the Goulburn-Murray Irrigation District in Northern Victoria, Australia during the first 13 years of water trading. The use of water markets was first adopted within the part of the district with the largest potential tradeoffs between high and low value producers and between irrigators with productive and unproductive soils. The adoption of water trading within the other parts of the GMID has been driven by increased scarcity induced both by drought and policy changes and made possible by successive easing of trading restrictions and the emergence of a water exchange. By 2004 about 85% of all farm businesses have had some exposure to water markets and during 2003/04, 60% of all farm businesses were trading in water. Larger irrigators have been far more active that small irrigators, with as many as 80% of the larger irrigators trading compared to 20% of the smallest irrigators.

Acknowledgements

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Irrigated agriculture and the environment in the Tarim River watershed: case study of the Shaya irrigation district in the Ugen River basin

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Abstract

Irrigation in arid regions like the Tarim River watershed causes salinization and influences the regional environment. In this paper, problems between agricultural wateruse and environmental conservation are discussed by real conditions of the water resource utilities. The investigated area is the Xayar irrigated district in the Ugen River basin, one of branches of the Tarim River. The results confirmed by investigation are as follows: 1. The present conditions of irrigated agriculture have various contradictions and there are many points of improvement for conservation of the regional environment. 2. Water saving is necessary in the overall irrigation system for agricultural development. 3. Irrigated agriculture must be consolidated with the drainage system for the prevention of salinization and desertification.
Keywords: salinization, winter irrigation, arid area, Tarim River.

1 Introduction

The Tarim River, which flows south of the Tian Shan Mountains, is the longest inland waterway in China. Its main stream length is 1321 km. The irrigated area in the Tarim Basin measures 1.6 million hectares. Cotton and fruits are produced in this area. Land reclamation has caused an increase in irrigation water intake from the Tarim River, which has caused the river's discharge to markedly decrease.

This decrease has caused ecological damage at the middle and lower reaches, particularly at the lower reaches. For example, 94% of the Yingsu region, at the

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lower reaches of the Tarim River, has become desertified, and the Kumtag and Taklamakan deserts are starting to merge. This desertification has forced inhabitants to relocate, and abandoned villages dot the lower reaches of the basin. Some regions in the Tarim River basin began using large amounts of irrigation water in the 1960's, when large-scale development of irrigation channels was conducted, but there was no construction of proper drainage. The groundwater level of much agricultural land rose rapidly, and salt accumulation has occurred in about 80% of the irrigated area.

Agricultural use accounts for 90% of the water supply. Regional environmental conservation requires a reconsideration of agricultural water use. This paper examines the relationship between agricultural water management and the regional environment in an arid area by understanding agricultural water use in the Xayar Irrigation District of the Ugen River basin. (The Ugen River flows into the Tarim River at the middle reaches of that river.)

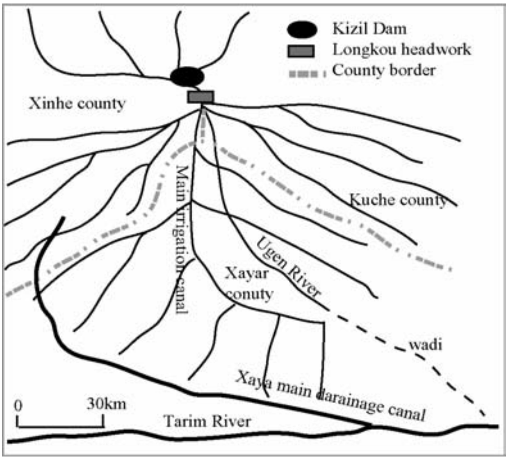

Figure 1: Outline of Ugen River basin.

2 Study area and method

2.1 Study area

The Ugen River is a branch on the Tarim River, and it flows from the Tian Shan Mountains. Kizil Dam was constructed where the mountains meet the plains. The Longkou headworks, downstream of this dam, distribute water for irrigation in the Ugen River Irrigation District. The district is in eastern Akesu Prefecture and borders the Tarim Basin to the south, the Tian Shan Mountains to the north, farmland of the Xinjiang Production and Construction Corps to the west, and Bugur County of Bayin'gholin Mongol Autonomous Prefecture to the east. The land slopes from northwest to southeast at a gradient of 1/400 to 1/4000. The climate classification of the irrigation district is arid (BWk); the annual mean temperature is 11.4 °C. The annual temperature range is great, with a maximum of 46.5 °C and a minimum of -27.4 °C. Annual rainfall is 67.3 mm, and the potential evaporation is 2,131 mm.

The Ugen River Irrigation District has three counties: Xayar, Kuche and Xinhe.

2.2 Materials and methods

The investigation area is the Xayar Irrigation District in the Ugen River basin. The district has 8 townships. The irrigation area has increased to 70,000 ha in 2003 from 20,000 in 1949. The main crops are wheat, corn, cotton and fruits. Table 1 breaks down the cultivated areas of these crops.

Most of the data on water use and management were provided by the Xayar Water Resource Agency. Field surveys and interviews with representative of the branch offices of the agency were conducted from 2003 to 2005.

Table 1: Crops and water supply demand [2].

kinds	wheat	corn	cotton	cauliflower	fruits	alfalfa	others	total
Nurbac township	733.3	666.7	2060.0	33.3	703.3	600.0	320.0	5117
Gurbac township	1733.3	1333.3	5000.0	33.3	1116.7	563.3	310.0	10090
Toibow town	3333.3	3000.0	8066.7	133.3	1600.0	650.0	410.0	17193
Honqi town	2333.3	2000.0	2333.3	166.7	1366.7	700.0	260.0	9160
Igimeri town	2666.7	2666.7	4553.3	180.0	1350.0	210.0	305.0	11932
Kairou town	1933.3	1933.3	4955.3	113.3	1316.7	310.0	290.0	10852
Xayar town	133.3	66.7	280.0	6.7	146.7	100.0	276.0	1009
New cultivated farm	266.7	133.3	3186.7	0.0	200.0	200.0	129.0	4116
total (ha)	13133.3	11800.0	30435.3	666.7	7800.0	3333.3	2300.0	69469
Planning irrigation water supply (mm)	540	390	540	465	435	345	480	
Irrigation water demand (million	71	46	164	3	34	12	11	341

3 Results

3.1 Water resources

The average of annual discharge of the Ugen River is 2280 million m^3/y, and the average discharge is 72.3 ton/s. The Ugen River takes its water from snowmelt and glacier melt of the Tian Shan Mountains. Much of the water in this river is meltwater from snow and glaciers, which means that the water discharge is greatest in summer. Figure 2 shows the average monthly discharge at the Kizil gauging station from 1954 to 1998. The discharge from June to September accounts for 60% of the annual discharge, and there is less discharge during spring. Spring discharge is so low that the water for sowing is limited. Kizil Dam, at the upper reaches of the Ugen River, reserves 644 million tons for water supply in the dry season.

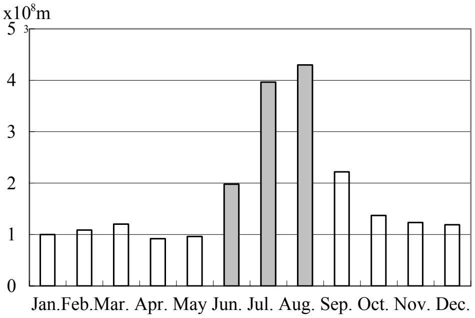

Figure 2: The average monthly discharge at Kizil water management office from 1954 to 1998 by using hydrological data of Xayar water management bureau [3].

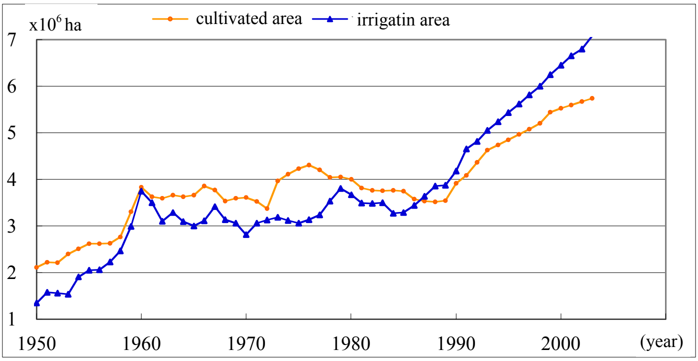

Figure 3: Change of cultivated area and irrigation area in Xayar by using hydrological data of Xinjiang water management bureau [4].

3.2 Development in Xayar County

Before 1949, cultivated land in Xayar county was generally owned by the landed gentry. The owner farmers practiced small-scale agriculture, and the tenant farmers practiced even smaller-scale agriculture. Large-scale irrigation facilities were not constructed by farmers because of their limited finances. Therefore, the cultivated area in Xayar did not expand much. Most farmers engaged in stock farming as a side job. From 1949, the Chinese social system changed completely and the People’s Commune system of collectivized agriculture began. In the 50 years since then, the area of cultivated land has undergone dramatic increase three times, in line with social changes and their accompanying changes in agricultural policy.

In the 1950’s, under the People’s Commune and the Great Leap Forward, large areas of grassland were converted into cultivated land [4]. Much cultivated land was developed in the 1970's, during the Cultural Revolution. In the 1980's the introduction of price supports for cash crops (e.g., cotton) and a contract work system encouraged farmers to produce crops. Land reclamation accelerated. Double cropping increased the demand for water, which promoted the expansion of irrigation.

3.3 Development of water resources

Irrigation is the most important factor for agriculture in an arid area. Most of the irrigated land in Xayar county went through four states of irrigation:

3.3.1 Irrigation using river water

All cultivated fields in the alluvial fan were irrigated with Ugen River water. Often in the past, the agricultural water rights for each community were managed by a community or community alliances. In practice, the rights were exercised by landholders or middle-class farmers. In times of drought, conflicts arose over agricultural water and these sometimes developed into armed conflicts between communities.

3.3.2 Irrigation using reservoir water

Before 1949, agriculture in Xayar county depended on river water flow. The water resources were developed largely after the People's Commune was established [5]. Nineteen reservoirs for irrigation water in Xayar county were constructed between 1958 and 1970. These reservoirs can hold 80 million m^3. Only two of these reservoirs were usable, because they were constructed by professional engineers. The 17 others were abandoned because of leakage or salinization of the surrounding farmland [4].

3.3.3 Irrigation using well water

Irrigation using well water: The socioeconomic changes resulted in increased water demand. Many farmers did not have enough irrigation water from rivers and reservoirs for their expanded farmland. By 1990, more than 1000 wells had been dug using state funds, but the costs of maintaining and operating those wells are too high, and the water quality is low. Farmers have not aggressively used well water.

3.3.4 Irrigation from the multipurpose dam

Twenty percent of the Ugen River's annual discharge is stored in Kizil Dam, a multipurpose dam constructed at the upper reaches of the river in 1991. As result of that construction, the irrigated area in Xayar county greatly expanded.

3.4 Improvement of irrigation and drainage

The irrigation water is supplied from the Longkou headworks to the Xayar Main Irrigation Canal (length: 50 km). The water is delivered using a five-step canal irrigation system (Table 2).

The Xayar Main Irrigation Canal has 10 diversion gates. The design discharge is 60 m^3/s at the uppermost gate and 30 m^3/s at the lowermost gate. The irrigation area is 70 thousand ha. The outflow to the Xayar district is 740 million m^3 per year, which accounts for 32.5% of the annual average discharge of the Ugen River. Four percent of the irrigation canal length is unlined. The water supply efficiency is only 40%. Drainage canals have been dug since 1966, the decade when irrigation canal improvements were launched. The drainage canal system consists of three types of drainage canal: the Xayar Main Drainage Canal, three secondary canals, and nine tertiary canals. The Xayar Main Drainage Canal extends 84 km, from northern Xayar to the Tarim River. However, the government and farmers have no incentive to develop farmland drainage. There are few ditches connected with tertiary drainage canals. The drainage system seems to be inadequate.

3.5 Water management system

Water distribution from the Longkou headwork was decided by agreement between three counties in the Ugen River Irrigation District. From those consultations, 32.5% of the water was been allotted to the Xayar Irrigation District. The Xayar Water Management Office manages this water and distributes it to its eight branch offices. Distribution is proportional to farmland area. Each branch office controls irrigation facilities, distributes irrigation water to farmland, confirms the irrigated area, records amount of irrigation water and collects water fees.

Table 2: Types of irrigation canal.

irrigation canal types	count	discharge (m^3/s)	total canal length (km)	total lining canal length (km)	ratio of lininng
main canal	1	60<30	50.5	33.5	66.3
first branch canals	25	1 ~ 7	471.4	82.2	17.4
second branch canals	79	1 ~ 5	589.6	31.2	5.3
third branch canals	402	1 ≤	1316.0	0.0	0
farm ditches	unknown		1142.0	0.0	0
total			3569.5	146.9	4.1

3.6 Irrigation methods

In the Xayar district, the water management offices supply irrigation water twice a year: once in the warm season (Apr. to Sep.), and once in the winter season (Nov. to Feb.). Warm-season irrigation aims at crop growth. The purpose of winter irrigation is to increase soil moisture content in the field even in the cold season.

Irrigation is by border method, whose efficiency is low. From late 1990's, wide levees were narrowed and long levees were shortened. The present standard lot size is 60 m x 40 m. But due to a lack of interest in water conservation, farmers often over-irrigate to the point of flooding their fields.

The water supply efficiency is only 40%, which means that only 296 million m^3 of irrigation water reaches farmlands. There is a 45-million-m^3 shortage of irrigation water, because demand is 341 million m^3 in this irrigation district. Cotton production per unit area in the district is nearly 30% less than on farmland of the Xinjiang Production and Construction Corps, whose water supply meets the demand. This means lack of water is a barrier to growth. As a remedy, it is necessary to increase the efficiency of irrigation by improving irrigation methods, and to increase the water supply efficiency.

4 Discussion: problems in irrigation and drainage systems

4.1 Irrigation and the regional environment

Border irrigation was introduced to farmlands in the district. The groundwater level has risen due to poor drainage. Because the discharge of the Ugen River is low in the sowing period of early spring, a unique irrigation method (winter irrigation) has been introduced to keep supplying water in the post-harvest period. Drainage has not been systematically developed, even though the reclaimed land is at a low elevation. The construction of drainage canals did not start until salinization occurred. This is careless planning and management.

The area of land that underwent salinization expanded rapidly due to rises in groundwater level and the absence of a functional drainage system. Water waste seems to promote desertification. Many farmlands have been abandoned. For example, 10% of reclaimed farmland has been abandoned in Nurbac Township of Xayar County. Not only has such irrigation caused farmland salinization, it has also raised the salinity of the drainage water. This drainage water has adversely affected the environment of the Ugen and Tarim rivers.

4.2 Problems of water management

4.2.1 Water management organization

The Xayar District Water Management Office is under the control of the Xayar County government. The office's budget comes from general operating expenditures of the county government. The government's annual revenue increases with increases in the sale of water. But this means that government revenue decreases if conservation results in an unsaleable surplus of water. The management office has less incentive to conserve water, because the government guarantees its finances.

4.2.2 Water fee

Water fees vary from one area to another. Each irrigation block is managed by several farmers. The water fees are calculated by dividing the irrigation volume supplied to each irrigation block by the area of farmland owned by each farmer. A farmer cannot save on water fees by conservation unless all farmers in that block conserve water. As result, many farmers have no incentive to conserve water.

4.2.3 Political flaws in the development of water resources and in land reclamation

Water resource development and land reclamation should be integrated. But the water management office, incomprehensibly, has no jurisdiction over land reclamation. Therefore, the expansion of farmland and tenant farmland has exceeded the water supply. Since the office supplies a fixed volume of water to each farmland, some farmers have suffered from water shortages.

4.2.4 Farmer cooperation for water management

Controlling the irrigation system requires cooperation between farmers. Cooperation in the maintenance of irrigation canals can foster in farmers a sense of community and responsible water management. In government-led, large-scale irrigation, the water supply and distribution depend on the decisions of water management offices. Therefore, no sense of community is fostered in farmers.

4.3 Sustainable irrigated agriculture

The establishment of appropriate irrigation methods and a drainage method for control of the groundwater level are significant issues in preventing salinization. Some farmers understand the importance of water-saving irrigation. However, capital investment in water-saving irrigation by the farmers themselves seems difficult at this time. There are several water-saving irrigation systems that have been introduced using state funds; however, some have not been used efficiently by farmers due to their lack of skill and facilities. In the light of this, state funds must be supplemented by improvement of farmers' skills in water-saving irrigation. It is expected that development of farmland drainage and improvement of water supply efficiency will avoid groundwater lowering and water salinization. The winter flood irrigation that is unique to this area has the potential to accelerate groundwater salinization. Suitable irrigation methods need to be determined, including winter flood irrigation.

5 Conclusion

In arid areas where water resources are insufficient, water for expanded agricultural production – that is, expansion of the irrigated area – must be secured by water-saving irrigation. Toward this, the principles of agricultural water use must be understood by users and managers. Concretely, the principle means reducing water loss by ensuring appropriate control, building water-saving incentives into the water supply system, and reducing water waste by rational water management.

Additionally, it must be realized that developing and promoting farmland-level water-saving irrigation and educating farmers about it is necessary. Furthermore, it is necessary for regions where the main industry is irrigation agriculture to promote socioeconomic development and to comprehensively review and improve irrigation systems, water supply administrations, and a production structure that has various contradictions.

Regional environmental conservation is only secured by maintaining sustainable irrigated agriculture in this region. Irrigation that does not exceed the Environmental Carrying Capacity must be sought.

Acknowledgments

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Energy revenue in irrigation systems: a case study

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Abstract

Irrigation systems are generally characterized by a greater discharge than that which usually flows in drinking water supply systems. Moreover, they are supplied in limited periods of the year (irrigation periods) and sometimes a pump station with a high level of energy consumption could be needed. Therefore, when the geodetic heads are relevant it is possible to produce hydroelectric energy from these systems. Through the application on a real case study, i.e. an irrigation system managed by Consorzio Valle del Liri in Southern Italy, a simple optimization method of the system efficiency is herein illustrated. This work results in a feasibility study of the investigated system, leading to increasing social and environmental benefits.
Keywords: irrigation systems, energy revenue, hydroelectric plants, sustainable development.

1 Introduction

The diversification and the environmental sustainability of the energy production represent a fundamental aspect for the social and economic development of modern society. The need to reduce the strong dependence by oil and coal represents a new and hard challenge for the future: the economical costs to buy raw materials and the environmental costs that follow the energetic provisioning by traditional techniques clash both with the sustainable development idea and need of lower manufacturing costs. For this reason the new European laws go to liberalization of the energy production market with economical incentives to new private producers. In this context the energy revenue could have an important

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role as done by existing systems at lower initial investment cost (Celentani and de Marinis [1]). The Italian laws allow energy production by private companies but the distribution must be made only by GRTN (*Gestore della Rete di Trasmissione Nazionale* – Government controlled company which has the monopoly of the electric energy transmission in Italy). Moreover the government gives further economic incentive to private producers for the initial eight years as shown in the following table [2–6]:

Table 1: Amount of economic incentives to private energy producers.

	Production range [kWh / year]	GRTN	Incentive	Total (0-8 years)	Total (> 8 years)
		€ / kWh	€ / kWh	€ / kWh	€ / kWh
1	0 – 500000	0.09565	0.09739	0.19304	0.09565
2	500000 – 1000000	0.08054	0.09739	0.17793	0.08054
3	> 1000000	0.07048	0.09739	0.16787	0.07048

1.1 The opportunity represented by irrigation systems

Irrigation systems are usually characterized by great discharge during limited periods of the year (irrigation periods) commonly shorter than inactivity periods: in Italian regions the irrigation periods go usually since May to September. Conversely, if high discharge is a common peculiarity for all irrigation systems, the geodetic heads can change from case to case. In fact this aspect depends on different reasons, like the distance between the source and farthest network sites, the geodetic head difference between these sites and, in general way, the orography of irrigated lands. Therefore only where geodetic head is sufficient the hydroelectric energy production becomes an interesting opportunity.

Under these assumptions it is possible to convert the normal network operation from an energy consuming system to a hydroelectric energy producing system, utilizing the main pipes to carry the water from the highest points of the network to the lowest ones. Sometimes this system modification implies an inverse working of the network without excessive costs as shown in the present paper in reference to a real-life case study.

2 Irrigation system description

The irrigation network presented here is part of a whole irrigation system managed by Consorzio di Bonifica Valle del Liri. It is located in Lazio region (southern Italy) and it comprises among the towns of Cassino, Piedimonte San Germano, Aquino, Castrocielo and Pontecorvo. The served area is about 100 km^2. The system includes 637 km of pipes and it is divided in two different parts. The first part is composed of two interconnected lots indicated with letter A and B in Figure 1, while the second part, unconnected with the former, is indicated with the letter C in Figure 1.

In Figure 2 is shown the working scheme of the irrigation system using the same numeration as the hydraulic elements in Figure 1. The characteristic data of the reservoirs, tanks and natural sources and the characteristics of the main pipes of the network are reported in Table 2 and Table 3, respectively.

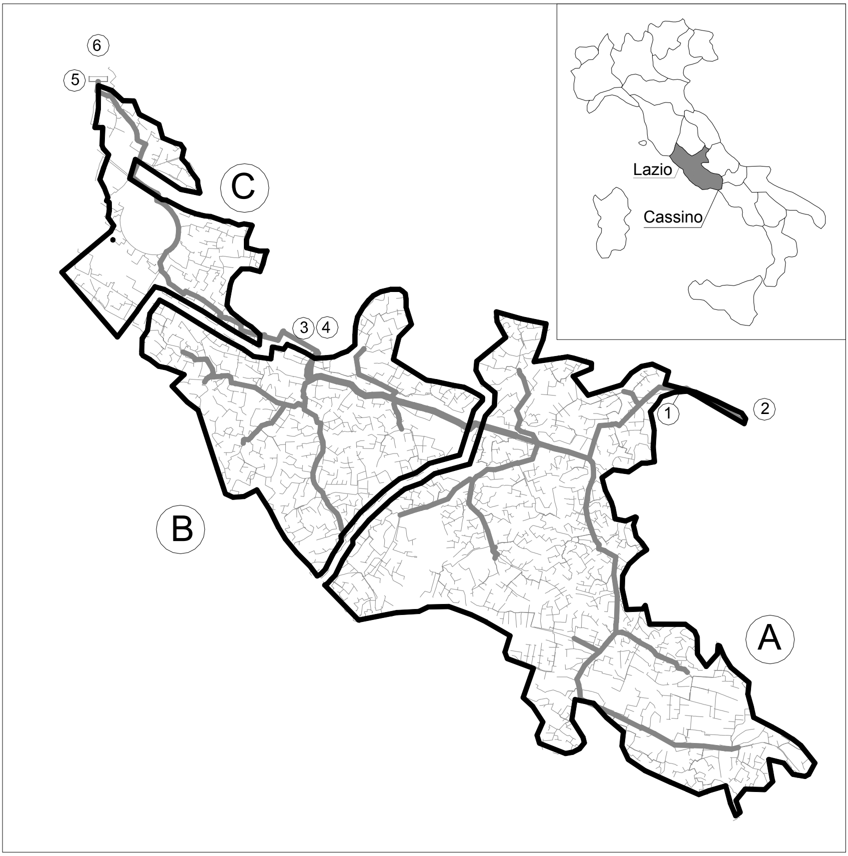

Figure 1: Map of the irrigation network.

Table 2: Characteristic data of the natural source, reservoirs and tanks.

number	type	volume	height
		m^3	m asl
1	river	-	31.00
2	reservoir	120000	102.00
3	reservoir	18000	90.00
4	tank	150	137.00
5	lake	-	115.33
6	tank	150	149.00

Table 3: Characteristic data of the main pipes of the network.

pipe	material	diameter	K_{ST} Strikler coefficient	length
		mm	$m^{\frac{1}{3}} \cdot s^{-1}$	m
5 – 14	concrete	1600	65	158
14 - 11	cast iron	1000	70	487
12 - 10	steel	700	80	8716
3 - 9	cast iron	900	70	4728
9 - 8	cast iron	1000	70	200
8 - 13	steel	1200	80	1079
13 - 7	steel	1400	80	1824
7 - 6	steel	1500	80	665

A discharge of 1100 l/s is taken from Gari river (1 in Figure 2) and is pumped from a head of 31.00 m to 102.00 m in the reservoir of Monte Trocchio. Hence it is distributed in the network: the 60% of discharge is supplied in lot A, while the residue feeds the reservoir of Piumarola (3 in Figure 2). Another pump station works from this reservoir to a tank 4 (Figure 2) and from here the discharge is supplied in lot B. The part C of the network was fed by Castrocielo lake (5 in Figure 2). From here a discharge of 480 l/s was pumped in the tank 6 and consequentially it is distributed in the network.

3 Feasibility study for hydroelectric system

Taking into consideration the main pipes of the same network system and adding some small structural and operational works, it is possible to convert the normal irrigation running into energy production plan at the end of the irrigation period. The new hydroelectric system can work 8 months per year, 24 hours per day.

The modifications that will be carried on the original system are shown in Figure 3. Two by pass from point 11 to 12 and from point 10 to back site of reservoir 3 are introduced. In this way it is possible to generate a unique water pipe penstock, 18 km long, from Castrocielo lake at 115.33 m on the sea level to Gari river at 31.00 m on the sea level. In this way, the available geodetic head $\left(\Delta H_G\right)$ is 84.33 m. It is necessary to evaluate the couple of values Q, ΔH_A that maximizes the produced energy, where Q is the discharge and ΔH_A the available head which is lesser than ΔH_G. We assume that the water pipe penstock is constituted by different pipes in diameter, roughness and material. If T is the number of pipes, the Q$[m^3 s^{-1}]$ can be obtained from the following relationship:

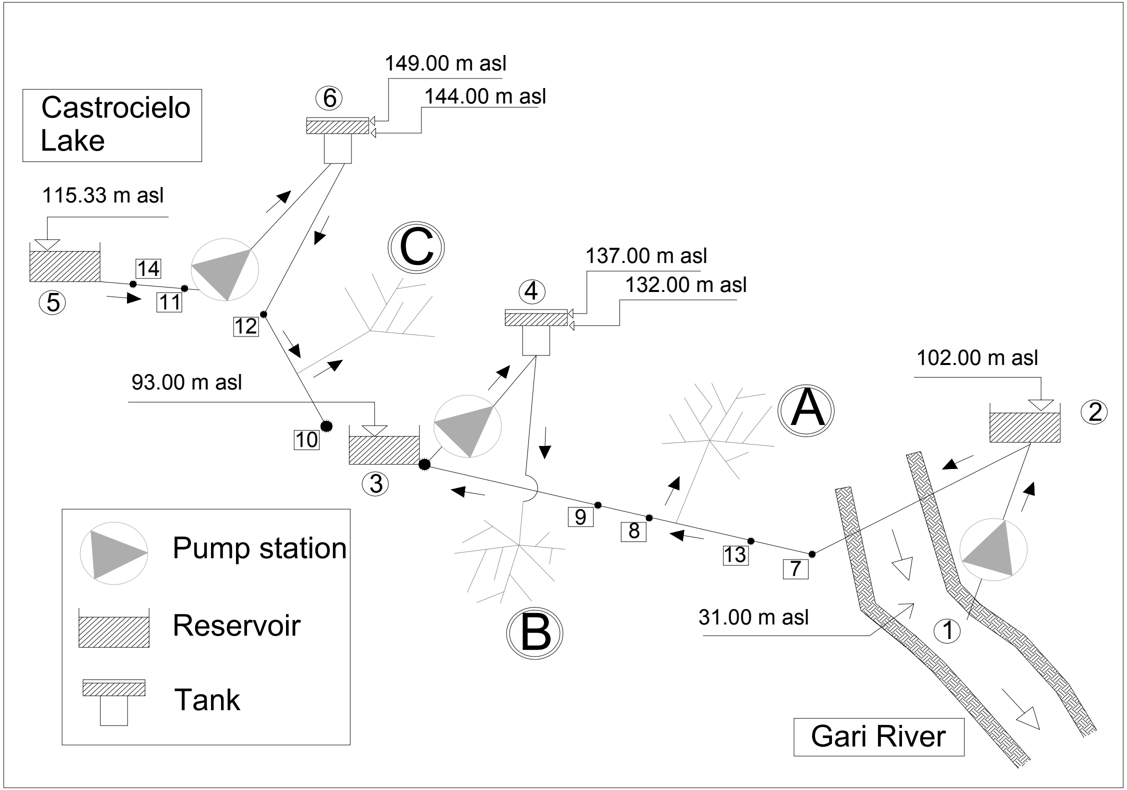

Figure 2: Working scheme of the irrigation system.

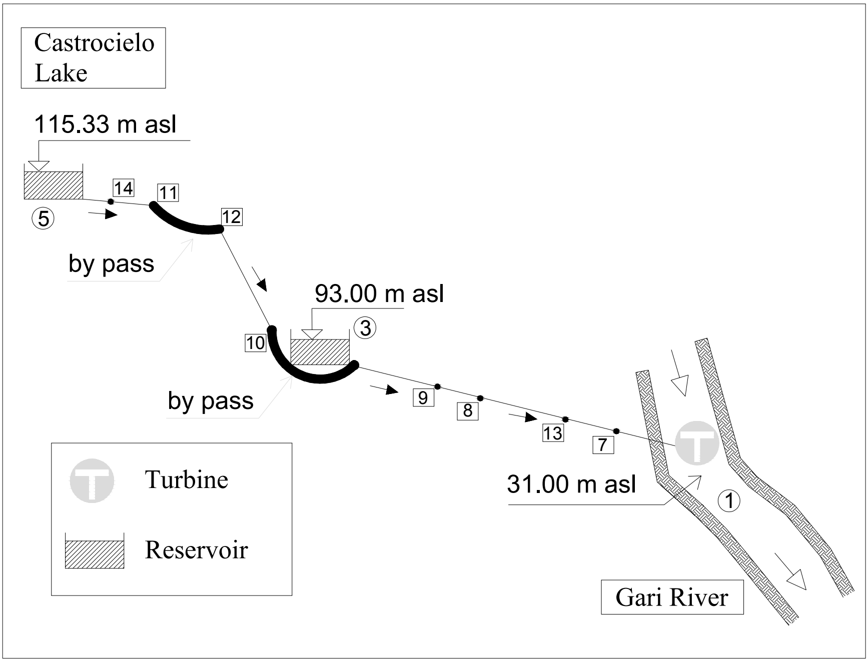

Figure 3: Working scheme of the hydroelectric installation.

$$\Delta H_{GA} = Q^n \cdot \sum_{i=1}^{T} \left(\beta_i \frac{L_i}{D_i^m} \right) \tag{1}$$

where ΔH_{GA} is the dissipated head, L_i the length of the i-th pipes, D_i the diameter and β_i the roughness coefficient. Moreover, it is possible to write:

$$\Delta H_{GA} = \alpha \cdot \Delta H_G \quad with \quad \alpha \in [0,1] \tag{2}$$

where ΔH_G is the available geodetic head.

Replacing eqn (2) in eqn (1) the searched Q is:

$$Q = \alpha^{\frac{1}{n}} \cdot \Omega_1 \tag{3}$$

where:

$$\Omega_1 = \left[\Delta H_{GA} \Big/ \sum_{i=1}^{T} \left(\frac{L_i}{D_i^m} \cdot \beta_i \right) \right]^{\frac{1}{n}} \tag{4}$$

The available head, ΔH_A [m], instead, according to eqn (2), can be formulated as:

$$\Delta H_A = (1-\alpha)\cdot\Delta H_G \quad with \quad \alpha \in [0,1] \tag{5}$$

In addition, the produced electric power [kW] can be expressed by the following relationship:

$$P = 9.81\cdot Q\cdot\Delta H_A\cdot\eta \tag{6}$$

where η is the turbine efficiency.

Replacing eqn (5) and eqn (3) in eqn (6) a relationship between the produced electric power and the α coefficient is obtained:

$$P(\alpha) = \Omega_2\cdot(1-\alpha)\cdot\alpha^{\frac{1}{n}} \tag{7}$$

where:

$$\Omega_2 = 9.81\cdot\eta\cdot\Omega_1\cdot\Delta H_G \tag{8}$$

Imposing the minimum condition for the function $P(\alpha)$, the best value of α coefficient is obtained:

$$\frac{dP}{d\alpha} = 0 \Rightarrow \alpha = \frac{1}{1+n} \tag{9}$$

Using the Gaukler-Strikler headloss relation, $n=2$ and consequently $\alpha = 0.3333$. In the case study herein under consideration, using the K_{ST} coefficient value reported in Table 3, the following values of Q and ΔH_A are obtained:

$$\begin{cases} Q = 496\dfrac{l}{s} \\ \Delta H_A = 56.20\,m \end{cases} \tag{10}$$

Considering the values (10) jointly with those one reported in Table 1 and assuming that is possible to withdraw the discharge 24 hours per day in 8 months per year (inactivity period for irrigation system), it is possible to realize the profit illustrated in Table 4.

The investment outlays for this scheme are about 400.000€ that can be amortized in the first two years.

4 Final considerations

In order to protect the environment and to guarantee socio-economical development, it is not possible to neglect the renewable energy production and in particular hydroelectric energy production. The present work showed the possibility to produce hydroelectric energy from existing irrigation plants adding some small structural rehabilitations and with an opportune management programme. Referring to the case study under consideration - the irrigation system managed by Consorzio di Bonifica Valle del Liri located in Southern Italy - it is analysed the possibility to produce about 1.340.000 [kWh / year] of energy, utilizing the available water resource unused during inactivity period. Moreover, incentives to private energy production, made by Italian and European laws, permit to amortize the investment outlay in the first two years. For this reason, since the planning phase, it seems suitable to anticipate the conversion of great irrigation, industrial and urban systems into energy producers. Furthermore, for many existing systems, it appears interesting to note that with small economic outlays it is possible to produce a high sustainable energy level.

Table 4: Produced energy and relative profit.

Range	Produced energy	Profit € / years	
	kWh	0 - 8 years	> 8 years
1	500000	96520	47825
2	500000	88965	40270
3	339811	57044	23950
Total	1339811	242529	112045

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Rio Grande Basin water conservation project

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Abstract

The Rio Grande is 3,057 Km long with water sources from the Rocky Mountain snowmelt, the Rio Conchos in Mexico and the Pecos River in Texas. It serves as the only major source of surface water for two U.S. and five Mexican states, and supports 5 million people. The Lower Rio Grande Valley is one of the most productive agricultural areas in the U.S., generating roughly $ 500 million of annual growth sales and accounting for approximately 85 percent of the region's water use. However, the population in the Basin is expected to double in the next 50 years causing doubled municipal water demands and serious agricultural impacts. The Treaty of 1906 distributed the water between Mexico and the U.S., giving 74 million m^3 per year to Mexico, while the Treaty of 1944 divided the waters of the Lower Rio Grande and the Colorado River and stated the U.S. should receive 432 million m^3 of water per year from Mexico over 5 year cycles. However, between 1992 and 2002, only half of the required water was delivered. The water debt grew and Mexico currently owes 81.9 million m^3. The future of irrigated agriculture in the Rio Grande Valley is facing many challenges. The Rio Grande Basin Initiative is focused on helping solve these rising problems by implementing the following nine task groups: Irrigation District Studies; Irrigation Education and Training; Institutional Incentives for Efficient Water Use; On-Farm Irrigation System Management; Urban Water Conservation; Environment, Ecology and Water Quality Protection; Saline and Wastewater Management and Reuse; Basinwide Hydrology, Salinity Modeling and Technology; and Communications and Accountability. This presentation discusses the concerted results and outcomes from these tasks.
Keywords: efficient irrigation, water conservation, Rio Grande.

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1 Introduction

Increased water demands in the Rio Grande Basin make efficient water-use and conservation a topic of utmost importance. Irrigated agriculture claims 85 percent of the region's water. The Basin's population is expected to double in the next 50 years, and thus increasing urban water demands. This rapid population growth, along with the strong agricultural industry, will further stress limited water resources already constrained by salinity and other water quality issues.

Rio Grande surface water is shared by two U.S. and five Mexican states, supporting 5 million people. Both U.S. states, Texas and New Mexico, have a similar interest in preserving the waters of the Rio Grande to meet current and future water demands.

Texas and New Mexico scientists, irrigation districts and policymakers have identified opportunities for conserving water to increase availability in the Basin. Research and educational efforts help improve the efficiency of water delivery canal infrastructure, and help both agricultural and urban irrigators use water more conservatively.

2 The beginning of the Rio Grande Basin Initiative

In 2001, a team of Experiment Station researchers, Cooperative Extension specialists and county agents from the Texas A&M University System Agriculture Program and the New Mexico State University College of Agriculture and Home Economics began working with local irrigation districts and other agencies, agricultural producers, and homeowners to address these Rio Grande Basin water issues.

Funded through the U.S. Department of Agriculture Cooperative State Research, Education and Extension Service (CSREES), the Rio Grande Basin Initiative (RGBI) focuses on efficient irrigation and water conservation. CSREES funding has supported the Initiative since 2001 and continues supporting its efforts at a level of approximately $ 3.5 million per year.

2.1 Rio Grande Basin Initiative goals and objectives

The goal of the RGBI is to meet present and future water demands through conservation measures that not only expand efficient use of available water resources, but also create new water supplies. By taking care of needed improvements in water conveyance canals and implementing more efficient irrigation systems, additional water resources will be available. Broadening outreach and teaching programs on how to efficiently utilize water resources to agricultural producers and urban water users is another objective in the water use efficiency education process.

The Texas and New Mexico Agricultural Experiment Stations and Cooperative Extension work hand in hand with other federal and state agencies, farmers, citizens and local governments to conserve water in the basin.

To achieve these goals, the Initiative is divided up into nine task group. Each task group focuses on a specific area of concern in the region. The nine task groups are: irrigation district studies, education and training, institutional incentives; on-farm irrigation management; urban water conservation; environment, ecology and water quality protection; saline and wastewater management and water reuse; basinwide hydrology, salinity modeling and technology; and communications and accountability. Task groups conduct research, educational outreach programs and demonstrations, and strive toward significant water savings.

3 Researchers, economists, engineers and irrigation districts

Three of the nine tasks focus on irrigation district management, irrigation education, irrigation training and institutional incentives for efficient water use. Researchers, economists and engineers evaluate districts and infrastructure, conduct cost-benefit analyses, study policies and legalities, and conduct research and educational programs.

3.1 Irrigation district studies

Researchers, economists and engineers evaluate irrigation district infrastructure using Geographic Information Systems (GIS), improve canal seepage loss measurements and conduct cost-benefit analyses of proposed projects. Task members also help irrigation district managers evaluate proposed infrastructure improvements, and develop and implement a standard economic model to evaluate on-farm irrigation improvements.

Engineers have completed irrigation district maps for each Texas irrigation district along the Rio Grande. These maps will provide an indispensable tool for district modernization and rehabilitation, regional water resource analysis, and other planning efforts.

Economists have analyzed the cost of saving water and energy for rehabilitation projects throughout the Lower Rio Grande Valley. Initial calculations show that about $ 200 million in investments will provide 260.3 million m^3 of water savings a year from the water delivery infrastructure in the area.

Researchers estimated seepage losses from 10 to 30 percent of the total amount of water delivered in El Paso’s Franklin Canal. Ponding results show water seepage rates from 123,750 m^3 to 479,000 m^3 per Km along the canal. Losses along the Westside Canal measure 309,000 m^3 to 617,000 m^3 per Km.

3.1.1 Irrigation education and training

Researchers and engineers evaluate and demonstrate minimum performance standards for irrigation systems, and train private and commercial irrigators on improved methods and systems. They also conduct research and extension educational programs to help convey information more easily to the public.

A project called User Friendly Drip Irrigation and Mulch Systems for Urban Specialty Crop Production, aimed at increasing the use of drip irrigation and mulch systems for urban specialty crops, has helped New Mexico Master Gardener cooperators to reduce water application by 29.3 percent.

Engineers have teamed with the San Antonio Water System and the Texas Turf Irrigation Association to complete a detailed irrigation system design. The design will be used as a public service project to rehabilitate the irrigation systems of the San Antonio Botanical Gardens.

3.1.1.1 Institutional incentives for efficient water use Efforts of this task are focused on identifying legal and institutional barriers that limit water conservation; analyzing impacts of alternative water management and incentive policies; and developing an electronic database of historical irrigated acreage in the Rio Grande Basin.

"Database Recommendations for Irrigation Districts" reports are available, which offer irrigation districts suggestions for better GIS and data management integration. The upgraded database will allow easier incorporation with software tools and facilitate the use of data to make management operational decisions.

Engineers assisted the City of Brownsville, Texas with justification of an on-farm water metering program that will result in an estimated water savings of 104 million m^3 per year. Technical assistance such as this has saved districts $ 1.8 million in the cost of hiring consultants.

Researchers in El Paso, Texas have teamed with New Mexico State University and Siena College researchers to collaborate on integrated economic, institutional and hydrologic models to be used to study the Upper Rio Grande Basin. Initial research shows drought losses could be reduced by 20 to 30 percent.

4 On-farm and urban conservation and management

Due to the expected doubling of the Rio Grande Basin's population, water conservation is one of the most important measures that can be taken to ensure water availability for current and future demands. On-farm irrigation management and urban water conservation are the next two tasks which both focus on this particular issue.

4.1 On-farm irrigation system management

Researchers and extension personnel demonstrate improved irrigation scheduling to optimize crop growth, yield and quality while conserving water. They develop water conservation strategies for flood, microspray and drip irrigation systems, and they assess the costs and benefits of water management systems. Crop production models and decision support systems (DSS) are also adapted for irrigated agriculture.

Information on how much water can be saved by adopting on-farm water conservation technologies is scarce due to a lack of accurate records of crop water-use. This information is required for improved irrigation scheduling to reduce water inputs and losses. Researchers are working with in-ground monolithic weighing lysimeters to determine phenologically specific crop coefficients (Kc) of crops grown in the Rio Grande Basin. These Kc are then used for calculating crop water-use for crops grown in each region of the basin utilizing a network of weather stations. Furthermore, research and extension specialists demonstrate decision support systems such as PET and the CroPMan model to improve real-time water management, maximize production and profit, increase irrigation efficiency and identify limitations to crop yield. Extension agents coordinate demonstration activities with sugarcane, corn, sorghum and cotton research programs in the Lower Rio Grande Valley

Water is the primary factor limiting production of sugarcane in the Lower Rio Grande Valley of Texas. A research project is providing improved understanding of crop water-use by sugarcane. This results in better recommendations for irrigation of sugarcane which increase yields while using less water. Water savings of up to 30 percent could be achieved with overhead sprinkler or drip irrigation, but the cost of such systems has limited their acceptance. The 18,000 hectares of sugarcane grown in the Lower Rio Grande Valley of Texas in 2005 required roughly 247 million m^3 of irrigation water to produce. Use of improved furrow irrigation techniques and scheduling developed based on the results of this project would save 10 to 15 percent of this irrigation water, or between 25 and 37 million m^3.

Conservation tillage is becoming increasingly popular compared to conventional tillage for row crop production for various reasons, including reduced costs and long-term improvement in soil properties. Better water-use efficiency should result from reduction of losses caused by tillage as well as improvement in water retention as soil properties, including organic matter content, improve. In a subtropical environment, however, such benefits are proving to be difficult to obtain. Water savings by reductions in tillage can be lost depending on the timing of rainfall. Cover crops to improve soil properties require more water to produce. Crop residues decompose quickly in a subtropical environment making it difficult to build up water retaining organic matter. While conservation tillage offers distinct advantages for producers, it has thus far been difficult to show water savings that can contribute to this advantage.

Our research with onion production in the Lower Rio Grande Valley indicates that a substantial amount of water could be saved by using subsurface drip irrigation instead of furrow irrigation. These water savings were obtained without compromising productivity. This translates to nearly 10 million m^3 of potential water savings in onion production for the Lower Rio Grande Valley given that only about 10 percent of the 5,000 ha of onions currently grown in the Valley are drip irrigated.

Volumetric monitoring of on-farm water-use provides the most accurate means for documenting on-farm water-use, fine-tuning irrigation scheduling and quantifying the success of water conservation when best management practices are implemented. Volumetric flow-metering, when used in conjunction with other water conserving strategies, can increase growers' profit margins by reducing production costs. There are roughly 40,000 ha of highly-value, mostly furrow-irrigated vegetable crops grown in the Valley. Converting from furrow to drip irrigation of major vegetables grown in the Valley could conserve a significant amount of water and actually increase productivity and the competitiveness of the industry.

The evaluation of drip, microjet spray and flood irrigation practices in citrus under the on-farm irrigation task project has resulted in increased dollars from the State of Texas to monitor water-use and water conservation practices in the Lower Rio Grande Valley. Documented water savings as a result of these on-farm water conservation studies led to the acceptance of a larger proposal to assess water use in citrus and other horticultural crops in the Rio Grande Basin. In February 2005, the Texas Water Development Board provided funding to assess long-term (2005-2014) water-use in citrus and vegetable production in the Lower Rio Grande Valley under the direction of the Harlingen Irrigation District, Texas A&M University and Texas A&M University-Kingsville. The information gathered from ADI (Agricultural water conservation Demonstration Initiative) on-farm demonstration projects will further evaluate low-water-use systems like drip and microjet spray irrigation, and varying flood irrigation practices. These demonstration sites consist of water conservation on farm-scale land areas ranging from 5 to 25 ha each. The ADI funding will couple well with the scientific research studies being performed on smaller areas under the RGBI on-farm water conservation work in citrus. The combination of research and demonstration sites on grower's fields will provide a great baseline of information regarding overall water-use in the Rio Grande Basin and will provide answers on how to address improved water-use while maintaining good agricultural production in the Valley.

Through the RGBI, impacts of efficient water conservation practices using subsurface drip irrigation and center pivot systems on economically important vegetable crops have been confirmed in the region. Researchers have been focusing on spinach, onions, watermelon, artichoke and several varieties of peppers to evaluate and develop deficit irrigation practices. These practices also include different plant populations and nitrogen fertilization rates, which is environmentally important for the soil and groundwater resources. In collaboration with local partner agencies and industries, an increased interest is being placed in large-scale evaluations of the less expensive low-pressure drip system (LPS) which is being considered to be incorporated into the United States Department of Agriculture Cost Share Programs.

Outcomes from these experiments are educating many “progressive farmers” in water conservation practices. Data from research experiments are being used in pilot studies in growers' fields to demonstrate the ability to save a minimum of 25 percent of the normal crop water requirements without depleting yields. Furthermore, the Precision Irrigators Network (PIN) is including the growers in the research process. This way of conducting research allows the growers to take ownership of the research findings a lot quicker than if the research was conducted in another location and the results delivered to the growers. From the results of our study we estimated that on a “typical” 50 ha field with a fall vegetable rotated by a summer row crop, water savings can amount to 150 to 200 mm of water per ha per year or 380 to 510 million m^3 of water per year based on 251,000 ha of irrigated land in the Rio Grande region alone.

4.1.1 Urban water conservation

Conserving water through improved landscape ordinances, designs and irrigation systems are just a few of the methods demonstrated in this task. Guidelines are developed for urban water conservation, salt-tolerant plant varieties are identified, and the use of brackish wastewater for irrigation is demonstrated. In-home water conservation studies have also been conducted to reduce the amount of water families use on an everyday basis.

Extension housing specialists conducted a water conservation study to determine how much a family of four can reduce its water consumption over a three-month period by installing water saving toilets, showerheads and faucet aerators. Fifteen families from five counties participated in this study, and at the study's conclusion the 15 households had a total combined water savings valued at approximately $ 4,900.

Some 91,000 to 129,000 m^3 of water could be salvaged each year if homeowners practiced landscape water conservation. More than 800 homes were surveyed in Weslaco and 51 percent were found to be using excess water for landscape irrigation. By using monthly water budgets based on landscape size, potential evapotranspiration value and landscape coefficients, homeowners could reduce their landscape irrigation water-use by 48 percent annually.

Many turf managers throughout New Mexico are making plans to convert to the water-saving application of sub-irrigation. Research conducted at New Mexico State University shows a dramatic potential water savings of 80 percent.

5 Water quality protection, environment, salinity and reuse

The environment is yet another important component to consider when dealing with the Rio Grande. Ecology and water quality are vital elements that need to be studied in order to preserve and protect the Rio Grande. Salinity in the water can also be a major water quality problem for irrigators as well as homeowners. Both wastewater management and reuse are focused on through the next two tasks.

5.1 Environment, ecology and water quality protection

Several measures are taken to ensure that the Rio Grande's surrounding environment and its water quality are protected. Screening private water supplies for purity, demonstrating how soil testing can help protect water quality and quantity, and demonstrating control of invasive aquatic weeds are a few examples of efforts taken on by researchers and extension specialists involved in this task. Analyzing the Rio Grande's water for the presence of pathogens that could pollute irrigation water is an important ecological measure taken. Saltcedar along the river is another major concern because of the amounts of water these invasive trees take away from the river. Therefore, determining how much water can be salvaged by saltcedar controls is a top priority in this task area. Increasing water-use efficiency and reducing erosion on rangeland are equally important.

The Pecos River in Texas is one of the main sources of water that flows into the Rio Grande, however more than 50 percent of the 670 Km of the Pecos River are infested with saltcedar. Efforts are under way to treat this saltcedar infestation through the Pecos River Ecosystem Project. More than 1,200 ha of saltcedar were treated and removed in 2003 along the Pecos and its tributaries.

Researchers have determined exactly how much *Cryptosporidium* and *Giardia* are present in river water after release from wastewater treatment plants along the Rio Grande. Genetic typing is also under way to determine the human or animal source of the detected pathogens so potential risks to humans can be assessed.

5.1.1 Saline and wastewater management and reuse

Researchers demonstrate the use of treated wastewater and brackish water for irrigation as an alternate water source to further conserve the waters of the Rio Grande. Extension educators train homeowners to install septic systems and implement self-help programs for wastewater treatment in "colonias" (generally, sub-standard construction outside of municipal services) in an effort to reuse the water and provide another water resource.

Extension specialists have conducted several short courses on basic and advanced on-site wastewater treatment for homeowners, and spray distribution of effluent and high strength wastewater for practitioners in areas along the Rio Grande. Fact sheets, presentations and demonstrations about rainwater harvesting, graywater, subsurface drip distribution fields and wastewater treatment have also been developed.

Researchers have studied the plant-salt-tolerance relationship for different species of plants, providing guidelines for use of a specific amount of saline irrigation on different plant varieties. Tolerant plants can tolerate up to 10,000 parts per million (ppm) of dissolved salts without suffering. Sensitive plants can only take up to 1,000 ppm. Research is still under way to develop management practices to reduce overall saline content in soil and irrigation water.

Reclaimed wastewater is a major contributor to both urban and agricultural landscapes in the El Paso area. Reclaimed wastewater is about 60 to 90 percent of the cost of potable water supplies. Emphasis has been placed on the detection of contaminants in these water sources. By using phytoremediation treatment, $ 120 per cubic meter can be saved. This will also help extend existing water supplies, ensure food safety and quality, create a safe and reliable water supply, and develop sustainable agronomic strategies to utilize reclaimed waters.

6 Modeling, technology and communications

Technology plays a major role in everything today, and the RGBI project is no exception. The last two tasks both involve the use of modern technology in one form or another.

6.1 Basinwide hydrology, salinity modeling and technology

Task researchers and extension specialists cooperate with the Texas State University System, New Mexico State University, and other state and federal agencies to develop GIS-based historical and resource databases. They also develop coordinated, basinwide hydrology and water quality modeling efforts.

Natural resource data has been collected for counties along the Rio Grande and organized into spatial databases that provide GIS coverage for a particular county. To date, 16 Texas counties have been analyzed and mapped. Stakeholders can access and identify environmental, natural resource and socioeconomic information for each county. Data for additional counties has been collected and processed for Web hosting.

A Coordinated Water Resources Database and GIS Web site has been created to collect, synchronize and provide timely online access to flow and water-quality data for use by stakeholders, scientists, water agencies and irrigation districts. By effectively and efficiently monitoring and operating the passage of Rio Grande flows and water quality in the region, water quality can be maintained within acceptable limits for effective water treatment, especially during low-flow periods.

6.1.1 Communications and accountability

Providing project oversight, communications support and accountability are key elements in this project as a whole. Members of this task group report program outcomes and results of collaboration among scientists, extension specialists, institutions, agencies, and urban and agricultural clientele. They ensure timely communication of outcomes and impacts to various audiences through reports, feature stories, newsletters, conferences and electronic media. This is the group responsible for “getting the word out” about the project’s accomplishments and noteworthy news. They collect project information and reports, keep them on file and compile an annual booklet with all accomplishments and outcomes listed under each task group.

Quarterly, the Rio Grande Basin Initiative *Outcomes* newsletter is distributed to project participants and other interested parties to communicate recent accomplishments, water savings and other project information. News and feature stories are written throughout the year as well and are posted on the Rio Grande Basin Initiative Web site (http://riogrande.tamu.edu) so they are accessible to everyone at any time. These communications materials allow project participants to stay involved and up-to-date with the activities of other tasks and project members.

Communications and accountability helps hold everyone together and keeps everything on track – making each person responsible for the efforts and work to which they were assigned. Communication plays a key role in keeping everyone well-informed of the activities of other task members and project participants, as well as recognizing individuals for their own project accomplishments.

7 Conclusion

RGBI efforts and activities have greatly impacted the region as well as the waters of the Rio Grande. Millions of dollars have been saved due to new technologies and irrigation and conservation methods being implemented in the area. Millions of m^3 of water have been saved through these methods as well.

Visible improvements have been made to the canal infrastructure – building new infrastructures and replacing or renovating canal gates, linings and other canal equipment and infrastructure. A new understanding of methods for saving water is now available to growers, urban water-users and stakeholders. These results are made possible by a concerted effort of several scientists, extension specialists and agents, and communication specialists. Furthermore this project overcomes interagency barriers using the best possible resources available at various institutions.

As a final note, the success of this project needs to be attributed equally to the all the people that participate in it. They are: Naomi Assadian, Red Baker, Max Bleiweiss, Chris Braden, Raul Cabrera, David Cowley, Bobby Creel, Leeann DeMouche, George Dickerson, George DiGiovanni, Monty Dozier, Keith Duncan, Juan Enciso, Mike English, Connie Falk, Sam Fernald, Guy Fipps, Robert Flynn Tom Gerik, Steve Guldan, Ereney Hadjigeorgalis, Bill Harris, Janie Harris, Charles Hart, Woods Houghton, Brian Hurd, Jennifer Jacobs, John Jifon, Allan Jones, Ron Kaiser, Phillip King, Connie Kratzer, Ron Lacewell, Eric Leigh, Bernd Leinauer, Bruce Lesikar, Daniel Leskovar, Gino Lujan, Wayne Mackay, Michael Masser, Alyson McDonald, Mark McFarland, Denise McWilliams, John Mexal, Mike Mecke, Ari Michelsen, Seiichi Miyamoto, Mark Muegge, Shad Nelson, Genhua Niu, Keith Owens, Geno Picchioni, Giovanni Piccinni, Ed Rister, Craig Runyan, Rossana Sallenave, Zohrab Samani, Ted Sammis, Bob Sanderson, Jill Schroeder, Barak Shemai, Zhuping Sheng, Erin Silva, Val Silvy, Rhonda Skaggs, Curtis Smith, Raghavan Srinivasan, Tamaron Stewart, Rolston St. Hilaire, Allen Sturdivant, Danielle Supercinski, Jaclyn Tech, David Thompson, April Ulery, Frank Ward, Ellen Weichert, John White, Richard White, and Bob Wiedenfeld.

Some of RGBI's key collaborators include: Texas Water Resources Institute, Texas Agricultural Experiment Station, Texas Cooperative Extension, New Mexico Cooperative Extension, NMSU Agricultural Experiment Station, NMSU Water Task Force, USDA Natural Resources Conservation Service, U.S. Bureau of Reclamation, U.S. Geological Survey, Regional Water Planning Groups, Texas Department of Agriculture, Texas Water Development Board, irrigation districts, commodity organizations, North American Development Bank, Border Environmental Conservation Commission, selected consultants, International Boundary and Water Commission, and the Lower Rio Grande Development Council.

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Promoting the effective use of water in the irrigation of permanent crops in the Western Cape Province of South Africa

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Abstract

South Africa is an arid country with an average annual rainfall of little more than half the world average of 900 mm per annum. In terms of international norms, the per capita availability of water will lead to a “water-stressed” country classification soon. The competition for water increase and the irrigation sector, that is responsible for more than 50% of the water usage, will have to get involved to find balanced solutions to the looming water shortage crisis.

This provided the motivation in 1998 for the Department of Agriculture in the Western Cape Province of South Africa to start with the Agricultural Water Conservation Project. The aim of the project is to monitor the actual on-farm irrigation water use and to compare the water use with the farming practices applied by the individual farmers and to compare it with the theoretical calculated water requirements.

The optimum farming practices that lead to optimum use of irrigation water will be determined from the data collected and can then be used to assist other irrigation farmers to increase their water use efficiency (WUE - kg of fruit produced per m^3 water used) and to determine what research is required in this field. A Best Management Practices document will be compiled and distributed at the end of the project to assist all irrigation farmers to increase their WUE.

Keywords: water use efficiency, best management practices, irrigation, plant water requirements, water conservation, agriculture.

1 Background

Water is a scare resource across South Africa and also in the Western Cape. Water usage by the Western Cape agricultural sector amounts to more than 43%

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of the total water usage and there remain few catchment areas where additional water can be allocated to the agricultural sector. Extension of existing irrigation will have to be derived from savings in current water usage levels.

The national Water Act, 1998 (Act 36 of 1998), demands the economical and sustainable usage and efficient management of water usage. Proof must also be given of the effectivity of existing water usage before licenses for the use of water will be issued or renewed in future.

The graph below indicates the usage for the various sectors in the Western Cape.

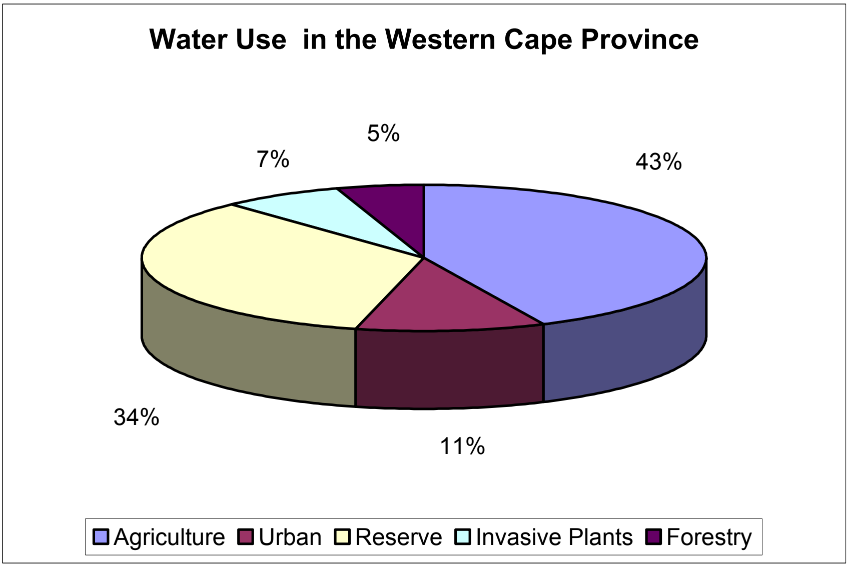

Figure 1: Water use by the different sectors in the Western Cape Province.

2 Possible effects of water conservation in the agricultural sector

Agriculture uses approximately 160 million m^3 water per year from the Berg/Riviersonderend system. The annual increase in the demand for water from this system amounts to approximately 20 million m^3 of which 5 million m^3 is needed for agricultural usage.

The result of more effective usage of water by the agricultural sector is illustrated by the following statement: a saving of 10% in agricultural water usage represents a volume of 16 million m^3 per year, which is enough to provide for the increase of the agricultural demand for water for the next three years, by which time the demand could be further decreased due to water conservation measures.

The rivalry for water will continually increase and the irrigation sector, which is responsible for 50% of the water usage in the country, will have to become more involved in the quest for balanced solutions within the agricultural sector and between agriculture and other water users. Water saving can have a huge impact on the construction of future water supply schemes at enormous costs and can have a direct and positive influence on the economy of the Western Cape.

3 Reasons for the ineffective use of irrigation water

Ineffective water usage at farm level can be attributed to the following:

- Poor designs of irrigation systems
- Inadequate maintenance of irrigation systems
- Ignorance regarding irrigation scheduling
- Sub standard application of irrigation scheduling
- Complexity of farming and irrigation management
- Lack of tried, practical and accessible information
- Lack of training of water managers on the farms
- Relative low cost of water in relation to other input costs

In order to improve the situation the Department of Agriculture: Western Cape initiated an investigation into the water use efficiency (WUE) of four main irrigation crops in the winter rainfall region. For the purpose of this project WUE can be defined as the quantity of fruit (kg) produced per unit irrigation water (m^3) applied.

4 Objectives of the Agricultural Water Conservation Project

The objectives of the project can be summarized as follows:

- Promote the efficient use of water on farm level by documenting management practices that result in water savings. Hereby, optimal farming practices (including irrigation) that promote the effective use of water at farm level can be determined.
- Determine why certain producers achieve higher levels of effective water usage than others.
- Assist participants in the study that have poor levels of water savings to increase their efficiency.
- Compile a list of Best Management Practices for distribution amongst producers.
- Thus the water use efficiency of the broader irrigation sector in the Western Cape can be increased.
- Information derived from the project will be used to identify extension and research actions to increase the WUE of all crops in the Province.

5 Methodology

In order to determine the optimal use of water, the water use and yield (quantity and quality) of various producers were compared, considering the farming practices applied. Four crop types were chosen to represent the main irrigation practices in the Western Cape – wine grapes, table grapes, pears and plums. The following areas were chosen for monitoring the various crop types:

Worcester (Worcester East)	Wine grapes
De Doorns (Hex River Valley)	Table grapes
Ceres (Koekedouw)	Pears
Stellenbosch (Devon Valley)	Plums

In order to ensure involvement and cooperation from the agricultural sector, the following procedure was followed:

- Meetings were held in the various regions to inform producers about the objectives of the project and to convince them to take part in the project
- Experts such as soil experts, economists and a statistician were involved.
- A soil survey was done on the farms where producers agreed to be part of the project. After consultation with the experts of every region a decision was made about the irrigation blocks that conform to the requirements. The aim was to choose blocks of the same cultivars, of approximately the same age, planted in the same type of soil and in a similar micro climate.
- A project committee was composed for every region, including soil, irrigation and crop specialists, as well as a representative of the irrigators. The four project committees reported to the Steering Committee, which evaluated results from time to time and advised the project committees. The project committees met three times per year to evaluate progress.
- A rain meter and water meter were installed at each block. Producers contributed half of the cost of these meters.

6 Monitoring of farming practices and water consumption

6.1 1999/2000 irrigation season

Various soil and system parameters for all irrigation blocks were obtained in order to gain base line information. This included the following:

- Completion of a questionnaire to gain information regarding the crop, soil preparation practices, irrigation systems and the source of water. Farming practices were also noted.
- Soil samples were taken to determine the soil moisture release curve, water retention ability as well as the texture.
- In-field evaluation of the identified irrigation blocks

- Two weekly gravimetrical soil water determination
- Weekly reading of water and rain meters
- Two weekly noting of weed growth
- Monthly determining of the conductivity of the irrigation water. If the reading was 80 mS/m an analytical laboratory did a complete water analysis.
- Five weekly determining of the vigour of the shoots.
- Problem soils were analysed for salinity just prior to harvesting season and where possible, the quality of the drainage water was determined monthly.
- Information regarding the climate for the harvesting season was obtained from the closest weather station.
- The yield per block is obtained from the wine cellars or pack stores.
- After the season the producers were informed about the shortcomings of their irrigation systems and corrections were made where practical and economically viable.
- Advice provided regarding effective pressure control, as well as the supply of guidelines for improved maintenance of the irrigation systems.

6.2 Irrigation seasons: 2000/01 up to 2003/04

- The measurement of water usage, rainfall, weed growth and the vigour of the crops were continued in every season.
- In certain areas more irrigation blocks were included in the study to fill in certain gaps in the information gathered.
- Frequent soil moisture measurements were done by scheduling experts and recommendations were made to the producers. The Department and producers share the costs involved with this action.
- Continuous training was given to all individuals involved with water management on the participating farms

7 Results of the project

Space limits the detail of the results and the factors that played a role in each year that can be provided in this paper. Only a summary of each area is provided.

7.1 Wine grapes: Colombar cultivar: Worcester East

From figure 2 below it is evident that the cumulative water usage exceeded the theoretical gross irrigation requirement (blue line without marks) in only two irrigation blocks out of the total of seven. This indicates that irrigation water is already being used efficiently and that irrigators in this area, which is fairly water poor, have learned to use the available water efficiently.

Indication is that more water is given during the early part of the season compared to the theoretical calculated demand. It also indicates that four of the producers do not compensate for the higher water demand of the crop during the latter phenological stages of the season. In some cases this can be attributed to a shortage of water during the last part of the irrigation season.

The actual production measured per hectare of the participating irrigation blocks are indicated in Figure 3 below. In order to compensate for a higher quality grape produced, the actual sugar tonnage produced were recorded instead of just normal tonnage production.

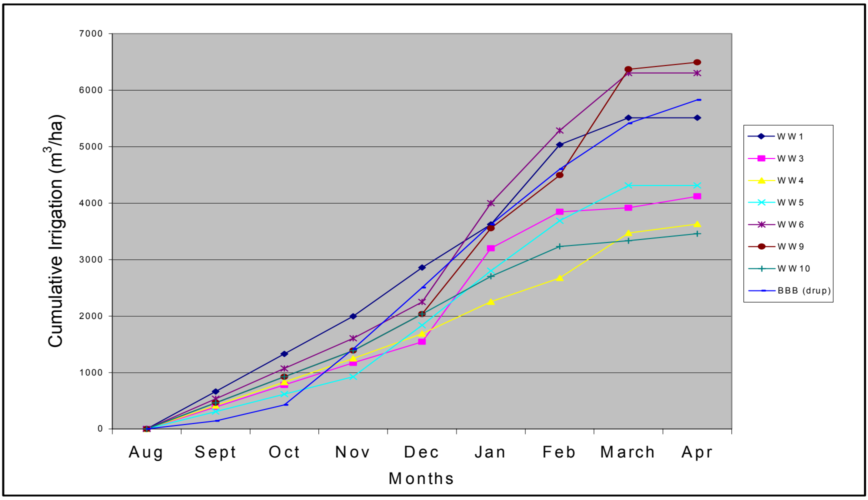

Figure 2: Cumulative water use Colombar wine grapes 2000/2001.

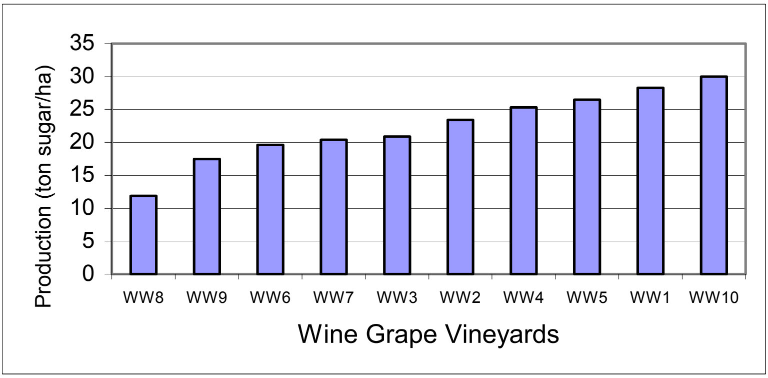

Figure 3: Production of the participating irrigation vineyards 2000/2001 (ton sugar produced/ha).

The WUE (kg of sugar produced per m^3 of water applied) are shown in Figure 4.

From figures 3 and 4 it becomes clear that the highest production (ton sugar/ha) does not necessarily results in the best WUE (kg sugar/m^3). In both cases block WW 10 performed the best (30 t/ha and 8,7 kg/m^3) while block WW1 had the second best production (28 t/ha) but only the fourth best WUE (5,1 kg/m^3).

The big differences regarding the tonnage produced and the WUE between different blocks indicates that there is scope for improvement

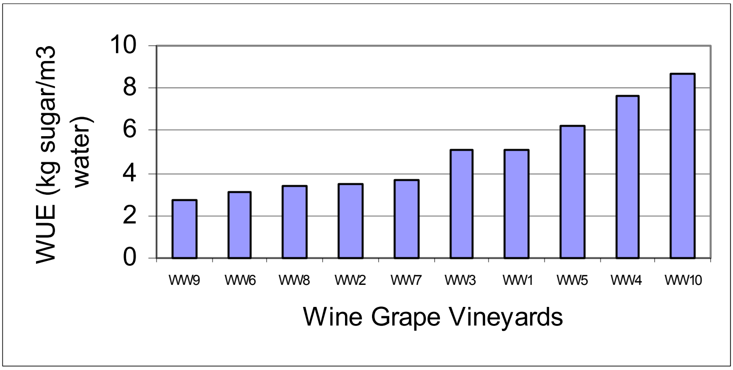

Figure 4: WUE of the participating irrigation vineyards 2000/2001 (kg sugar produced/m^3 water).

Table 1: Average water use and production: Colombar wine grapes (Worcester East).

Season	**99/00**	**00/01**	**01/02**	**02/03**	**03/04**
Average water use (m^3/ha)	4783	4957	5500	4678	4608
Average production (ton sugar/ha)	22,46	22,38	29,4	28,67	27,87
Average WUE (kg sugar/m^3 water)	4,70	4,51	5,94	6,23	6,05

The small differences in the data of the 1999/2000 and 2000/2001 seasons can mainly be attributed to various factors. The ET$_0$ was 220 mm and 240 mm respectively December 1999 and December 2000. There was a close correlation between the total rainfall figures of the first two irrigation seasons. 2001/02 had very low rainfall, resulting in below field capacity soils after the winter and additional irrigation was required at the onset of the irrigation season.

Although the project led to a decrease of only 3,67% in water use, the production was significantly increased and the WUE was increased by 28,7% over the five years of the project.

7.2 Plums: Cultivar Ruby Nel: Devon Valley, Stellenbosch

A summary of the results is presented in Table 2 below.

Table 2: Average water use and production: Ruby Nel plums (Devon Valley).

Season	**99/00**	**00/01**	**01/02**	**02/03**	**03/04**
Average water use (m^3/ha)	7239	5585	5412	7555	6408
Average production (class 1 and 2) (ton/ha)	12,63	21,52	20,01	27,43	19,05
Average WUE (kg fruit/m^3 water)	1,99	4,12	3,87	3,73	2,87

Rain during the blooming period of the plums in 2003/04 resulted in poor pollination and a huge decrease in the fruit produced. The data indicates that the project made a significant difference to the production and WUE of the various plum orchards with an increase in the WUE of 94,2% up to 2002/03. Relatively little attention was previously given to the effective use of water. Previously more effort was put into orchard management and other pomological aspects. The value of effective water use came to the forefront with this study and producers bought their own neutron soil probe for use in irrigation scheduling.

7.3 Table grapes: Cultivar Alphonse Lavaleé: Hex River Valley, De Doorns

The Hex River Valley is one of the major table grape export areas in our country. Regular water shortages are experienced and one would expect a fairly high level of WUE in the valley. The summarized results are shown in Table 3 below.

Table 3: Average water use and production: Alphonse Lavaleé table grapes (Hex River Valley).

Season	**99/00**	**00/01**	**01/02**	**02/03**	**03/04**
Average water use (m^3/ha)	7182	6681	7368	7144	6489
Average production (export ton/ha)	20,75	22,42	29,47	26,70	23,30
Average WUE (kg export fruit/m^3 water)	2,98	3,54	4,24	3,74	3,59

During the 2000/2001-season, a couple of thunder storms brought rain to the valley and this reduced the water requirements for irrigation. Damages due to the wet conditions resulted in lower export tonnages than the previous year. Climatic conditions were ideal for table grapes during 2001/02 with resulting high yields and WUE's. An abnormal dry winter in 2003 led to sub-optimal production in 2003/04.

Regular soil moisture readings indicated that although the farmers intended to use their limited water resources efficiently, the availability of water in the root zone of the vines were not sufficient during all the phenological stages of berry development. Regular measurement of soil moisture and the accompanied adjustment to their irrigation scheduling brought about the required results.

The project resulted in an average increase of export tonnages of 12,3% over the 5 years of the project, mainly due to higher quality berries produced and thus a higher percentage of the harvest qualified for export. At the same time, the WUE was increased by 20,5%.

7.4 Pears: Cultivar: Forel and Packham: Ceres

Ceres is one of the main apple and pear producing areas in South Africa and climatic conditions play a major role in fruit production. The results are shown in Table 4 below:

Table 4: Average water use and production: Forel and Packham pears (Ceres).

Season	**99/00**	**00/01**	**01/02**	**02/03**	**03/04**
Average water use (m^3/ha)	9707	9403	8676	7703	7638
Average production (export ton/ha)	48,29	37,96	43,1	52,22	44,91
Average WUE (kg export fruit/m^3 water)	5,10	4,21	4,87	6,69	5,82

To determine the actual increase in WUE for these orchards proved very difficult due to the fact that the 1999/2000 harvest was the best harvest in many years due to a culmination of climatic and pomological factors and we thus started off with very high production per hectare during 1999/2000.

Over the five years of the project we nevertheless managed to reduce the water consumption by 21,3% and increased the WUE by 14,1%, with a highest increase in WUE of 31,2% in 2002/03.

8 Participants tot the project

Participants to the project are the Department of Agriculture: Western Cape, the relevant irrigation boards, participating producers, the Western Cape Regional Office of the Department of Water Affairs and Forestry and the Agricultural Research Council (ARC – analyses of soil samples).

9 Summary

In order to make provision for the climatologically differences of each year it was decided that the monitoring of water use will be continued for at least three years after the base line information has been gathered. The relative wet summer of the 2001/2002 season, confirmed this decision.

It is not only the climate of a specific irrigation season that impacts on the yield (tonnage and quality) of the crops, but also the climatic factors of the previous winter. The most important factors are rainfall, spread of rainfall, temperature, cold units and the climate during flowering.

The project was also extended to include potatoes in the Sandveld area (West Coast region) and wine grapes in the Vredendal region as from the 2002/2003 season.

The project is not completed yet and as such no final recommendations and findings can be made at this stage. It is however clear that in many instances producers strive to use the available water as efficient as possible. The big differences regarding the tonnage produced and the WUE between the different participating irrigation blocks however indicates that there is scope for improvement.

The data that is being collected can also be used in future during the process to evaluate water license applications, which has become compulsory in terms of the National Water Act of 1998. In this evaluation process the effective use of water will play a major role in deciding whether a water use license will be granted.

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Surface measurements of hydraulic properties in an irrigated soil using a disc permeameter

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Abstract

With a view to determining in situ the hydraulic properties of soils with macropores, disc permeameters are currently used which allow evaluation over time of water infiltration values and selective activation of preferential flow paths through variation in water supply potential imposed on the soil surface. It is then possible, through the resolution of wetting 3-D flow fields, to obtain soil hydraulic characteristics at or near saturation. In this study two different methods to calculate the hydraulic conductivity of a structured soil, based on disc-permeameter data, are compared. Laboratory core measurements based on the crust method are also used in the comparison. The first method based on a single disc at the same location with multiple water supply potentials gave results that are accurate, whereas the second method based on a single disc at different locations and water supply potentials gave biased values. The advantage of the examined equipment and procedures is that they are simple to apply and use. Moreover, useful applications of disc-permeameter techniques also consist in the measurement of soil structural parameters, especially pore size and areal macroporosity under irrigation practice.
Keywords: 3-D infiltration, disc permeameter, unsatured flow parameters.

1 Introduction

In recurrent open field situations, above all in soil surface layers, structural and textural variations as well as various geometric characteristics of the matrix may entail significant space-time variations in the processes of water and solute movement.

The action of raindrops, the boundary forces provoked by surface flows and chemo-physical factors linked to water quality may, on the soil surface, lead to

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disaggregation of the aggregates and the formation of less permeable crusts which condition the infiltration process.

Moreover, the presence of surface cracks which characterizes many vertic-soils, and the proliferation of macroporosity, caused by the ground fauna and by the great presence of roots, may create vertical by-passes and preferential flow paths which produce a transfer of the solutes during rain or irrigation, by means of infiltration water. Such a transfer occurs more rapidly than the advance of the average moisture front, with a consequent alteration of the space-time scales of the process of mass exchange between the various porous domains of the matrix (Beven and Germann, [1]).

In the light of the above mechanisms, the danger of widespread pollution processes has been confirmed with regard to particularly vulnerable underground water resources due to the extent of the boundary surface directly exposed to contributions from agricultural land use (Thomas and Phillips, [2]; White, [3]).
Today, numerous mathematical models based on the solution of Richards' equation allow the numerical simulation of water and pollutant transfer in the vadose zone and thus may be essential instruments for assessing environmental pollution. However, the solutions offered by such models may contain considerable errors in the case of structured soils with heterogeneous pore systems which cannot be adequately described by the generally used unimodal retention and hydraulic functions. In such cases, for characterizing the flow regime, it is essential to separate the flow through macropores from the one through the soil matrix (Bouma, [4]). Recognition of this dichotomy is important because the properties of the macroporous system tend to dominate the infiltration process at and near saturation, while drainage, redistribution and root water uptake depend on those hydraulic properties which reflect the nature of the matrix.

Given the complexity of the problem, specific macropore models have recently been set up (Jarvis et al., [5]; Chen and Wagenet, [6]; Gerke and van Genuchten, [7]) which may more simply be considered as dual-porosity models. Implementation of such models requires new technologies and, because of the ephemeral nature of macropores, a new class of experiments to be conducted, if possible, in the field, so as to obtain input data for quantifying soil hydraulic properties, macropore distribution and spatial variation of macropores.

Various methods to obtain macropore parameters have been set up, such as tracer-breakthrough curves, computerized tomography, dye-staining and sectioning (Bouma and Dekker, [8]; Warner et al., [9]). However, in most cases such methods require undisturbed soil samples and they cannot be easily transferred to the open field. More simple methods, as recently suggested, are based on measuring unconfined infiltration rates with a disc permeameter (Perroux and White, [10]; Watson and Luxmoore, [11]; Ankeny et al., [12]) or a surface crust to restrict flow rates into the soil (Booltink et al., [13]). By offering slight hydraulic resistance to water movement, discs and crusts allow a water supply potential h to be applied at the soil surface, with a negligible head loss. By appropriately choosing the resistance value and ensuring that h is only -0.01 to -0.02 m, an acceptable approximation of soil hydraulic conductivity is obtained, which excludes the macropore system. It is thus possible, by the resolution of the 3-dimensional moisture flow field, to obtain soil hydraulic properties for water content values near saturation.

Finally, it is worth mentioning particular calculation methods proposed in the literature and set up for estimating hydraulic conductivity from disc permeameter data. Among others, the most commonly used are those proposed by White and Sully [14] and by Ankeny et al. [12]. Such methods vary in complexity and simplificatory assumptions, as well as having different advantages and limitations.

In order to further our knowledge in this field, this paper presents an application of disc permeameter equipment, analysis techniques and procedures in the examination of field hydraulic conductivity of a structured soil.

In section 2 the constructional characteristics of the disc permeameter equipment are presented (2.1); the theoretical underpinning for using the disc permeameter to infer hydraulic conductivity are illustrates (2.2). Section 2.3 illustrates the physical properties of the soil in question, the methods of the infiltration test and the calculation procedures used. Finally, some considerations are made and several conclusions drawn.

2 Materials and methods

2.1 Disc-permeameter

The apparatus used to impose Dirichlet's boundary condition $h_0 \leq 0$ at the soil surface, in which h_0 is the water supply potential, are called tension infiltrometers or disc permeameters in the literature.

Following the design of Perroux and White [10], a prototype permeameter (figure 1) was set up jointly by the Institute of Agricultural Hydraulics of the University of Naples.

The permeameter in question consists of a bubble tower which may be considered a Mariotte double regulator connected to a perspex disc 200 mm in diameter covered by a porous nylon membrane with air entry value of approximately 0.25 m.

The first regulator allows us to apply via the membrane a constant water supply potential which can be controlled by adjusting the water level inside. The second regulator, which functions as a reservoir by means of a graduated scale, allows infiltration water volumes to be evaluated in time.

The experimental observations which may be carried out with such a device necessitate, between the base of the disc and the soil surface, that there is adequate hydraulic contact by means of a thin sand stratum previously wetted up to a volumetric water content close to 0.01.

2.2 Theory

The theoretical foundations for using a disc permeameter to infer soil hydraulic properties have been discussed in detail elsewhere (Perroux and White, [10]; Smetten and Clothier, [15]). Only the salient features are recalled below.

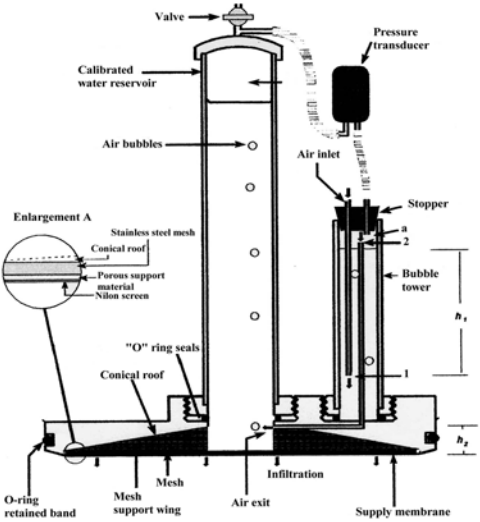

Figure 1: Schematic diagram of disc permeameter.

2.2.1 Sorptivity

The water flow emanating from a disc source according to Dirichlet's boundary condition:

$$h = h_0 \leq 0; \quad z = 0; \quad t > 0$$

where h_0 is the water supply potential, z is the depth and t is the time, is initially controlled by soil capillarity (Philip, [16]):

$$\lim_{t \to 0} \left[\frac{Q(t)}{\pi r^2} \right] = 1/2 S_0 \, t^{-1/2} \tag{1}$$

in which Q is the flow rate $[L^3 T^{-1}]$ from the disc source, t the time, r the radius of the source [L], $S_0 = S(h_0, h_n)$ the sorptivity $[LT^{-1/2}]$ and h_0 and h_n, respectively, the supply and initial water potential [L].

Integrating eqn. 1 with regard to t, we obtain:

$$I = S_0 t^{1/2} \tag{2}$$

in which I is the cumulated infiltration [L].

For lower time values starting from infiltrated water volumes, S_0 may be simply deduced from the slope of I with regard to $\sqrt{t}$.

The geometric time scale of Philip [16], t_{geom}, may be used to evaluate when the geometric dominance of disc source should have been established. This time is considered to be:

$$t_{geom} = \left[\frac{r \Delta\theta}{S} \right]^2 \tag{3}$$

in which $\Delta\theta = \theta_0 - \theta_n$; θ_0 and θ_n are, respectively, water content values corresponding to the supply and initial water potential.

2.2.2 Steady state flow

The water flow rate will reach a stationary value henceforth termed Q_∞ for greater time values (Philip [17]).

In the case of multi-dimensional flow processes, Philip [18] showed that a characteristic time scale t^* for the steady state flow rate is that for which the flow from the source is 1.05 times the steady flow rate. His calculations show that when the characteristic size of source r equals or exceeds the macroscopic capillary length scale, λ_c, an “innate soil length scale” as defined by Raats [19], then it may be held that $t^*=t_{grav}$, with t_{grav} given by:

$$t_{grav} = \left(\frac{S}{k_0} \right)^2 \tag{4}$$

The above findings were recently confirmed by Warrick's studies [20]. Physically, t_{grav} represents the time in which the effects of gravity equal the effects of capillarity (Philip, [16]).

In the case of "alpha" soils, that is those soils in which hydraulic conductivity takes the exponential form (Gardner, [21]):

$$k = k_0 \exp(\alpha h)$$

in which k_0 is the saturated hydraulic conductivity and α a constant equivalent to λ_c^{-1}, Wooding [22] showed that the steady flow from the source, for an assigned value of water supply potential, may be approximated with sufficient accuracy by the following expression:

$$\frac{Q_\infty}{\pi r^2} = \Delta k \left[1 + \frac{4\lambda_c}{\pi r} \right] \tag{5}$$

in which $\Delta k = k_0 - k_n$.

Subsequently, White and Sully [14] demonstrated that between the characteristic length scale λ_c, sorptivity and hydraulic conductivity, there may be the following type of relation:

$$\lambda_c = \frac{bS^2}{\Delta\theta \Delta k} \tag{6}$$

in which b ($1/2 \le b \le \pi/4$) is a shape factor frequently set at approximately 0.55 for agricultural soils.

If, as happens in many open field situations, it may be assumed that: $\Delta k = k_0 = k$ and if we substitute eqn. (6) in (5), the following simplified expression is obtained:

$$\frac{Q_\infty}{\pi r^2} = k + \frac{2.2S^2}{\Delta\theta \pi r} \tag{7}$$

An alternative approach based only on Wooding's solution is possible when we know the flows Q_∞ corresponding to the different r values of the source (Scotter et al., [23], Smetten and Clothier, [15]). This approach allows k and λ_c to be evaluated directly, thereby solving two type (5) equations.

The same principle may be applied for a single r of the disc source but with infiltration measurements at multiple potentials (Ankeny, [12]). In particular, in this case, if the flow is measured with a single disc source at two pre-established potential values h_1 and h_2, two type (5) equations are obtained, which may be solved simultaneously, thereby supplying:

$$k_1 = \frac{Q_1}{\pi r^2 + 2\Delta h r\left(1+\frac{Q_2}{Q_1}\right)\left(1-\frac{Q_2}{Q_1}\right)}$$

$$k_2 = \frac{Q_2 k_1}{Q_1} \tag{8}$$

$$\lambda_c = \frac{\Delta h(k_1 + k_2)}{2(k_1 - k_2)}$$

in which Q_1 and Q_2 are, respectively, Q_∞ at h_1 and h_2.

2.3 Soil site and measurements

Infiltration tests were conducted in the spring of 1994 at the experimental farm of the University of Basilicata near Corleto (Potenza, Italy) on a bare soil which had undergone minimum tillage during the winter. The dominant soil at the experimental site is sandy clay with a clay content of approximately 30% as shown in figure 2.

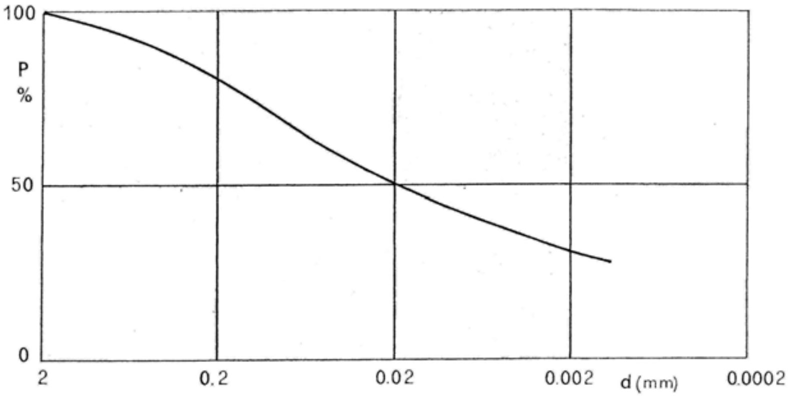

Figure 2: Particle size distribution of examined soil.

From the pedological point of view, the soil may be classified as "vertic ustorthens" according to the USDA classification system. Other important properties comprise moderate permeability and the vertic traits of clayey land which cracking renders quite appreciable during the summer.

At the test location one (1x1 m^2) plot was isolated and subdivided into 4 equal subplots of 0.5x0.5 m^2. To determine soil hydraulic conductivity with White and Sully's method [14], three water supply potentials were used (-0.02; -0.06; -0.10 m), each in a single subplot.

According to the Ankeny et al. method [12], in the 4th subplot the disc permeameter was not moved for trials at the three potentials (-0.06; -0.04; -0.02 m). With this method, steady state flows were measured in an ascending sequence of supply potentials: first with a -0.06 m water supply potential followed by -0.04 and -0.02 m.

In each subplot, three undisturbed soil samples, 4.8 cm in diameter and 2.8 cm in height, were taken from the soil surface before and after the infiltration tests in order to measure bulk density and volumetric surface water content θ corresponding to h_0 and h_1. The mean dry bulk density of the first 2.8 cm of soil measured on undisturbed soil samples was estimated at 1.198 g/cm^3 and the standard deviation at 0.05 g/cm^3.

Following disc permeameter measurements, the soil was allowed to drain for about three hours and then an undisturbed soil sample 15 cm in diameter and 20 cm high was dug out of the 4th subplot immediately below the porous disc, to measure the hydraulic conductivity in the laboratory with the crust method (Booltink et al., [13]).

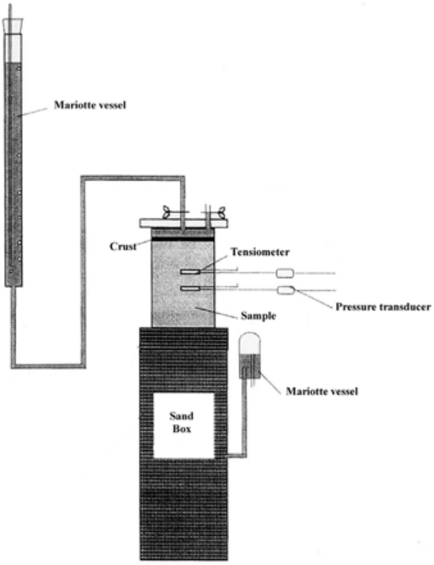

Figure 3: Apparatus for measuring soil hydraulic conductivity by *crust method*.

This method requires a pedestal of soil and a Stackman sand filter (figure 3) for draining the soil samples slowly saturated from the base. Conductivity values are determined during steady vertically downward flow under unit hydraulic gradient measured with small tensiometers. Once it has been ascertained that the water flux density in is equal to the water flux density out, the hydraulic conductivity will be equal to the imposed water flux. Moreover, it is worth noting that under the condition of unit hydraulic head gradient the matric potential at different depths is uniform, the water content is fairly uniform and, consequently, the accuracy in the estimate of k will only depend on measurement errors. Thus, the function $k(h)$ of the soil in question was deduced with great accuracy, applying a series of steady water flux densities for an extended period of time by means of a porous disc connected to a bubble tower to control the water supply potential in a field of variation between 0 and -0.20 m and evaluating the hydraulic gradient from the tensiometer measurements at depths of 0.025 and 0.075 m.

3 Results and discussion

White and Sully [14]) calculate sorptivity by means of eqn. (2). By contrast, Q_∞ is estimated for greater time values and the same authors use eqns. (6) and (7) to calculate the hydraulic conductivity. Thus, in using eqn. (6) $\Delta\theta$ is still required.

The main theoretical assumption underpinning the method is that cumulative infiltration I for lower t values varies linearly with the square root of time and, for greater values, linearly with t. figures 4a and 4b show that for the soil in question the features of flow theory for disc permeameters are satisfied.

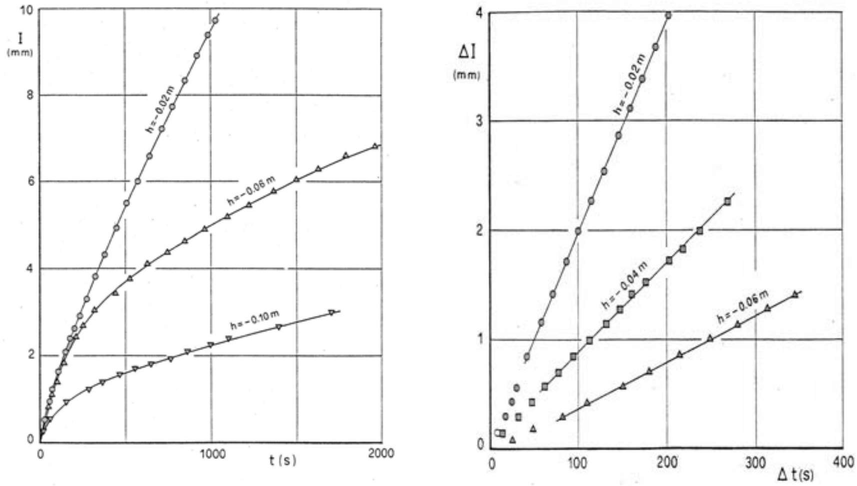

Figure 4: a) In situ cumulative infiltration over time and b) over square root of time, during 3-D flow from disc permeameter for 3 water supply potentials at 3 measurements sites.

Indeed, the above figures clearly show that for the 3 different water supply potentials, data quality is sufficient and that data are always widely available to determine S_o by regression of I against t at the straight line portion of figure 3b for t values from 0 to roughly 100 s. On the other hand, Q_∞ may be evaluated by regression of $I(t)$ against t for the long straight portion of figure 4a. In the observed situation, it seems reasonable to expect a steady flow rate within less than an hour, which allows sufficient Q_∞ data to be obtained most rapidly. This last consideration is interesting in the case where it is intended to conduct inquiries to ascertain the level and pattern of spatial or temporal variability.

Amongst the methods based on Wooding's equation (5), the method proposed by Ankeny et al. [12] is based only on measurements of steady-state flow rate Q_∞. However, determining when Q_∞ is reached may be very difficult (Warrick, [20]).

With regard to figure 5, for the soil in question the mean time for reaching steady-state flow for the -0.06 m water potential was 100 s, followed by 400s to attain steady-state flow at -0.04 m water potential and finally 650 s for -0.02 water potential. In the above case, Q_∞ is obtained by the regression of $I(t)$ against t from figure 4 and eqns. (8) are used to calculate conductivity k.

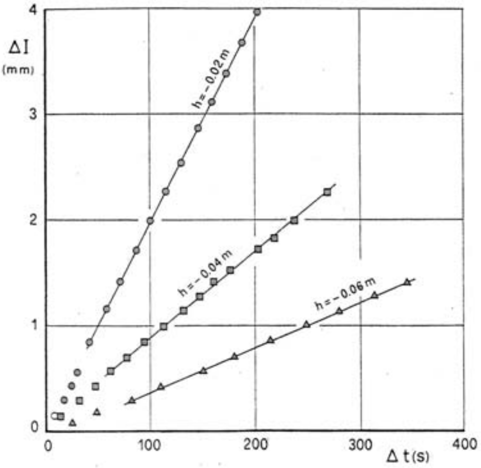

Figure 5: Steady-state flow intake for 3 water supply potential at the same measurement site.

Unlike the White and Sully method, in the Ankeny method measurements of θ_0 and θ_n are entirely avoided.

The conductivity values calculated by the various methods adopted are given in figure 6, which also supplies, for the sake of comparison, laboratory core measurements of k based on the crust method.

In particular, note that the k values calculated by the Ankeny method are in good agreement with the k values determined with the crust method. In any case, the bias ascertained for the White and Sully method to underestimate k values is within less than one order of magnitude.

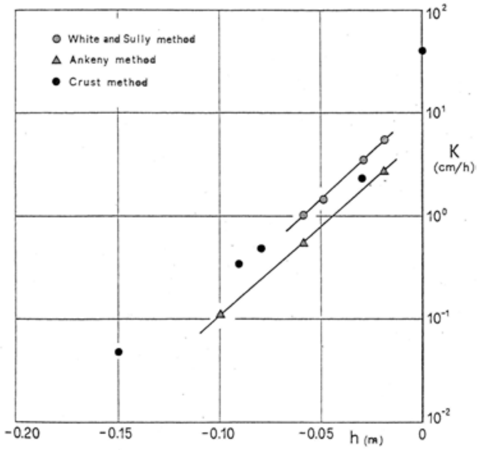

Figure 6: Comparison of estimates of unsaturated hydraulic conductivity obtained using White and Sully method [14]; Ankeny et al. method [12]; Boolting et al. method (=crust method) [13].

The analysis of behaviour at the origin of function $k(h)$ evidences a bimodal distribution of the porous system of the examined soil, with a water potential break-point at ≅ -0.03 m. With the increase in water potential from -0.02 m to 0, hydraulic conductivity increases by about an order of magnitude, nonetheless assuming numerical values greater than those measured in a previous measuring campaign (Ciollaro et al., [24]) on undisturbed soil samples taken in the same sites. Such behaviour suggests that the structural porosity of this clay soil may play a dominant role in determining the pattern of water flow in the field.

Furthermore, to represent this bimodal pore system, a two-line regression model may be more responsive than the usual linear model, or than the model with several parameters proposed by van Genuchten [25]. Such findings were also reached by Messing and Jarvis [26] in a similar pedological context.

Philip [27], starting from macroscopic capillary length λ_c, infers a representative pore size λ_m (mm) by using the capillary theory:

$$\lambda_m = \frac{\tau}{\rho g \lambda_c} \cong \frac{7.4}{\lambda_c} \tag{9}$$

in which τ and ρ are, respectively, the surface tension and the water density, and g is the acceleration of gravity. The characteristic size λ_m defined by White and Sully [14] to be a "physically plausible flow weighted pore size" may be considered a representative index of soil structure.

Starting from the measured values of S_0, k and $\Delta\theta$, estimates were made by means of eqn. (9) of λ_m values which are supplied in table 1 together with the values of λ_c and t_{grav}.

Table 1: Values of the physical and hydraulic properties of examined soil.

h (m)	S (mm/s$^{1/2}$)	$\Delta\theta$	k (mm/s)	t_{grav} (h)	λ_c (mm)	λ_m (µm)
-0.020	0.193	0.180	0.00697	0.17	13.1	572
-0.060	0.161	0.146	0.00154	3.04	64.4	118
-0.100	0.095	0.090	0.00035	21.20	122.6	61

Examination of the table shows that the bimodal distribution is clearly evidenced by λ_m which shows a 9-fold change between -0.02 and -0.1 m water potential compared with a 5-fold change between -0.02 and -0.06 water potential and only a 2-fold change between -0.06 and -0.1 m water potential. At h>-0.06 m the influence of capillarity is very strong and t_{grav} is large. However, macropore flow increases as h approaches 0 and thus gravity flow is dominant at h<-0.06 m.

4 Conclusions

The Australian School of Soil Physics must take the credit for having made a great contribution in the analysis of multi-dimensional infiltration processes. Today, with a new class of experiments, it is possible to apply to the soil surface, via a porous membrane, a controlled water supply potential with water infiltrating according to Dirichlet's boundary condition. Infiltration is then evaluated as unsteady flow or it is possible to monitor the quasi-steady infiltration which follows the condition for which dI/dt is constant. By then applying the theory of 3-D steady infiltration, soil hydraulic properties at or near saturation may be inferred, thereby breaking the existing link between gravity, capillarity and geometry of the disc source, as is evident in the analysis performed in section 2 of Materials and Methods.

With regard to the soil considered, the results obtained show good agreement between the methods used for determining hydraulic conductivity. The Ankeny et al. method [12] undoubtedly supplies the most accurate and reproducible results, and only requires steady state flows for 2 or 3 water supply potentials at the same locations, with the possibility of reducing the noise on $k(h)$ estimates caused by spatial variability. The bias of the White and Sully method [14] in underestimating k could be attributed to the increasing spatial variability of hydraulic properties and previous volumetric water contents of the soil among the measuring sites. In situations of accentuated heterogeneity, as reported by Logsdon and Jaynes [28], the White and Sully calculations could even provide negative k values.

In the light of the experience gained in this study, in the case of fine texture soils it would appear necessary to automatize the method, which would allow more accurate estimates of sorptivity. Finally, it is expected that there will be further and more extensive testing of the various methods, with a view to defining the hydrologic effects of soil structure, by using data from infiltration tests to be carried out on pedologically different soils. Such research efforts are clearly important for the quantitative assessment of soil management practices, soil irrigation and for studies of land degradation.

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The contribution of water accounting to irrigation efficiency

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Abstract

Water accounting can be a key to optimising the yield from water stored in dams. In particular, where large numbers of water users are supplied from a headwork, accurate accounting of each user's water during and between seasons and years can provide flexibility to water users and dam operators alike.

With diversification of irrigation, creativity in managing risk, both for dam operation and water use, becomes more important as a means to facilitate irrigators' varying and changing water requirements. In eastern Australia, parallel water accounting methods were developed by State governments, with slightly different features, related to the variety of climate, irrigation enterprise and levels of supply reliability suitable to the water users. The major rivers experience significant-to-extreme annual fluctuations in flow; consequently, water accounting methods developed to provide differential supply reliability from the same dam and foster economic productivity by providing irrigators with some choice in supply characteristics. Further, accounting has facilitated water saving between years and a degree of borrowing from future years, as well as reinforcing in the minds of irrigators the level of risk their choices reflect. This paper outlines the development of water accounting in Australia, the pre-requisites for its introduction, as well as its potential role and benefits for irrigation.

Keywords: water allocation and distribution, dam operation, irrigation efficiency, sustainability, river management, water accounting, capacity sharing.

1 Introduction

Irrigation schemes normally contain large numbers of water users, but the allocation and distribution of water is commonly managed uniformly and

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relatively inflexibly. Water accounting can have a role in permitting flexibility in several aspects of irrigation management, including (i) providing differential water volumes among irrigators (although infrastructure and layout may impose limitations – as in inter-connected paddy rice areas), (ii) allowing the continuation of water entitlements between seasons or years, (iii) providing differential long-term reliability, (iv) giving irrigators greater control over the timing, volume and long-term reliability of their supply.

Water accounting is defined as any method for assigning a volumetric account to each water user, which represents the water to which that user is entitled. The water account is maintained in a similar fashion to a monetary account, with inflows (deposits) and outflows and other reductions (withdrawals and fees). Knowing the amount of water in the account is useful to both the dam operator and the water user. Water accounting is closely related to water rights, whether or not the rights are legally formalised, but without legal security an effective water accounting system is more difficult to maintain because some of its value in providing certainty to the water user is counteracted.

Reliability of supply refers to the degree to which an individual's water entitlement can be satisfied in the long term. Water availability means the extent to which water is predicted to be available in a specified accounting period. In Australia, reliability is estimated by modelling, using data from the past 100 years or more and projecting equivalent climate and river flow into the following 100 years. Availability is determined by the conditions at the start of the accounting period and an assessment of possible changes during that period. Availability normally increases as conditions (for example inflows to the dam) improve.

Establishing water accounts for the water held behind a dam in storage, is a way to link the headwork element of an irrigation scheme with its downstream water distribution network. There is a tendency for the operation of large dams to be separated from the irrigation channel schemes they supply. However, water accounts directly linked to irrigators should help to ensure that the operation of both the dam and the distribution channels are meeting irrigators' requirements.

2 Water rights and accounting in Australia

2.1 Origin and development of water rights

Australia is the second driest continent after Antarctica. Hence, water for irrigation and other uses has relied on major infrastructure development starting early in the twentieth century. After the more economic water supply options had been taken up, focus shifted to improving the performance of existing schemes within sustainable limits. The need to better define available water and estimate long-term reliability provided the impetus for developing water user accounts. It also allowed the water requirements of the environment vis-à-vis water users to be better defined and it can accommodate changes to climatic conditions cater for improved understanding of ecological water requirements.

The current legal basis for water allocation in Australia originated in the 18th century application of the British common law by colonial governments, including the riparian doctrine which defines the rights of land owners to take water from streams. That legal regime failed in Australia because rivers were too extended and their flow too variable, so that land holders were taking it upon themselves to cut into upstream dams to obtain a '*reasonable*' flow downstream. Furthermore, it was impossible to build a dam in the upper reaches of a river and guarantee the water would flow to a distant downstream diversion point without interference from riparians. Late in the 19th century, royal commissions were held to investigate these problems, resulting in changes to the law (eg Victoria *Irrigation Act, 1886*, New South Wales, *Water Rights Act, 1896*) so that it was generally decided to vest water rights (*the use, flow and control of water*) in the Crown – a situation which continues to the present. Thereafter, the colonial (subsequently State) governments allocated water by the issue of licences and permits.

That change paved the way for a program of dam building from early in the 20th century until the 1990s. When large dams were constructed, their water was assigned firstly to government built irrigation schemes and later to individuals outside the schemes. Burrinjuck Dam on the Murrumbidgee River, the most prolific major tributary of the Murray River, was completed in 1914, while the Murrumbidgee Irrigation Areas (MIA), which it supplied, were completed shortly afterwards, some 500 km downstream, through a 150 km diversion canal. When land in the MIA was apportioned to prospective irrigators, the volumes to be supplied were estimated by taking water orders and calculating the area to be irrigated, along with a formula for transit 'losses'. Private landholders along the river could apply for a licence for some of this water, which specified an area permitted to be irrigated. The area 'entitlement' or more accurately, a water order stating the area to be irrigated at the time, was then used by the dam operator to calculate how much water should be released.

Differences in irrigation enterprise and climate led to differences in water allocation schemes. Water use in northern Victoria was mainly supplied for the irrigation of improved pasture for dairying, which required a very reliable annual supply, as farmers would lose their milk quota if it was not fulfilled every year. Therefore, the Victorian government settled on a 'water right' at a level which could be supplied in all years except for the driest. This was possible because the flow in the Murray and Goulburn rivers, the main sources for northern Victoria, was more reliable than most tributaries of the Murray River to the north. If water remained available after the water right had been supplied, further 'sales water' would be announced for purchase. Over time, many irrigators came to rely annually on some sales water, as though it was part of their core entitlement.

By contrast, in New South Wales (NSW), rice growing made the major demand on water in the southern valleys. Although horticulture was important, it consumed less water. Rice, as an annual (non-staple) crop, could be planted in greater or lesser areas from year to year, and even if no water was available at all in a particular year, the enterprise could continue the following year. Many farmers in NSW therefore preferred a less conservative approach, because they could take greater advantage of good supply years and accept a greater risk of shortfall the following year – a 'use it now' policy.

This less conservative approach was given support after the review of Keepit Dam in 1969 (Munro et al. [1]), when its yield was found to be significantly less than originally estimated. The study led to the promotion of financial as well as hydrologic risk as the basis for public expenditure on water infrastructure and these principles were applied to dam design methodology (Munro [2]). Munro argued, after investigating Keepit Dam that "*irrigation dams should not be regarded primarily as a drought- proofing project, but rather as a means of increasing production in non-drought years*", and "*the system of operating the dams should aim at irrigating the area which will provide optimum national net benefit*". This approach formed the basis of water licensing policy in NSW for the next 20 years. This view was formed on the basis of calculations which seemed to demonstrate that taking as much advantage of 'normal' and 'good' years, by expanding production in those circumstances, would outweigh the benefits in the long term of operating more conservatively in order to provide irrigation drought-proofing. At the same time, some water uses, such as town water supply, still required a much more reliable supply from year to year.

2.2 Change to volumetric allocation

The Keepit Dam review and drought in the 1960's were the triggers for a shift to volumetric allocation of water in NSW. In order to give farmers an incentive to measure their water use and conserve water, as well as to ensure maximum efficiency of the dams, a state-wide volumetric conversion programme was initiated. The conversion formulae were intended to be based on history of water use, but ultimately political factors ensured that a uniform megalitre-per-hectare figure was applied for annual crops state-wide. Perennials such as fruit trees, vines and other 'permanent plantings' were given an annual volume entitlement along with 'high security' status, meaning higher priority. This laid the foundation for a two-class system of water entitlements for irrigation, applied in practice by dam operators retaining a volume of water in storage to guarantee a full supply for 'high security' water uses in the following year.

From this point, the availability of water at the beginning of each water year was defined as a percentage of the entitlement volume, calculated by estimating total water demand against water in storage and expected minimum inflow during the year. Thus, if 78% was announced, each irrigator on a 'normal' licence knew that 78% of the licensed entitlement volume was guaranteed for the year, although if good inflows occurred during the season, that percentage could be progressively revised upward. This situation led in turn to irrigators taking a greater interest in the nature of the risk of shortfall and planting accordingly.

2.3 Development of water accounting

The calculation of annual water availability requires information on future (next year's) demand, likely catchment runoff and river flow, dam storage behaviour and tributary flow contributions. However, to provide better estimates, predictive river models, initially based on long term monthly data and later upgraded to daily data, were developed to incorporate all the above (Simons [4]). This became very important in the 1990's when environmental water requirements were being identified and later included in statutory water sharing plans.

The dams are managed during the irrigation season using operational models which enable dam operator to decide how much water to release from time to time. Dam releases of water are adjusted daily or several times per day depending on downstream tributary inflows. These operational models are based on the predictive models but are continually re-calibrated using real time data. Any inflow during the current year is assigned to water entitlements to the point where 100% of current year's entitlement is available and the water set aside for the following year is also taken care of. Flow from tributaries entering the river downstream of the dam are also introduce into the accounts, as this uncontrolled flow needs to be made available to irrigators in place of water from the storage. During low-to-normal flows, dam releases are determined, using gauging stations located at the same travel time as the dam from water user off-take points.

The combination of a volumetric entitlement linked to water storage in the headworks, and the progressive updating by adding and subtracting from the entitlement, amounted to a de facto water accounting system. The next step was to allow some carrying over of entitlements to the following year. Thus, if less than 100% of that year's entitlement was taken by the irrigator (remembering that if availability was less than 100%, the water user was not entitled to more), a certain proportion could be held over in storage and used the following year – in addition to the normal entitlement for that year. Farmers could benefit when a dry year was expected, along with a decision to use less water in the current year. However, some penalties applied to such carry-overs (to recognise evaporation losses and to prevent excessive storage of water) which could not be retained indefinitely without being lost. Borrowing from a future year was also permitted within limits.

These developments were providing irrigators with greater flexibility and were moving towards a system where water entitlements, being accounted separately, were becoming individualised.

Figure 1 shows the categories of water in the accounting scheme for New South Wales, and the manner in which carry-over and borrowing is accounted. The environment's water needs have legal priority in New South Wales. Therefore, all other water entitlements must be calculated after environmental water provisions have been established. The current arrangement uses a planning system in which water for the environment is excluded from water which may be abstracted for irrigation, by the application of environmental flow rules (such as minimum flow requirements) or through specific allocation for environmental purposes (e.g. 160,000 megalitres per year for the Macquarie Marshes, an internationally recognized wetland). Water may also be purchased from licensed water users by the government or a private person, to provide additional environmental benefits.

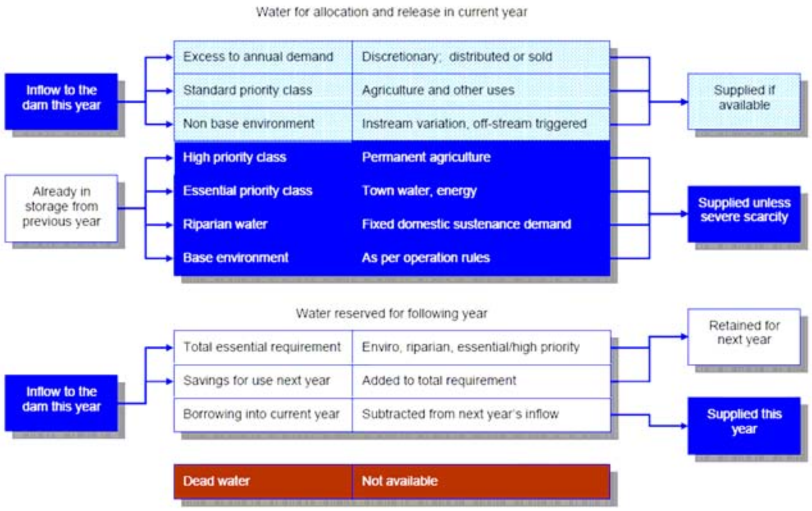

Figure 1: Example of categories of water in storage.

At the start of the water year, a determination of 'available water' is made and, on that basis, the dam operator releases water for the environment and the various classes of water user. In NSW, a riparian flow is also assigned for access by landholders who do not require a licence, but are allowed to take a restricted amount of water from rivers for domestic purposes. Water trading is also legally permitted, both temporary (meaning for one year or part of a year only) and permanent. When trades are made, the dam operator must adjust the relevant water accounts in the storage. Although the water accounting example shown in Figure 1 appears complex, in practice it is well understood by irrigators who are familiar with it as it applies to them.

An associated mechanism, known as capacity sharing, is also being used in Australia. Capacity sharing of water in storage is the method whereby the space in the storage is divided into shares, each of which is assigned to a different user, who also receive a proportion of inflow to the dam (Taylor et al. [3]). There are two examples of its use on a large scale, but with few users or 'shares'. Firstly, Lake Eucumbene, incorporated into the Snowy Hydro scheme, is divided into two 'developments' which earmark the water for discharge to the Murray River or the Tumut River. The water runs though a three-tier hydro-power facility in each case but to a different river. This was worked out to satisfy the water sharing interests of the States of New South Wales and Victoria, since the water was differently owned, depending on its destination. The second example, governed by the Murray-Darling Basin Agreement, involves the water sharing rights of the same two States. The storage space in the headwork dams, Hume and Dartmouth, is notionally divided equally into two halves in which inflow is stored for the two States. In the past, the State water shares were re-set to zero and the end of each year. As a result, NSW was taking more than 50% of the water because of its less conservative policy, and Victoria was therefore unhappy. The capacity sharing arrangement redresses the balance to a significant degree by allowing Victoria to hold up to 50% of storage space, after which further inflow, which would otherwise be allocated to Victoria, 'spills' into NSW's storage space and water account.

Capacity sharing has been promoted as the ultimate water allocation methodology for large numbers of water users, which would give water users complete control over their entitlements and allow them to act quite independently of other entitlement holders. In reality, capacity sharing must be tempered by general rules governing storage losses, and minimum and maximum storage volumes need to be applied in order to protect the economic efficiency of the dam and the value of all water entitlements. Further, changes over time in user demand pattern and reliability criteria cannot be completely cordoned off from the behaviour of the dam storage as whole. Capacity sharing for large numbers of water users was investigated by the governments of New South Wales and Victoria and rejected on the grounds of cost versus estimated benefit.

3 Features of storage water accounting

3.1 Prerequisites

Since governments are increasingly promoting improved irrigation performance and diversification, the benefits of dam storage water accounting should be considered. However, there are prerequisites, chiefly that water must be allocated by volume and its supply and use measured. Prerequisites for a water accounting system, as described earlier, are (i) a volumetric water entitlement system, preferably legally supported so that water entitlements are not subject to a dam or irrigation scheme operator's manipulation beyond operational and technical elements – i.e. entitlements cannot be administratively or arbitrarily re-allocated or significantly altered in value by an agency except with due legal process, (ii) a sufficiently accurate measuring and recording system to update the account that defines the volume to which the user is entitled, (iii) an information system which provides current data to the dam operator and water user about water used, water available and predicted availability, (iv) a model that provides information on catchment and river system (all significant inflows to the point of water diversion) and predicts its behaviour under various operation and water demand scenarios. The options open to irrigators are also important.

3.2 Benefits of water accounting

Water accounting can assist in the provision of differential grades of reliability. Reliability (as an assurance of receiving the full volume of the entitlement in the long term) can be traded off against volume. This is occurring in the eastern States of Australia, under the general system, based on classes of priority. Thus, based on a conversion factor, a larger volume of water can be converted to a lesser volume with higher reliability. There are limits to such exchanges, because a dam supplying only entitlements with a high level of reliability would have to retain a large volume of water for the following year. This is the case for dams devoted entirely to urban and domestic water supply, where future certainty is very important, but the question of high degree of certainty versus volume is more relevant to irrigation. The natural tendency is to design for and promise a very reliable supply, but it may be the case that the long term economic benefit to irrigators would be greater in the long term if they took a greater risk. However, there are important social and economic factors to consider. Unless irrigators are able to survive a poor year or a series of poor years, they cannot so readily capitalise on the better years. Irrigators must also have the capacity to modify their agricultural practices in line with water availability. In many countries farmers do not have great flexibility.

Water accounting facilitates short-term water trading in Australia, where water is purchased for a single season or year, because both buyer and seller have a better understanding of the value of the remaining water entitlement. Water can be purchased part way through the year when a water user realises that more or less is needed to finish crop requirements.

Water accounts need adjustment in line with changes occurring to the whole of the storage and supply regime controlled by the dam and its operator. The factors affecting river management do not remain static in the long term, and therefore operation rules and guidelines need to be modified progressively.

Possible change factors for irrigation supplied from headworks include (i) location of irrigated area, (ii) extent of irrigated area – increase or decrease, (iii) type of crop and related demand pattern – seasonal timing, (iv) intensity of water application, (v) reliability requirement. Other changes to flow patterns may occur due to upstream diversions, change in catchment condition, urban development, climate change and change in the quality of water. In response, the dam operator needs to consider whether the value of water the entitlements of any group of water users or specific individuals will be significantly affected. An accounting system such as described helps the operator to identify the impacts of such changes and also to adjust for them.

The creation of water accounts call attention to the fact that each irrigator has a right to a specific volume of water in the headwork storage. Irrigators tend to take a more proprietary attitude to such accounts and consider them to be in the nature of a property. This may be intended by those who manage the schemes. In this view, the dam operator acts a storekeeper who manages accounts that belong to others, namely the water users. Likewise, an expectation may grow that the water should be more at the water user's disposal. This change of mind-set could have implications for the relationship between irrigation scheme management and water users – promoting the idea that the scheme is a service which only operates for the benefits of the farmers, rather than the more paternalistic model as an institution which decides how and when to distribute water. This aspect should be recognised in any case where water accounting is being considered. Ideally the relationship between operator and irrigators is one of mutual negotiation and agreement on the nature of the services and the related operational rules and decisions.

3.3 Risk sharing and risk management

An important outcome of water accounting is the fostering of a risk management approach by irrigators. This is demonstrably the case in Australia, where many irrigators, knowing that water availability fluctuates from year to year, are used to estimating the risk of shortfall and deciding how to proceed. Their understanding of risk results from experience in predicting the likelihood of water becoming available during the annual cycle, and where they have the ability to decide how much or what crop to plant, they learn from their decisions. Water accounting also causes water users to think volumetrically, provided they have some control over the diversion of water to the farm and an incentive to conserve water. Such thinking is conducive to the promotion of risk-sharing between irrigation scheme operators and irrigators, and the understanding of how to manage risk to advantage.

The recent Australian Intergovernmental Agreement on a National Water Initiative [5] identifies who should bear the risk of possible future reductions in water entitlement resulting from seasonal or long term changes in climate, increases in the knowledge of rivers' capacity to sustain water abstraction levels and increases in extraction and better understanding of the water needs of the environment. The National Water Initiative has specified a formula for cost sharing between water users and State and Federal governments.

4 Conclusions

Water accounting methods in south-eastern Australia evolved following the volumetric conversion of irrigation water entitlements, which drove the idea that the volume of water assigned to each water user should be clearly identified. This in turn enabled more flexible water management with a number of important characteristics, namely (i) widening of choices by the water user as to how much water to use in any season or year, (ii) adoption of some risk by water users, (iii) incentives for efficient water use, and (iv) facilitation of water trading. Water accounting also allows water users to obtain a more exact definition of the water to which they are entitled at any time.

Water accounting is most likely to provide benefits where (i) there is relatively frequent and significant water scarcity and failure to fulfil water demand, (ii) two or more types of water user with differential reliability requirements or demand patterns are supplied from the same headworks, or there is an opportunity to develop differential types of irrigation, (iii) irrigators have the ability to make individual choices about how much water to apply to land and what land to irrigate.

Finally, water accounting is a basic mechanism to achieve and maintain sustainable irrigation both from an economic and ecological perspective. It allows for orderly changes in demand and supply and reduces conflict between users and also enables environmental requirements to be identified and managed.

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Crop management in a district within the Ebro River Basin using remote sensing techniques to estimate and map irrigation volumes

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Abstract

An assessment of water management in the Flumen District, Central Valley of the Ebro River Basin in Spain, using the remote sensing technique *Surface Energy Balance Algorithm for Land* (SEBAL) was performed. This assessment was based on the estimation of the actual ET (ET_a) to compute net water volumes (Vn). This work extended the analysis by also computing net irrigation volumes (Vi) by introducing a water application efficiency as a function of morphopedologic units (Ea_m). Two approaches were adopted for SEBAL Vi: a) the crop water demands including months outside the crop season (SEBAL_F1) and b) the crop water demands of the six main crops only in the growing season (SEBAL_F2). The comparison analyses for SEBAL_F1 and SEBAL_F2 Vi show a very good agreement with a bias of 0.09 hm^3 and 0.56 hm^3, respectively. As a result of an accurate estimation of Vi, the water use efficiency (Ea) for the whole Flumen District was determined to be from 80% to 90%. These are actual figures, thus it is possible to review the current crop and water management, identifying the possible causes for low irrigation efficiency on some plots.

Keywords: crop water requirements, remote sensing, evapotranspiration, SEBAL, IRRIVOL, water resources management, Ebro Basin, Flumen District.

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1 Introduction

For several hydrological and agricultural issues such as water resources management, irrigation scheduling, crop water requirements and others, to know how they are affected by the climatic and agronomic variations (soil and plant conditions) is basic. In order to cope with these variations it has been demonstrated that a confident estimation of evapotranspiration (ET) is essential, not only because it provides information that can be applied directly in the water budget, but also because ET has a high sensitivity which can be used to define some biophysical parameters [1]. Direct and indirect ET methods have been developed and give a good accuracy, however, some authors such as Schultz and Engman [2] have demonstrated that studies based on conventional field data collection are often limited because they cover only the area close to the weather station. Although this ET estimation is adequate for local studies, in large irrigated areas it is important to have reliable spatial and temporal ET values to determine the actual crop water demands and the water need over time. It is important to consider spatially distributed data covering any time period throughout the system. As no conventional method can be regarded as suitable to cover both spatial and temporal scale [3] and because the constant lack of data [4], an important alternative has been the introduction of remotely sensed data. This data can provide information about a specific crop and land condition covering both spatial and time variations. It has been demonstrated [2] that the combination of remotely sensed and ground-meteorological data can create more realistic and physically based models to analyse heterogeneous evaporative surfaces. Reliable ET_a values produce accurate estimations of the real crop water requirements (WR_n) and net crop water volumes (Vn) for the irrigated districts.

In a first attempt [5], the Surface Energy Balance Algorithm for Land (SEBAL) [6] was applied to provide reliable ET_a values for large areas. These values were used as input data in water management models such as the IRRIVOL methodology used in the Flumen district at the Central Ebro Valley (CEV), Spain [7]. A general problem in the Ebro Basin is the low water efficiency associated with the irrigation districts [8]. The direct benefits of accurate Vn values are the improvement of the water use. The conclusions of this study indicated that despite some variations observed between SEBAL and IRRIVOL, which uses the Blaney and Criddle equation to compute crop ET (ET_c) [9], the agreement was good. The variations observed were mainly associated to climatic factors (haze and *bochorno wind*) present during the image capture. Once these variations were detected and removed from the analysis, the agreement obtained between both methods improved significantly. This confirmed that the SEBAL method provides ET_a data that represents the actual spatial field conditions. However, for WR_n and Vn, the agreement between SEBAL and IRRIVOL was fair. The variations between the two methods could be ascribed to an arrange of causes including over-irrigation, use of additional water for land preparation, or atypical crop cultivation resulting in the actual crop development that differs from the theoretical one used by traditional methods. Also, an important difference was observed in the water requirements for constant flooded crops such as rice. The satellite data in this case could not determine the actual condition of the crop and the ground because the water layer. However, similar differences between the theoretical and practical rice WR_n have been obtained using conventional methods making it necessary to consider an extra water requirement.

In this paper, the water demands analysis of the Flumen District has been extended to compute net irrigation volumes (Vi) considering the field and climatic factors identified previously and applying a water efficiency per morphopedologic units (Ea_m). This will provide a real water efficiency (Ea) for the whole District and determine the actual crop water requirements and its impact on the availability of the water resources.

2 Field sites

The Ebro Basin is the most extensive hydrographical basin of Spain with an area of 85,399 km^2 (almost 17.3% of the total country area) of which the Aragon Community occupies the Central Ebro Basin (CEB). In the Depression or Valley (CEV) at the CEB, which corresponds to a flat topography, the Riegos del Alto Aragon (RAA, *Irrigation lands at the Aragon's Northern Area*) system is located. The RAA is one of the most ambitious extensive irrigated districts in the Basin with an irrigated area of 1,685 km^2 (71.4% of the total irrigated land in Aragon). The RAA is integrated by the subsystems: Cinca, Monegros, Flumen and Violada, each one is named according to the main canal that irrigates it [10,11], fig. 1.

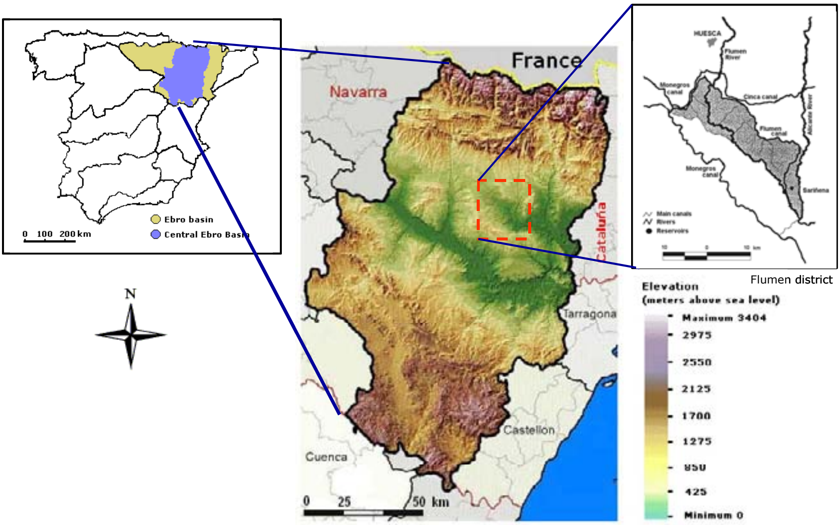

Figure 1: Central Ebro basin covering the Aragon Autonomous Community and the location of the Flumen District.

The Flumen District covers an area of 33,729 ha (20% of the RAA irrigated land) [10], it includes a main irrigation system (50 years old) and some enclaves (territories included within a bigger territory but with different geographic characteristics), and old irrigated plains (i.e. *huertas,* older than six centuries) along the riverbanks [7].

According to Bielsa *et al.* (1998), the physical availability of water in the CEV can be divided into the left and right banks, having the Ebro River as common collector. Thus, the canal system is very important since it provides the water for irrigation. Almost all rivers in the RAA system have an irregular flow and present salinity problems [10]. However, the water availability depends strongly of the climatic variations in the zone. Martínez-Cob and Tejero-Juste [12] reported for the CEV mean annual variations for precipitation from 354 to 475 mm, for air temperature from 13.1 to 14.5 ^{o}C and for air relative humidity from 65 to 76 %. Precipitation presents two maxims in spring and autumn, and two minimums in summer and winter. Wind speed for the Flumen is moderate (from 1.0 – 2.5 $m \cdot s^{-1}$), although the topography reinforces the influence of continental winds. In extreme conditions, a northwest winter wind called c*ierzo* is present, whereas in summer there is a southeast dry and hot wind called *bochorno*. Both type of winds have a drying action, which imparts a high aridity to the zone throughout the year [10]. Although salinity of some soils is a constraint for agriculture, irrigation makes possible to grow a variety of crops. The main crops grown are: winter cereals (barley and wheat), maize, alfalfa, forage, rice, and sunflower covering an area around 66% of the District. They are responsible of most water consumption in the District [13].

3 Data and methods

This section provides a brief description of the available data to assess the applicability of remote sensing techniques in the computation of accurate Vi values. The methodology includes the estimation of ET_a, WR_n and Vn these steps are mentioned briefly since they were reported in a previous paper [5].

3.1 Data sources

The meteorological data for the Flumen District were collected for the four-year study period (1997 to 2000) from two main sources: 1) Sariñena and Monflorite National Automatic Weather Stations Network (EMAs) that record 10-minute intervals for each variable measured (precipitation, air temperature, relative humidity, wind speed and wind direction and atmospheric pressure); and 2) Basic Weather Stations (BWS) that record daily precipitation and temperature and some stations also recorded sunshine hours.

The phenological information collected was sown and harvested dates, and vegetation characteristics such as height. Also, records of water delivered by the Ebro Hydrographical Confederation (CHE) were available in a continuous daily basis, thus records of the monthly and annual water requirements (V_{nCHE}) were achieved. The CHE supplies the water requested for the farmers, who estimate the water demands based on the crop sown and the area occupied using empirical methods, experience or both. The CHE checked the amount of water requested with the land area registered and the crop declared to be sown, however, the water application is determined by the farmer.

Finally, fifteen Landsat images (TM and ETM+ sensors) were used for the four-year study period. Images were acquired for the maximum crop-growth stage periods, thus summer images were chosen. Winter images have not been included, because winter crops are in their initial stage (more bare soil) or they have not been sown yet. The images were atmospheric, geometric and radiometrically corrected. Also, an enhancement was performed and problems associated to haze occurrence were identified. As result, two images were eliminated from the analysis.

3.2 Methods

For a number of years, ET_c in the Flumen District has been calculated using the Blaney-Criddle (BC) equation with data from the Sariñena BWS, local experimental crop coefficients (Kc), and corrected by a local coefficient of 0.88. These BC-ET_c values have been utilised in the IRRIVOL methodology that follow the FAO guidelines to compute WR_n and Vn [9]. The IRRIVOL methodology utilises remotely sensed data to derive an annual land cover-classification map for the six main crops. This map is combined with meteorological data to provide WR_n and Vn maps using Geographical Information System (GIS) techniques [7]. The estimation of water requirements includes zones with and without water metering points or plots with potential reuse (runoff or seepage) [13].

The advantage using remotely sensed data was increased by the use of remote sensing algorithms such the SEBAL technique. This involves the determination of the land surface physical parameters from spectral reflectance and radiance and the introduction of meteorological data such as air temperature, humidity, and wind speed at a reference height. The SEBAL technique uses these variables to estimate the energy flux parameters (sensible, soil and latent) and obtains ET_a as the residual form of the energy balance equation [14]. The SEBAL ET_a values correspond to the instant of satellite overpass, thus a temporal interpolation must be made to determine daily values. Moreover, as the CHE water invoices are available in a monthly basis, the crop water demands need to be compared on this timescale. Thus, the SEBAL daily ET_a values are extrapolated to monthly values using scaling factors developed from the FAO-56 Penman-Monteith equation [15]. Monthly SEBAL ET_a values were used to compute SEBAL WR_n subtracting the effective precipitation (Pe) from SEBAL ET_a according to Cuenca [16]. Pe was assigned as fixed value to each pixel using Thiessen polygons.

IRRIVOL computes WR_n on a monthly basis subtracting the value of Pe from the BC-ET_c. Then $WR_{nIRRIVOL}$ values are assigned according to the land classification map, thus $WR_{nIRRIVOL}$ values for each one of the six main crops are obtained. SEBAL WR_n are compared with IRRIVOL WR_n obtained from previous researches [13].

As the land cover classification maps were available for each year under study, the SEBAL and IRRIVOL WR_n values were multiplied for the hectarage of the six main crops to compute Vn per crop, and these are then summed up to obtain the total monthly Vn for both IRRIVOL and SEBAL. For SEBAL Vn predictions, two approaches were adopted. The first considered the crop water demands including months out of crop season (SEBAL_F1) and compared the Vn estimate with the water delivery invoices by CHE, that is the water supplied for irrigation. The second considered the crop water demands for only the six main crops growing period (SEBAL_F2) and the Vn values obtained were compared with those obtained by IRRIVOL [13].

The irrigation water volumes (Vi) were calculated as indicates eq. 1.

$$\mathrm{Vi} = \mathrm{V_n} \times \mathrm{Ea}_{\mathrm{m}}^{-1}, \mathrm{hm}^3 \tag{1}$$

where Ea_m is the soil water efficiency, which was obtained experimentally for each of the morphopedological units in the Flumen District [17], table 1 [18]. Vi values for both SEBAL and IRRIVOL were computed for each type of crop and for each type of structure. In order to check if these calculated values correspond to the actual water demands, a final comparison was made using the water delivery CHE records (V_{CHE}).

Table 1: Surface water application efficiency for land evaluation units in the Flumen District.

Morphologic type	Area, (ha)	Efficiency, Ea_m
Platforms	7558	0.4
Slopes	17263	0.6
Terraces	2905	0.8
Bottoms	4517	0.8

4 Results

The ET_a validation process carried out to test the reliability of the SEBAL technique at regional (Flumen District) scale confirmed that SEBAL produces reliable representations of the ground and crop conditions except for crops under constant flooded fields such as rice. These differences occur because the satellite sensed the rice fields as shallow water bodies. Thus, the standing water background affects the spectral reflectance of rice, the sensitivity of spectral vegetation indices and the surface temperature (Ts), which is lower than would be observed for this crop under a different irrigation system [19,20].

4.1 Crop water requirements, WRn

As SEBAL can detect variations associated to irrigation practices, rainfall events and climatic variations on the particular instant of satellite overpass, the estimation of WR_n has a high level of confidence. SEBAL WR_n values were lower than $WR_{nIRRIVOL}$ since they involve the actual conditions on the field including changes in the crop development, fig. 2.

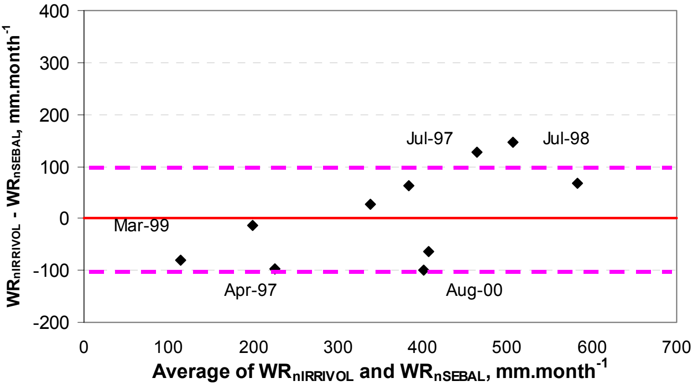

Figure 2: Differences between WR_{nSEBAL} and $WR_{nIRRIVOL}$ without rice WR_n. Dotted lines are the upper and lower limits of the standard deviation of the differences (sdiff).

The most significant WR_n differences were observed for sparse canopies such as sunflower (SF), maize (M) and rice (R) and during the summer season. The WR_n variations for rice were considerable because the irrigation practice, which was a limitation for the SEBAL procedure. Rice IRRIVOL WR_n uses the Tolosa adjustment [21] that adds an empirical factor of 15,000 $m^3 \cdot ha^{-1}$ to the theoretical WR_n values in order to cope the crop water demands. However, this factor was not considered appropriate for SEBAL, because the algorithm could reflect accurately the crop and ground conditions.

Casterad [22] explained the WR_n under-estimations obtained using IRRIVOL as result of an inappropriate estimation of the Pe. This is because rainfall in summer is short and heavy followed by strong wind and high temperatures that dry the foliage almost immediately [22]. However, this is an aspect that merits further work.

4.2 Crop water volumes, Vn

SEBAL_F1 was expected to be close to the CHE invoices, which recorded the total monthly water supplied to the whole district. SEBAL_F2 should be similar to the $Vn_{IRRIVOL}$ values, since they are also restricted to the crop period established, according to the practice in the Flumen District. As a result, SEBAL_F2 and IRRIVOL Vn values should be lower than the CHE records, because the six main crops are responsible for almost 90% of the overall water requirements. However, significant V_n differences were obtained between IRRIVOL and SEBAL, and these were mainly related to the SEBAL problems for rice fields, fig. 3.

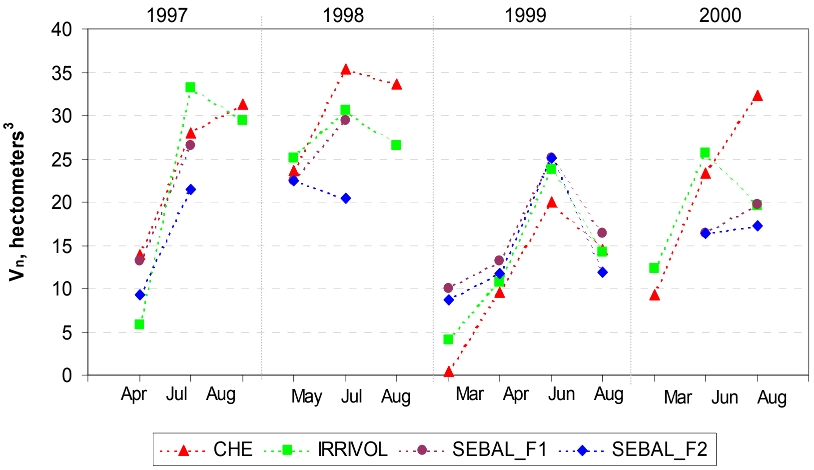

Figure 3: Net water volumes (Vn), hm^3 for CHE, IRRIVOL and SEBAL.

To allow the comparison of total volumes with CHE data, and knowing that IRRIVOL already includes for rice the Tolosa adjustment factor (15,000 hm^3), the rice-$V_{nIRRIVOL}$ were used instead of the rice-V_{nSEBAL}. Thus, total SEBAL_F1 and SEBAL_F2 Vn were adjusted as indicated in eqs. 2 and 3:

$$V_{nSEBAL\_F1(r-adj)} = \lfloor \text{total } V_{nSEBAL\_F1} - \text{rice}V_{nSEBAL\_F1} \rfloor + \text{rice}V_{nIRRIVOL} \qquad (2)$$

$$V_{nSEBAL\_F2(r-adj)} = \lfloor \text{total } V_{nSEBAL\_F2} - \text{rice}V_{nSEBAL\_F2} \rfloor + \text{rice}V_{nIRRIVOL} \qquad (3)$$

Fig. 4 shows a good match between V_{nCHE} and $V_{nSEBAL\_F1(r-adj)}$ and $V_{nIRRIVOL}$ and $V_{nSEBAL\_F2(r-adj)}$ as expected, excluding those months affected by the *bochorno wind* and *haze* problems and Mar-99 due to the water shortage in the dams at the Pyrenees, which provide river flows and the irrigation water to the Districts.

The final agreement between SEBAL_F1(r-adj) and CHE was good with a bias of -1.45 hectm^3 and a s_{diff} of ± 4.95 hm^3. The comparison between IRRIVOL and CHE indicates that the crop water requirements are higher than the water supplied by the CHE. As IRRIVOL only considers the water demands for the six main crops, this result was foreseen. Although, the agreement between IRRIVOL and SEBAL_F2(r-adj) was expected good it was moderate, quite similar to the one obtained between CHE and IRRIVOL, giving a bias of 1.49 and a sdiff of ± 5.74 hm^3.

The reliability of the Vn_{SEBAL} values obtained allows the introduction of irrigation performance indicators, which permit to evaluate the performance of an irrigated district based on their sensitivity to the irrigation management [23]. In this work, the ratio between RECORDED/COMPUTED Vn [13] or the field application ratio (Ea= COMPUTED/RECORDED Vn) were used. These rations together with a major farmers' participation help to monitor, identify and quantify some problems in order to reduce the low water efficiencies. This low efficiency could be related to differences between the estimated and reported cropped area, poor crop husbandry (e.g. sunflower which is often grown only to receive the EU subsidy), not considering the water requirements for tillage, or non-accurate water request for supply by the farmer.

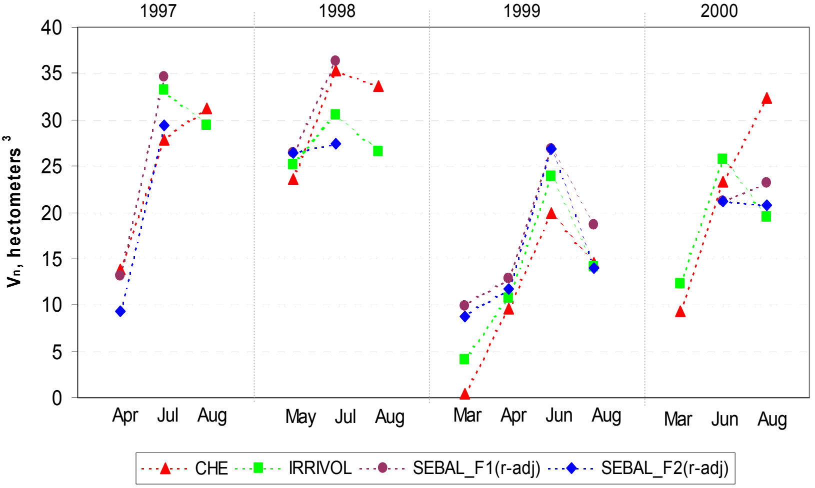

Figure 4: CHE, IRRIVOL and SEBAL net water volumes (Vn), hm^3 adjusted.

4.3 Net irrigation volumes, Vi

$Vi_{IRRIVOL}$ values were taken from previous research in the area for each of the years under study [24]. Rice-$Vi_{IRRIVOL}$ values were considered the same for rice-$V_{nIRRIVOL}$ because of the irrigation method. For SEBAL again the two approaches SEBAL_F1 and SEBAL_F2 were considered as well for SEBAL V_n. In a similar way to V_n, to evaluate properly the differences observed for the SEBAL estimations and knowing that IRRIVOL already considers for rice the Tolosa adjustment factor, the rice-$Vi_{IRRIVOL}$ were used instead of the rice-Vi_{SEBAL}. Thus, total SEBAL_F1 and SEBAL_F2 Vi are redefined as indicated in eqs. 4 and 5:

$$Vi_{SEBAL\_F1(r-adj)} = \lfloor \text{total } Vi_{SEBAL\_F1} - \text{rice}Vi_{SEBAL\_F1} \rfloor + \text{rice}Vi_{IRRIVOL} \tag{4}$$

$$Vi_{SEBAL\_F2(r-adj)} = \lfloor \text{total } Vi_{SEBAL\_F2} - \text{rice}Vi_{SEBAL\_F2} \rfloor + \text{rice}Vi_{IRRIVOL} \tag{5}$$

Fig. 5 shows the Vi differences obtained for CHE&SEBAL_F1$_{(r\text{-}adj)}$ and IRRIVOL&SEBAL_F2$_{(r\text{-}adj)}$ plotting the differences against their averages.

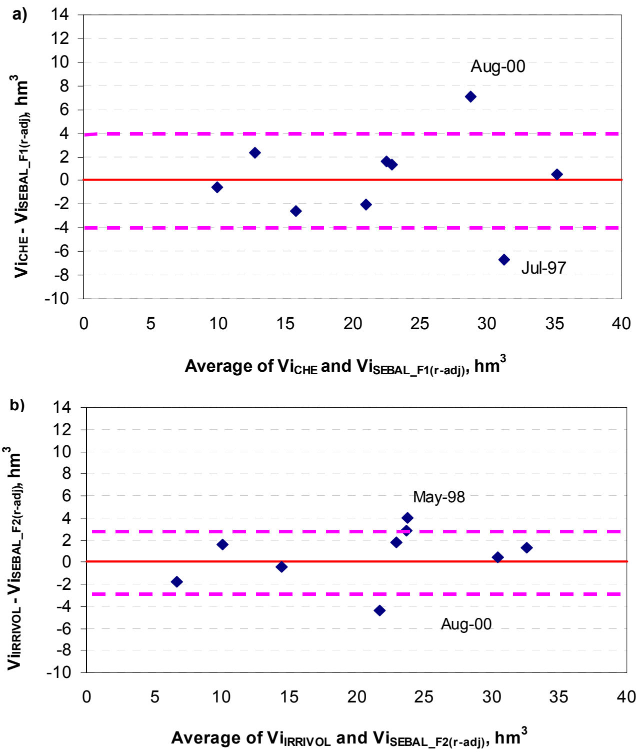

Figure 5: Monthly Vi, hm^3, differences plotted against their average between (a) CHE&SEBAL_F1(r-adj) and (b) IRRIVOL&SEBAL_F2 (r-adj).

The difference range for CHE&SEBAL_F1(r-adj) and IRRIVOL&SEBAL_F2 (r-adj) remains almost constant as the average increases. The agreement between CHE and SEBAL_F1(r-adj) was good with a bias of 0.09 hm^3 and a s_{diff} of ± 3.82 hm^3; the months with higher differences were Jul-97 and Aug-00. Also, the agreement between $Vi_{IRRIVOL}$ and $Vi_{SEBAL\_F2(r-adj)}$ was good with a bias of 0.56 hm^3 and a s_{diff} of ± 2.53 hm^3. The main advantage of accurate Vi values is that Ea can be calculated with high accuracy for the whole system. In this case, Ea was around 90% for each year under study.

Additionally, the SEBAL Vi map not only permits the analysis for the whole district, but also, very significantly, the analysis at field scale can be achieved with high precision, fig 6.

For the first time this allows those plots with low water efficiency to be pinpointed, allowing specific, targeted actions to be taken to improve crop management and, in consequence, guarantee better water and land use.

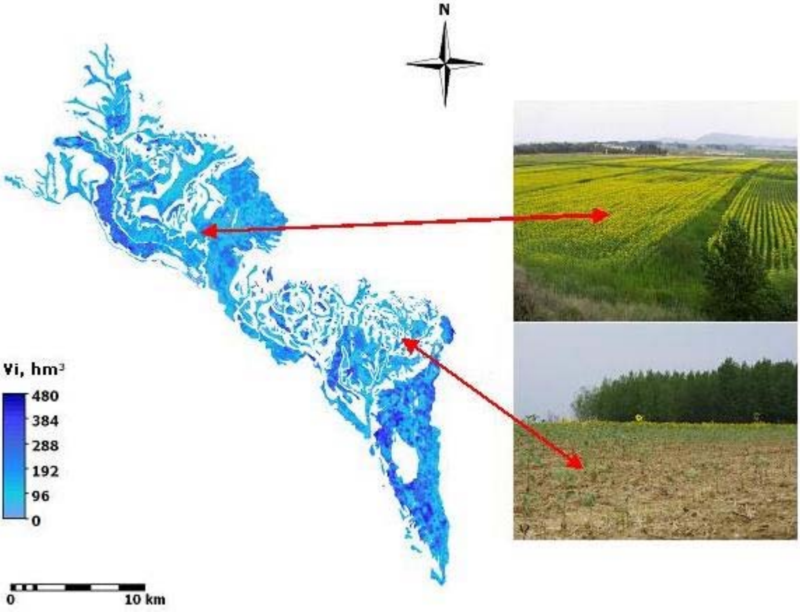

Figure 6: Irrigation requirements, Vi [10^6 m^3], in the Flumen District. Image date Aug 14th 1999. Zero values are covers non-classified.

5 Conclusions

The differences observed between SEBAL-F1$_{(r\text{-}adj)}$ and CHE highlight some problems of the CHE in achieving an effective timing and allocation of water requirements and quite frequently CHE tends to cause over-delivery of water.

Results obtained give confidence in the use of SEBAL to compute the irrigation volumes, although for rice-water requirements further studies are required. This confirms that the SEBAL procedure is one of a number of techniques that identify crop-water-soil conditions using satellite based remote sensing. This facilitates crop, land and water management offering a wide range of alternatives to maximise yield with less water use. Spatial coverage permits the detection of spatial inconsistencies related to the crop conditions, water application, soil types, micro-relief, etc. On a regional scale, the computation of more accurate water balances will allow the allocation or re-allocation of the water resources. Also, the analysis of alternative crops could be based on its water and land requirements and not only on its economic value. On a local scale, the identification of problems associated with the crop development can be achieved, thus improving the crop management, which can be monitored using ET_a, V_n, Vi, or the crop yield.

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Cost-effectiveness analysis of measures to reduce nitrogen loads from agriculture: do secondary benefits matter?

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Abstract

Over the past years a large number of studies have explored cost-effective strategies for reducing nitrogen loads from agriculture. However, the majority of these studies focus on financial costs to agriculture alone, in spite of the fact that a number of relevant measures, e.g. establishment of wetlands and reduced livestock hold, lead to significant secondary environmental benefits. Ignoring these benefits in cost effectiveness analysis leads to a risk of inefficient policy recommendations. In this paper we identify the relevant secondary effects of four measures to reduce nitrogen loads from agriculture and demonstrate the implications of including secondary benefits using an example of cost-effectiveness analysis (CEA) of reduced nitrogen loads based on financial and socio-economic cost estimates.
Keywords: nitrogen loads, cost effectiveness analysis, secondary effects, benefit transfer.

1 Introduction

Over the last 30 years the detrimental environmental effects resulting from nitrate losses from agriculture and other sectors have been in focus of the environmental policy in Northern Europe. Besides various national regulations the problem is addressed by HELCOM [1], in the EU Nitrate Directive, and in the Water Framework Directive, and recommendations on which policy measures to apply for reducing nitrogen losses has been addressed by the EU commission and OECD. This focus has also resulted in a number of economic studies analysing measures for reducing nitrogen losses from agriculture. The

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framework applied most often is cost-effectiveness analysis where the aim is to appoint the cost-minimising strategies resulting in a pre-defined environmental target. Among the large empirical literature e.g. [2–6], a common feature is that all cost estimates represent solely financial cost to the agricultural sector.

Regulating nitrogen emissions from agriculture also influence other environmental pressures such as emissions of ammonia and climate gasses, as well as changes in land use directly influence the supply of goods related to biodiversity and landscape. From a socio-economic point of view these secondary benefits should be reflected in the cost estimates and further, the implementation of the Kyoto protocol and the EU Habitat Directive has led to increased administrative attention to include the secondary effects in policy analysis. Therefore, when preparing the basis for the third Danish Aquatic Action Plan in 2003-04 an attempt was made to quantify the secondary environmental effects in terms of air emissions and include these in the economic analysis using the shadow price approach. In this paper we report the results from this work and, further, we illustrate how recreational and amenity benefits can be included using benefit transfer. Last the consequences of including these in policy analysis are demonstrated by presenting results from financial and socio-economic cost-efficiency analysis of four selected policy measures.

2 Principles of cost measurements and description of measures

In cost-efficiency analysis the monetary value of the improved environmental quality in target is not explicitly included as in a cost-benefit analysis. Therefore the focus of the economic analysis is to establish valid estimates of the costs of implementing different policy measures relevant for reducing nutrient loads. Costs estimates of the policy measures should represent the change in welfare to society caused by implementing the measure. This is approximated by the socio-economic rent, calculated as the difference between income (if any) and total costs from implementing the measure. Further, estimates for the economic value of effects on secondary benefits (e.g. reduction of climate gasses) are included in the net costs. Thus, the welfare-economic analysis focuses on costs as a proxy of the societal loss of consumption possibilities.

The measures that often are discussed and applied when regulating agricultural nitrogen loads lie within two groups; measures regulating input use, livestock production and crop rotation, and measures changing land use. This first type of measures reduces production intensity or gives incentives for implementing environmental friendly production technologies, but agricultural production is basically maintained. This group encompasses reduced nitrogen input, wintergreen fields, restrictions on manure application, etc. The latter type of measures changes land use permanently e.g. by establishment of wetlands, extensive grasslands, buffer strips or afforestration. Note as this analysis focuses on secondary environmental effects the starting point are the actual changes in activities, and therefore the policy leading to the changes (e.g. taxes, subsidies, quotas or command-and-control) is not considered.

We narrow down the analysis to four measures all leading to various scales of secondary environmental effects: mandatory reduction in nitrogen fertiliser input on all farms, reduced livestock hold, establishment of wetlands, and afforestation. In order to make the comparisons of the measures consistent the measures are scaled to result in a yearly reduction in N loads by 5,000 tonnes. In Table 1 the measures are described.

Table 1: Description of the measures.

Measure	Description
Reduced N input	Reduction of total nitrogen input by 5 percent on all farms
Reduced livestock hold	Reduction of agricultural livestock hold by 12 percent
Wetlands	50 000 ha agricultural land converted into wetlands
Afforestation	135 000 ha agricultural land converted into forest

Source: Anon [7].

All of the measures have been analysed as part of the preparation of the third Danish Aquatic Action Plan [8], however, only including secondary benefits with respect to air emissions; see [9] for a evaluation of the first two action plans. In the following section the secondary environmental effects of the measures are presented and the possibilities for including these in the socio-economic analysis are outlined.

3 Secondary environmental effects

When applying measures for reduced nitrogen loads from agriculture a number of secondary environmental effects are likely to occur. These encompass changes in ammonia (NH_4) and climate gas emissions (CO_2, CH_4 and N_2O) and provision of goods related to biodiversity and landscape. The economic value from each type of effect relates to changes in various goods. Ammonia emissions lead to eutrophication of low-nutrient nature locations such as bogs, oligotrophic lakes, dry grasslands and inland heath lands. The effects of changes in ammonia emissions therefore primarily relate to changes in the status for national biodiversity preservation. With respect to climate gas emissions the impacts are of a global scale and range from impacts on urban settlements and agriculture to biodiversity preservation (see for example ExternE [10]).

For both types of effects it is – at least ideally – possible to construct a quantitative system for assessing the welfare consequences of changes in the emissions. If the relationship between production activities, emissions, transport and decomposition, loads, and effects can be modelled, valuation of the effects is possible by use of revealed or stated preference methods or shadow prises. The principles of these types of valuations are found in Freeman [11] and practical examples of dose-response modelling can be found in the EcoSense model [10].

For some of the measures the secondary benefits relate both to effects resulting from changes in emissions and from direct changes in the provision of different goods. This is the case for establishment of wetlands and afforestration for which changes in the provision of recreational and biodiversity goods will occur as a direct result from changing land use. The provision of biodiversity and recreational goods at a given location are of cause correlated, but not unambiguously. Thus, a location with high biodiversity value does not need to have a high recreational value, as the realisation of recreational values is conditional on accessibility. Opposite an area with high recreational value need not possess high biodiversity value (e.g. think of a golf course).

When analysing the economic consequences of changes in land use it is useful to distinguish between use values and non-use values. Using this terminology recreational opportunity is strictly a use value where as biodiversity leads to both use and non-use values. In Table 2 the types of goods related to biodiversity effects of changes in land use are outlined.

Table 2: Types of goods related to biodiversity effects.

Type of good	Value function
Use value (amenity and recreational value)	The range of the value depend on public access to the area and distribution of property rights (e.g. fishing and game shooting)
Existence value (non-use)	The value of knowing that a given nature location, nature type, or species exist to day
Bequest value (non-use)	The value of knowing that a given nature location, nature type, or species are preserved for the benefit of future generations

For wetlands the areas will typically not be subject to public access so far they remain in private property. The secondary values related to the changes in the provision of recreational goods from this measure are, therefore, restricted to the owner in terms of e.g. fishing and game shooting.

The same values (except for fishing) will be affected by afforestation and, further, recreational values to the public are expected to arise. This is because the public access is legally ensured in Denmark to all public forests and all privately owned forests larger than 5 hectares.

4 Benefit transfer of values for non-market goods

Valuation of secondary effects often requires determining a monetary value for goods and services that are not traded on a market. The last decades have seen a rising attention on non-market valuation methods, but implementation of a valuation study is costly and time consuming. A less costly alternative would be to implement a benefit transfer study, i.e. the transfer of monetary estimates of environmental values estimated at one site (study site) to another, so-called policy site.

Benefit transfer refers to the practice of transferring non-market values for environmental goods and services from a “study” or “source” site (i.e. the site where an original valuation study was conducted) to the “policy” or “target” site (i.e. the site where benefit estimates are required for decision making). Benefit transfer as a research area started to gain attention about 12-15 years ago and has since made it into every book covering the issue of non-market valuation of the environment e.g. [12–14]. The US Environmental Protection Agency’s manual for cost-benefit analysis has dedicated a separate chapter to the subject of benefit transfer [15], and a similar OECD handbook is currently under preparation. The different benefit transfer approaches found in the literature can be broadly divided into four categories [16]: Unit value transfer; Unit value transfer with adjustment, e.g. for income; Benefit function transfer; Meta-analysis.

Unit value transfer is the easiest way of transferring benefits. It consists of applying unadjusted mean or median benefit estimates from the study site at the policy site. Simple unit value transfer basically assumes that the utility gain of an average individual at the study site is the same as that of an average individual at the policy site. This supposition will hardly hold in most circumstances as people at study and policy sites might differ from each other in terms of income, education and other socio-economic characteristics that affect their preferences for e.g. recreation. Likewise the good to be valued at study and policy site respectively might not be similar enough to be comparable, as well as the existence supply of the good and of substitutes might not be stable over time and space. Instead of transferring unadjusted unit values the policy analyst can adjust the value estimates to better reflect differences in socio-economic characteristics between policy and study site, e.g. by use of the Purchasing Power Parities.

By transferring the entire benefit function instead of per unit benefit estimates more information can be transferred between study and policy site. Benefit function transfer can directly account for differences in user and site characteristics. This, however, requires access to an original study where benefits are described as a function of different explanatory variables. A related method is to extract information on benefit values from a range of available studies, so-called meta-analysis. Here the relationship between benefit estimates of a number of different studies is quantified by employing regression analysis where the different study results are treated as the dependent variable, while model characteristics, country, etc. are used as explanatory variables.

The assessment of non-market secondary benefits in this study is entirely based on benefit transfer from existing studies. In order to reduce the uncertainty resulting from transferring values as much as possible most original studies are taken from Denmark. Given the large uncertainties associated with benefit transfer sensitivity analyses are conducted that indicate the impact of variations in unit values for the final ranking of the four analysed policy measures.

5 CEA based on financial and socio-economic cost estimates

In Table 3 the units derived from the benefit analysis applied in this paper are shown for the single measures. Amenity values for afforestation projects are transferred using average unit willingness to pay (WTP) values per house for different distances to the forest edge from two Danish hedonic prising studies

[17, 18]. These unit values are calculated as a percentage of the average house price in an area that allows for an adjustment for income differentials as reflected in house price differences. Recreational values are transferred using average WTP values per forest visit from a Danish contingent valuation study [19] and information about forest visitation patterns of the Danish population from [20].

Values for air emissions are estimated as shadow prises. The shadow prise approach holds the same characteristics as unit value transfer, as the shadow prise is calculated as the marginal abatement costs of a current or planned policy. The shadow prise approach can only be applied for including secondary benefits, and it requires an explicit target for reducing the emissions and the existence of a cut-off prise so that a marginal willingness to pay for reducing the emissions can be derived from existing policies.

The estimates for recreational and amenity values reflect differences in visit frequencies and housing prises between rural and urban areas. The range in estimates for climate gas values reflect estimates of the future compliance costs for the European Commission [21] and ExternE [10], where as ranges for fishing and game shooting values are based on marked data. We refer to Schou and Birr-Pedersen [22] for a technical description of how the benefit values are calculated.

The measures for which the secondary benefits with respect to recreation and biodiversity are most significant are establishment of wetlands and afforestration as these result in significant changes in land use. The other two measures primarily result in reductions in production intensity although reductions in livestock hold may lead to reductions in grasslands and grassing potential if cattle stocks are reduced. For the amenity values only the estimates from the rural and urban baseline scenario are shown. Note also that because wetlands typically are kept in private property without public access no amenity or recreational values are attached to this measure.

Table 3: Benefit values.

Secondary effect	Unit	Mean	Min	Max
Ammonia reduction	€/kg NH4-N	1.0	-	-
Climate gas reduction	€/tonne CO2-eqv.	11	11	46
Game shooting, wetland	€/ha	25	25	50
Game shooting, afforestation	€/ha	50	25	63
Amenity value forest urban areas	€/ha	1 976	751	3 200
Amenity value forest rural areas	€/ha	63	26	99
Recreational value forests	€/ha	132	13	660

By multiplying the unit values with the scale of the secondary effects or the scale of the measure and then dividing the aggregate costs by the estimated reductions in N loads of 5,000 tonnes, the range of the secondary effects per kg N load reduction is derived. For the afforestation measure values for the rural area are used, as the need for reducing agricultural nitrogen loads typically originates in rural areas. Therefore, the mean estimate for amenity values for rural areas is applied and the lower annual estimate of 13 € per ha for recreational benefits, which reflects an average annual visit frequency of 20 visits per ha. However in the case where afforestation can be targeted to locations nearby urban areas the recreational values can be increased significantly. As can be seen from Table 4 costs per kg N reduction turn out to be substantially negative when mean amenity values for urban areas and the annual mean value of 132 € per ha for recreational benefits is applied.

In Table 4 the result is shown together with the estimated financial costs of the measures according to Jacobsen [8]. The financial costs are expressed as loss of economic rent.

Table 4: Financial and socio-economic CEA, based on mean values (€/kg N).

Measure	Financial costs	Secondary effects			Socio-economic costs
		Emissions	Market use values	Non-market use values*	
Reduced N input	2.1	0.6	0	0	1.5
Reduced livestock hold	6.9	2.4	0	0	4.5
Wetlands	4.4	0.6	0.3	0	3.5
Afforestation, rural area	6.4	1.3	1.4	1.7 + 0.4	1.7
Afforestation, urban area	6.4	1.3	1.4	53.3 + 3.6	-53.2

* The first value reflects amenity benefits, while the second value reflects recreational benefits.

The inclusion of the secondary environmental effects in the net cost estimates shows two significant consequences for the CEA. First, the abatement costs are reduced significantly compared to those of the pure financial analysis. This indicates that policies formulated based on financial economic analysis alone will overestimate the aggregate costs and, thus, tend to lead to less ambitious policy goals compared to the socio-economic efficient solution. Secondly, the relative cost-efficiency of the possible measures changes. This is especially the case for measures involving land use changes where amenity and recreational values are expected to arise. Thus, the cost-efficient mix of policy measures changes when shifting from financial to socio-economic cost-effectiveness analysis. This indicates that the secondary environmental effects may play an important role when formulating environmental policies.

It is important to notice that the analysis is based on average values. For example if afforestation, for which the current analysis actually indicates a positive socio-economic performance, is implemented to a large extend the marginal recreational value should be expected to fall. Further, because of the increased demand for agricultural land to be used for afforestation the financial costs of this measure will rise. These two effects in combination will reduce the cost-efficiency performance of the measure eventually leading socio-economic costs to be positive. Therefore when analysing the cost-efficient mix of policy measures at the larger scale it is important to include considerations of how the demand functions and, thus, the marginal values, for the different goods will be affected in different policy settings.

6 Discussion and conclusions

In this analysis we demonstrate how non-marketed secondary effects can be included in the cost-efficiency analysis. A general feature of benefit transfer as well as primary valuation studies is that the exactness of the estimates depends on how specific the project is described. If the analysis relates to a well described project at a designated location it usually should be possible to develop a detailed description of the changes in land use, effects on environmental quality and biodiversity, and to which extend the project will change recreational possibilities. Such a description yields a good basis for deriving monetary estimates of the benefits. Further, the uncertainty of the benefit estimates will mostly depend on the benefit functions used and can be subject to a reasonably noncomplex sensitivity analysis.

If the analysis deals with policy choices at the more aggregated level, as is the case in this example, decisions as to where the measures should be implemented and the scale of the measures are often not explicit, and may for political reasons not be desirable to clarify. In this case benefit transfer may be difficult especially when the effects and benefits hold site specific elements. However, this analytical problem is not only related to benefit estimates but also to the financial economic and natural science evaluations. But because of the relatively limited data on benefits and their variations with policy relevant parameters the issue becomes more explicit. Given the limited amount of studies available in Denmark and internationally this project was not able to transfer values for changes in biodiversity particular non-use values related to changes in land-uses. Results from this paper indicate the substantial influence non-market values can have on the ranking of policy initiatives. It is therefore suggested that future research should focus on eliciting these non-use values in order to provide policy makers with an indication of their potential size and variability.

Decision making in an administrative context has a (very natural) tendency to seek simplifications of their processes. With regard to project and policy evaluation this becomes evident in an increasing focus on promoting and using so-called “approved unit values” in the form of € per measurement unit for benefit transfer. Such values are extremely context dependent and a cautious and qualified usage of these benefit estimates is therefore strongly required.

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