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Management of Mountain Watersheds

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Preface

Mountain catchments are some of the most challenging issues for watershed management. They include areas that are commonly remote, steeply sloping and marginal in many respects: geographical, economic and often socio-political. They are also, often, places that are the targets for the exploitation of natural resources. These resources begin with their scenic and tourist possibilities and continue to include geological resources, water resources and the forests that are their dominant vegetation. Mountain forests, frequently, lie on the front-lines of human development. They compete for space in those sites that are most targeted for human development and share the land with the most exploited and exploitable water resources, mountain rivers and lakes.

Today, mountain watersheds are also giving concern because of the effects of climate change. In strict scientific terms, the effects of these changes are, to date, more anticipated than actually proven. However, climate change contains the potential to be a serious problem because of the relatively extreme vulnerability of these mountain landscapes to catastrophic environmental change.

Formerly, mountain watersheds and their resources were managed often by Government agencies or commercial companies that were mainly oriented to resource development and extraction. The success of watershed management has been that today these lands are more commonly treated as integrated systems for management purposes. Simultaneously, this trend has given an increased voice to the inhabitants of these areas and with that increased voice has come increased responsibilities for environmental management. Increased responsibilities demand better informed communities who are able to understand the process and decisions that have to be taken to conserve and sustain their habitat. This realisation has given new emphasis and importance especially to environmental education in these mountain areas and to education that is constructed to give these communities sufficient understanding to manage their own resource and land use decisions (e.g. Watershed councils in USA).

This volume contains selected papers from the most recent meeting of the European Forestry Commission Working Party on the Management of Mountain Watersheds, which is co-sponsored by the FAO (Food and Agriculture Organisation of the United Nations). The Working Party has a long and distinguished history (described here in the paper by Hofer and Ceci), particularly concentrated now on forest-water relationships in high altitude and latitude regions, and climate change impacts.

This volume is also co-sponsored by the International Association for Headwater Control (NGO founded in 1989), which has sought to bring together the diverse voices of the applied science practitioners, researchers, policy makers and community groups and forge a collective vision of the best management strategies for mountain watersheds around the world.

Josef Krecek
Martin J. Haigh
Thomas Hofer
Eero Kubin

About the Editors

Josef Krecek is the founder and managing Co-Director of the International Association on Headwater Control (IAHC), and former President of the EFC/FAO Working Party on the Management of MountainWatersheds. He teaches courses on Applied Hydrology at the Czech Technical Univesity in Prague, and conducts forest hydrological research on Mountain Waters of the Earthwatch Institute. He is experienced with several international projects in Europe and Asia, and coordinated a number of publications on watershed management and headwater restoration.

Martin J. Haigh is a Co-Director of the International Association on Headwater Control, Senior Fellow of the Higher Education Academy (U.K.), former Vice-president of the World Association of Soil and Water Conservation, and Co-Editor of the *Journal of Geography in Higher Education*. He is also on the Editorial Board of *Asian Journal of Water, Environment and Pollution*, since 2004. He is currently Professor of Geography and University Teaching Fellow at Oxford Brookes University in England. He conducts research into Education for Sustainable Development and Community based Environmental Reconstruction. In 2010, he won the Royal Geographical Society's international 'Taylor & Francis Award' for his contributions to teaching and learning in Higher Education.

Thomas Hofer is Forestry Officer and leader of the Watershed Management and Mountains Team at the Food and Agriculture Organization of the United Nations (FAO). Since 2006, he serves as the secretary of the EFC/FAO Working Party on the Management of Mountain Watersheds. He has vast field project experience in Asia and Central Asia, Eastern Europe, Africa and Latin America. He has coordinated the development of a number of flagship publications on watershed management, sustainable mountain development and forest hydrology.

Eero Kubin is former president of the EFC/FAO Working Party on the Management of Mountain Watersheds, and Management Committee Member of EU COST Action 725. Over 15 years, he served as Director of the Muhos Research Unit of the Finnish Forest Research Institute, and he is leader of long-term research projects on phenology, and environmental aspects of forestry practices. As docent of the Oulu University and Helsinki University he is lecturer on forest ecology and supervisor of several doctoral thesis.

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1

Mission and History of the European Forestry Commission Working Party on the Management of Mountain Watersheds

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The European Forestry Commission Working Party on the Management of Mountain Watersheds, formerly called the Working Party on Torrent Control, Protection from Avalanches and Watershed Management, was established by the European Forestry Commission (EFC) of the Food and Agriculture Organization of the United Nations (FAO) on the occasion of its Third Session on 1 September 1950.

In the course of that session, the Commission considered that soil conservation, restoration and improvement in the plains and in hilly districts constituted an extremely wide problem which required the collaboration of all the actors involved in the rational utilization of soil and water resources. On the other hand, the Commission observed that torrent control and soil restoration in mountainous regions, the importance of which is undeniable, were generally entrusted to the forestry services in European countries. Based on these considerations, the Commission recommended the establishment of a Working Party with the objective to study the technical aspects of torrent control and soil restoration in mountainous regions.

In 1951, at the 4th EFC Session, the Director General of FAO was requested to contact European governments in order to organize in 1952 the first meeting of a Working Party dealing with issues related to torrent control and protection from avalanches. The 1st Session of the "EFC Working Party on Torrent Control, Protection from Avalanches and Watershed Management" was held

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in Nancy, France, in June 1952. The group considered that the mission entrusted to it by the EFC was primarily to study the problems related to the protection from torrents and avalanches of villages, croplands, lines of communication and hydroelectric structures in the densely populated mountain areas of Europe.

In 1970, a seminar on the future orientation of the EFC Working Party was held back-to-back with its 9th Session. At the seminar, it was concluded that the terms of reference of the Working Party had to be enlarged to cover five major points in the following order of priority: torrent control, protection from avalanches, soil and water conservation in mountain regions, mountain land use with a special focus on forest land, and the evaluation of the direct and indirect benefits of mountain watershed management. In view of the broadened mandate, it was decided to call the group “EFC Working Party on the Management of Mountain Watersheds”.

The core mission of the Working Party is to bring together member countries of the EFC in order to exchange information on forest and water policies, watershed and risk management practices, to fill knowledge gaps and to follow up on progress made. Its main objectives are to collect information, document technologies, monitor evolution, exchange experiences and discuss progress within mountain ecosystems in view of their sustainable management and conservation. Important areas of consideration are improved mountain livelihood systems and the security of mountain ecosystems, sustainable management with special attention to torrent control, avalanches, risk zoning and mapping, and early warning systems.

The Working Party has played an important role in the follow-up to Agenda 21, supported FAO’s role as task manager for Chapter 13 on mountain ecosystems, contributed to the implementation of the recommendations from the International Year of Mountains (2002) and International Year of Freshwater (2003) as well as of the commitments from Warsaw Resolution 2 “Forests and Water” (2007) of the Ministerial Conference on the Protection of Forests in Europe (forest Europe).

The Working Party meets every two years in a host country. Each member country is represented by a focal point who is directly nominated by the relevant ministry. National focal points can be based in academic institutions, research institutes or state technical departments. The dialogue among scientists and government technicians is one of the unique and particular features of the group. The Steering Committee of the Working Party is chaired on a rotational biennial basis by a member country, while the Secretariat is provided by the Forestry Department of FAO. Through the reports and presentations submitted for each session of the Working Party, the member countries and the external observers from different regions and organizations contribute to a flow of information on watershed-related issues. A number of inter-sessional activities ensure that communication and exchange of information between countries continue on a regular basis.

Besides working together with the member countries of the EFC, the Working Party collaborates with many organizations and processes, such as

Forest Europe, UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes, EU Water Framework Directive (WFD), International Union of Forest Research Organizations (IUFRO), UNESCO-IHP-HELP, Mountain Partnership, European Forest Institute (EFI) and its regional offices, UN Water, UN Forum on Forests (UNFF), UN Framework Convention on Climate Change (UNFCCC), UN Convention on Biological Diversity (UNCBD), etc.

In order to continue disseminating up-to-date technical and policy information to different groups of stakeholders, the Working Party must constantly cope with emerging issues of global importance. This is the case of climate change and increased hazards in mountain watersheds. Global warming is affecting vital mountain resources and in turn will negatively impact on the socioeconomic situation of mountain people. The Working Party is engaged in raising awareness on these issues, by assessing and disseminating state-of-the-art knowledge and strategies of adaptation to climate change. Acquainted with the most recent national and international institutional developments and the achievements at the level of field projects as well as with the global development priorities in an exchange with countries beyond Europe, the Working Party always keeps an active reflection alive on the impact of its activities and their relevance to respond to emerging country needs.

The Working Party recently initiated a major review of its mandate and modus operandi, in order to address strategic issues such as the positioning of the group within the evolving institutional landscape in Europe and the appropriateness of the current vision, mission and topics dealt with. The exercise is conducted through a desk review and direct consultations with the focal points of member countries and key partner organizations. The findings of the review show a strong interest from some member countries to expand the mandate of the Working Party to cover forests and water issues and to enhance the focus on disaster risk management in mountains, particularly in the context of climate change. The EFC will consider the outcomes of the review, provide guidance and make recommendations for the future direction of the Working Party. The work of the group will feed into the Strategic Plan of the Integrated Programme of Work on Timber and Forestry of the UNECE Timber Committee (TC) and FAO EFC for the period 2014-2019.

The Working Party, its biennial sessions, the inter-sessional activities, the continuous exchange between professionals from Europe and other regions of the world confronted with similar issues, the passion and dedication of its members to disseminate the findings of their work, all these ingredients are at the base of the present publication. The Working Party provided the opportunity to the numerous authors who contributed to this publication, i.e. experts belonging to different and complementing sectors, to know each other and exchange on a regular basis up-to-date information and case studies. Products like this publication, for which the Working Party provides an institutional framework, represent the added value of a technical, long-standing network such as the EFC Working Party on the Management of Mountain Watersheds.

2

Hydrological Change Management from Headwaters to the Ocean: HydroChange 2008, Kyoto

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1. Introduction

In October, 2008, an international conference in Kyoto, "HydroChange 2008", took on the task of trying to examine hydrological changes and management from the headwaters to the ocean and to integrate the perspectives and concerns of the different scientific, socio-economic and environmental management communities involved in these opposite reaches of the river basin. This ambition created huge problems because of the differences in scale, both geographical and timescale, emphasis – especially the balance between human and natural processes, technical skills, and, because of the march of specialization of each discipline, even technical language. Nevertheless, initiating this dialogue was seen as a necessary step towards the long-term goal of truly integrated watershed management (Fig. 1). It was also seen as a subject true to the spirit of the International Conferences on Headwater Control, which have always sought to integrate the perspectives of the different constituencies that affect the management of watersheds (Haigh and Krecek, 1991; Haigh, 2010). This paper summarizes some of the main outcomes from this initiative.

The conference was organized jointly by Research Institute for Humanity and Nature (RIHN, Japan), International Association of Hydrological Sciences (IAHS) and Global Water System Project (GWSP), and it was co-sponsored

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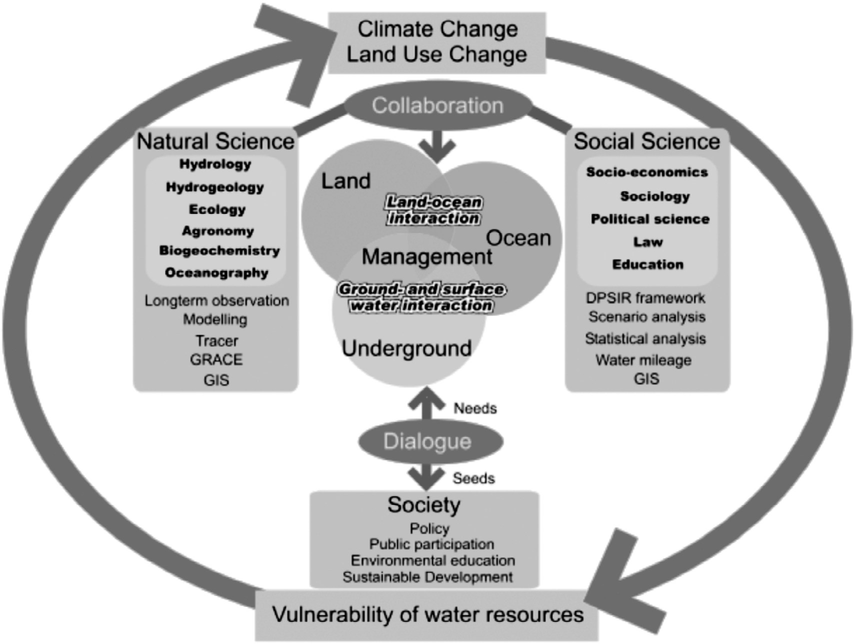

Fig. 1. Holistic approach to hydrological science.

by International Association for Headwater Control (IAHC) and European Observatory of Mountain Forests (EOMF). Some 149 delegates, representing 22 countries, attended and their main technical contributions are published in "*From Headwaters to the Ocean: Hydrological Change and Watershed Management*" (Taniguchi et al., 2009). In particular, this showcases results from RIHN (Research Institute for Humanity and Nature) projects such as *"Human impacts on urban subsurface environments (Project leader: Makoto Taniguchi)"* and *"Yellow River Project (Project leader: Yoshihiro Fukushima)"*, both major multinational initiatives that sought to integrate watershed issues from the headwaters to the ocean. It also carried forward the 'Headwater Control' agendas of the Sixth IAHC Conference in Bergen, Norway, 2005 and the Fifth in Nairobi, Kenya, 2002, which emphasized the need for truly integrated watershed management and for the sustainable management of headwater resources (Beheim et al., 2010; Jansky et al., 2005; Haigh, 2004). This report reviews some key results from the conference proceedings volume, but more importantly, it moves on to describe this meeting's thoughts about what needs to be done in the future.

2. Scope of "HydroChange 2008"

Human activities and climate change are increasing the vulnerability of water resources. However, examining and managing hydrological change is

Table 1. HydroChange 2008: Conference Sessions

Session	*Key topics*
1.	Land-atmosphere interaction
2.	Headwater environment: impacts of climate change and human intervention
3.	Strategic planning and environmental assessments of activities in headwater areas
4.	Environmental education for sustainable development: the role of mountain and headwater landscapes
5.	Hydrological models in support of integrated water resources management
6.	Groundwater-surface water interaction
7.	Remote sensing for measuring water balance, hydrodynamics and hydrological processes
8.	Interaction between the groundwater resources and ecosystems
9.	Socio-economic analysis and monitoring of vulnerable water resource
10.	Reconstruction of human impacts on the surface and subsurface environments during past 100 years
11.	Land-ocean Interaction

Further details are available on the official web site: http://www.chikyu.ac.jp/HC_2008/index.htm

complicated because of the complex interactions between natural climate fluctuation, global warming and human activities, especially changes in land utilization. The effects of these changes extend from the margins of every river basin to the ocean through coastal water exchanges (Fig. 1). This "HydroChange 2008" conference aimed to explore these patterns of interaction and the way they may change because of future climate change and increasing human pressure. Its key topics included land-atmosphere interaction, land-ocean interaction, groundwater-surface water interaction, and the diagnosis and management of environmental change, especially in headwater, estuarine, coastal and offshore environments (Table 1). Its papers included many natural scientific studies as well as, socio-ecological analyses, environmental management, besides social and policy related issues. The approach was interdisciplinary, problem-solving and aimed to raise consciousness about the issues facing integrated water management in the face of accelerating anthropogenic and climatic change.

After three days of presentations and discussions, delegates joined together to seek out the main conclusions and messages from their experience. These plenary discussions were led by Session chairs, who opened each discussion with their summary of the findings from their session.

3. Discussions and Findings

Sessions 1 and 7 concerned Land-Atmosphere Interactions and Remote Sensing. From Australia, CSIRO's Dr Helen Cleugh emphasized the role of land use change in changing the energy balance at the land surface, which had consequences that extended up into the atmosphere as far as the boundary layer and whose effects included storm generation. As ever, such matters complicated the debate about climate change. Several researchers had identified secular changes in precipitation, but these could as easily be the result of land use change (Tamai et al., 2009) as climate change (He et al., 2009). One novelty was a study that considered the atmospheric role of underground cavities (Weisbrod et al., 2009). Session 7 papers dealt with applications, especially of GRACE satellite data, to the study of evapo-transpiration, drought (Hasegawa et al., 2009) and to shallow aquifer water storage (Yamamoto et al., 2009). A key problem of the modelling was linking data sources effectively across different geographical scales. However, MODIS and AVHRR satellite data proved useful for estimating the amount of vegetation and for detecting patterns of vegetational change and their relation to environment factors.

The main IAHC contribution to the "7th International Conference on Headwater Control" was contained by Sessions 2, 3 and 4. Session 2 focussed on environmental change in headwater environments and reported results from an array of long-term, intensive field studies, most of which carried discussion beyond detailed analyses of long-term hydrological change into management strategies for combating the deterioration of water quality and resource. The effects of human actions were more apparent than the signals of climate change. However, the balance of evidence and opinion had shifted noticeably towards the latter since the conferences in Bergen and Nairobi (Beheim et al., 2010; Jansky et al., 2005). Here, the key topics were: runoff generation in headwaters, especially the evaluation of significant influences in the headwater environment upon stream flow and groundwater recharge (e.g., Katsuyama et al., 2009; Oda et al., 2009); the role of environmental change in increasing the incidence of natural hazards such as debris flows (Marchi et al., 2009); and impacts of forest stands and forestry management practices on runoff quality and volume (Kubin and Krecek, 2009; Fukushima et al., 2009). An array of important and detailed empirical studies of soil hydraulic properties demonstrated the ways that environmental changes, both natural (Liang et al., 2009) and/or anthropogenic (Hayashi et al., 2009), control runoff generation processes in small catchments. Isotope and chemical tracers were shown to be powerful tools for exploring these hydrological processes (Katsuyama et al., 2009; Oda et al., 2009). As the IAHC's Dr Josef Krecek noted, long-term monitoring was critical to understanding and clarifying the environmental response to processes such as runoff intensification, accelerated soil erosion and weathering, greater landslide and debris flow activity, and acid atmospheric deposition, as well as purely anthropogenic factors such as industrial pollution, resource exploitation and development, which remained problems in headwater areas (Krecek et al., 2009). The new evidence confirmed that both natural and near-natural forest soils helped stabilize headwater hydrology and that forest management practices play a powerful role in headwater environments for both good and ill. It also demonstrated that there was a need to improve the link between science and civil society to avoid further problems due to bad environmental management policy.

Environmental management policy and the communication of hydrological understanding through education in the community were the subjects of Sessions 3 and 4. Dr Takahiro Endo, speaking for Research Institute for Humanity and Nature (RIHN), reflected on the policy frameworks that guided environmental management in watersheds, on management intervention options that included hard engineering, soft engineering, land use regulation and institutional change, and asked the key question: how to pay? Two possibilities were discussed: first – the concept of local currencies, funded by the community through discounting in local businesses, which could be used to support environmental projects, and second – targeted taxes, where communities, howsoever defined, paid taxes that were specific for particular watershed functions, such as flood control and landslide prevention (Endo, 2009). Another paper discussed the problem of providing adequate training for future environmental managers and advocated field-based problem-based learning as an important, if not wholly unproblematic, way ahead (Haigh, 2009). A case study from Brazil described an excellent and original example of good practice in community education. This concerned a programme that linked research, environmental management and education through a system of School Catchments, which were operated by secondary schools, but which were integrated within both an educational programme and a system of water and flood hazard management required for municipal and research purposes (Kobiyama et al., 2009). Discussion focussed on an unresolved debate about the balance of emphasis and responsibility in environment policies formulation. Endo showed the effectiveness and limits of governmental action in environment management. Haigh and Kobiyama pointed out usefulness, but also limitations, of grass-rooted, community-based management. However, it was agreed that the bottom-up and top-down approaches could be combined as "two wheels" to carry forward better environment management practice and that realizing such better management structures at all levels will be an important topic for future research.

The main contribution from the International Association of Hydrological Sciences reflected the IAHS commitment to hydrological modelling, notionally in support of integrated watershed management. This has been a controversial topic at many of the international conferences on headwater control, where the limitations of research based on simulation rather than empirical observation have been much debated. Here, the large contingent of 18 papers received a critical review from Professor Vijay Singh (Texas A and M University) (Singh, 2009). He noted that of the 18 papers presented, only two actually dealt with integrated watershed modelling. Six presented models, often of some technical novelty, but, he argued, there was a need to go beyond mere models. In five of these cases, either the underlying scientific foundation was weak or the issues of error and model reliability were missing. In fact, only one paper tried to integrate its hydrological model with the social system (Wang et al., 2009), this effort was commended.

As in previous meetings, 5-6 papers struggled to evaluate the impacts of climate change (e.g., Coulibaly, 2009; Fujihara et al., 2009). Here, quality control and ground-truthing presented major problems.

Professor Singh concluded that the sessions had sign-posted three areas that needed future attention. First, there was a need to do more to recognize the needs of the model user. Second, much more work was needed to integrate the social, institutional and legal frameworks with the physical hydrological management models. Third, there was a need to go beyond the scientific comfort zone and both work and communicate with society at large.

Evaluation of human impacts during the last century was the focus of a diverse group of papers. These displayed the divides between the geophysical (e.g., Miyakoshi et al., 2009), hydrological (Iizumi et al., 2009), geographical (e.g., Yamashita, 2009), and socio-economic (e.g., Overton and Doody, 2009) approaches. One novelty was a paper that described an urban heat island effect in the groundwaters beneath part of the Tokyo conurbation (Miyakoshi et al., 2009). This paper was based on numerical analyses of subsurface temperature distribution in boreholes near Tokyo. Studies with a socio-economic emphasis tackled historical changes of flood risk and sewage system following urbanization. Several papers engaged Geographical Information Systems and employed statistical analyses but there remained the need for more widely integrated approaches.

Another session addressed socio-economic models and the management of threatened water resources. Reviewed by Professor Felino Lansignan (University of the Philippines) these presentations dealt with the problems of the allocation and multiple usage of water resources (e.g. Wang et al., 2009; Aoki et al., 2009; Jago-on and Kaneko, 2009), the impacts of environmental change whether due to human (Banchongphanith and Kaneko, 2009; Onishi et al., 2009) or climate (Palanisami et al., 2009) change induced drivers, and the development of indices for the evaluation of water resource stress (Lansigan, 2009). These studies employed an array of techniques including computer simulation, statistical analysis and scenario analysis. Discussions highlighted the vulnerability of water resources and emphasized the need for better development of technologies for water use efficiency. The applicability of the DPSIR (Driving forces, Pressures, State of the environment, Impacts and Responses) framework in the integrated assessment of vulnerability of water resources was discussed. Among the many opportunities and challenges for future research, collaboration across international and disciplinary boundaries provided a major way ahead.

The issue of ground and surface water interactions, the focus of Sessions 6 and 8, had been highlighted for urgent attention at the 6th IAHC Conference in Bergen, 2005. Dr Takeo Onishi (RIHN, Kyoto) noted several valuable attempts to integrate subsurface and surface flows in computer simulation (Nagano et al., 2009; Yamanaka and Wakui, 2009) as well as valuable papers that evaluated the role of deep bedrock groundwater effects on runoff in headwaters (Kosugi et al., 2009), and of shallow groundwater on dissolved iron production in wetlands (Onishi et al., 2009). This session, again, emphasized the need for interdisciplinary collaborative researches among Hydrology, Hydrogeology, Ecology, Agronomy, Socio-economics etc. to construct a broader understanding of the interactions between ground water and surface water processes and mechanisms, especially in key locations such as headwaters, wetlands, forests, irrigation areas and urban areas. Dr Yu Umezawa (Nagasaki University) saw the Session 8 papers setting climate change and human action side by side to look at the effects of environmental change on groundwater storage, salinization (Mekpruksawong et al., 2009) and contaminant transport. Problems were expressed in terms of factors influencing the shift or deterioration of natural vegetation (Doody and Overton, 2009), croplands (Kume et al., 2009), the species composition of benthic fauna and bacteria, and biogeochemical cycles. The main conclusion was the need for modelling based on intensive observation with improved monitoring techniques, as well as better water management policy, regulation and engineering.

A major attempt to integrate the analysis of hydrological change from the headwaters to the ocean, through both direct observation and modelling, was the focus of the final session, reviewed by Professor William C, Burnett (Florida State University). This session tackled land-ocean interactions head-on as well as the difficult interface between field observations and modelling. A novel feature was extended discussion of the submarine groundwater discharge (Taniguchi et al., 2009; Katsuki et al., 2009) and the role it played in offshore water quality (Peterson et al., 2009; Saito et al., 2009) and the observation of blooms of invasive macroalgae (Umezawa et al., 2009). The session opened up the possibilities for new and fruitful cooperation between oceanographers and hydrologists.

Concluding, the organizers reflected upon the degree to which the Conference had succeeded in its aims to integrate the concerns of watershed management from the headwaters to the ocean. They recognized that, while discussion of main-channel hydrologies had been underdeveloped in the meeting, the conference had done much to alert the extremely specialized scientific communities to work in sister areas.

4. Toward Holistic Approach to Hydrological Science

Today, society faces major problems from the vulnerability of water resources for drinking, irrigation, industry etc. Natural and social scientists need to define and predict explicitly the present and future condition of the water resources, and how to manage them appropriately. Hooper (2009) points out that each hydrologist has pursued researches with a different focus and each study defines different frontiers. Most studies describe subject areas, but few illuminate similarities or differences in the intellectual basis of their research. Hooper (2009) proposes that future researchers should recognize the three dimensions of the hydrologic cycle: vertical (boundary layer to bedrock), down-slope (ridge to stream), and down-valley (headwater to ocean). This framework provides a context for a key conclusion from this event, which is the need to define "Ground water-Surface water interaction" and "Land-Ocean interaction" (Fig. 1). To understand and manage properly the complicated hydrologic and other related phenomena within the wide range of land use such as forest, wetland, irrigation area, urban, coastal and so forth, it will be necessary to collaborate and integrate more effectively across many specialized disciplines of hydrogeology, ecology, agronomy, oceanography, biogeochemistry as well as hydrology. Tracers, remote sensing and satellite gravity mission GRACE, for example, are valuable tools for fostering better understanding of these interactions between ground water and surface water and/or land and ocean while GIS proves an increasingly effective way to analyze and interpret these results. Long-term, intensive observations and modelling studies are vital contributions for understanding and predicting the course of environmental change and must be protected from short term economic and political threats.

Hitherto, natural resource management, in general, has been conducted in a fragmented way; i.e. surface water is usually subject to public control, while ground water is regarded as private property of land owners, or land use policy does not pay attention to its impact to the ocean. The results reported in this conference challenge policy-makers to rethink their traditional natural resource management policies. However, the lines of communication between scientists and policy makers will have to be much improved before many of these scientific findings can or will be incorporated into more effective actual policies. While scenario analysis, water mileage, and the DPSIR framework may contribute to this goal, more systematic research on environmental education and communication as well as more interdisciplinary studies involving economists and political scientists should be developed. Simultaneously, the question of whether the research programmes that scholars ask their wider society to fund are really those that serve the best interests and needs of that society must be addressed more rigorously.

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3

Water Management Adaptation Strategies for Land Use Changes and Increased Climate Variability in Mountain Communities in Western Canada

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1. Introduction

The Columbia River in Western North America originates in the Rocky Mountains of British Columbia, Canada and flows into the Pacific Ocean in Oregon. The river is 2000 km long, has the highest vertical gradient of any major rivers in North America and covers an area of 670,000 km^2. There are 14 major hydropower stations on the main stem of the river and more than 300 smaller stations distributed throughout the basin that provide the majority of the electricity for the Pacific North-West. The Canadian portion of the basin covers only 15% of the total watershed area but provides approximately 40% of the water that flows downstream. Fifty percent of the electricity consumed by the 4.3 million people in British Columbia is produced in the Canadian portion of the Columbia Basin. More than 80% of the Canadian headwater area is forested and under alpine cover and the river system is dominated by snowmelt and selective contributions from glaciers.

There are 25 mountain communities in the Canadian portion of the basin and all are experiencing changes in land use and increased climatic variability. There is an urgent need for these communities to develop adaptation strategies in order to be able to cope with emerging water resource management problems relating to increased flooding, water shortages, terrain instabilities, sediment transport and associated water quality issues. Most communities rely on surface water in forested watersheds for their domestic water supplies and have poor

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and aging infrastructure systems in place. There is a general lack of water accounting because water metering is largely absent and few communities have quantitative information on their supplies and use of water. There is now a growing awareness that water supplies are under pressure because of increased climatic variability, hydrological impacts due to land use changes in the forest ecosystem and the need to maintain sufficient water for ecosystem services.

The aim of this paper is to document what the impact of climate change and land use activities are on the aquatic ecosystems and how communities must initiate source water protection strategies to assure water supplies are sustainable. The threats to the forested environments from increased temperatures, diseases, and fire is resulting in increased risk for community water supplies.

2. Increased Climatic Uncertainties

Climate models for the Columbia Basin suggest that warmer temperatures, highly uncertain rainfall, earlier snowmelt, more rain on snow event, accelerated glacial melt, and shifting streamflow pattern, with earlier and higher peakflow and lower baseflow in late summer will be the main impacts of climate change (Murdock et al., 2006; Hamlet et al., 2005; Stewart et al., 2005).

2.1 Evidence of Increased Climatic Variability

There is ample evidence that the average temperatures have increased by about 1.1ºC over the past 100 years (Murdock et al., 2006). More important is the more rapid increase in minimum temperatures in the winter (1.6ºC), particularly warmer night temperatures. There is also evidence that temperature increases are proportionally higher at higher elevation and this is of significant concern for the maintenance of glaciers and the snow melt regime (Redmond and Abatzoglou, 2007). Climate models project annual and winter minimum temperature to increase by 1.4-3.6ºC by 2050.

There are 14 glaciers in the basin and the majority of streams are snow dominated which means that increased winter temperatures will lead to potentially more rain than snow and earlier melting of snow in the spring. The historic data shows a 3% increase per decade of total precipitation but an increase of 36% in rain while the snow component has decreased by 6%. Snow cover data published (Mote et al., 2005; Hamlet, 2011) clearly shows a significant decline in April 1 snow depth over the past 60 years for most of the watersheds in the Pacific North-West. This means that peakflow in most streams will seasonally advance by 2-4 weeks and this results in extended summer low flows (Hamlet, 2011). Higher summer temperature, lower summer precipitation, and lower runoff will lead to more frequent drought affecting fish, water supplies, and recreation. Glaciers which contribute 10-20% to the annual flow and up to 50% of summer flow to the stream can make a significant contribution to keep summer water temperatures low and tolerable for most indigenous fish spcies and contribute runoff at the critical time of the year when evaporation and water use is highest. It was expected that with climate warming glacial-fed streams will moderate low flow conditions in the summer by accelerated glacier melt but as shown by Stahl and Moore (2006) there is ample evidence that many of the glaciers in southern British Columbia have already passed the initial phase of increased warming that induces increases in August discharge.

Uncertainties are emerging about how well the aquatic ecosystem will respond to the temperature, precipitation and runoff changes and how communities should prepare themselves to come with more extreme events, water quality impacts and declining water supplies. While it is very difficult to predict rainfall in these mountain environments, most global models suggest that the annual precipitation will not change significantly in the Canadian portion of the Columbia Basis, but the changes in snow and rainfall variability will result in major changes to the streamflow pattern.

2.2 Spreading of Pine Beetle Infestation due to Warmer Winter Temperature

Pine beetles have been present in British Columbia forests for a long time and outbreaks have been reported since the 1900's. Cold winters with at least one month of below -30 to -40 degrees Celsius usually kept insect outbreaks spatially limited. However, fire suppression resulted in the creation of large stands of mature trees, the hot dry summers have weakened tree resilience, and the mild winters experienced over the past 15 years allowed beetles to survive and attack pine trees at a scale never experienced in human history of British Columbia (Nelson et al., 2007; Hogg and Bernier, 2005).

This disease outbreak, caused primarily by climate warming, has resulted in the largest historic land use change in the forest of British Columbia and the hydrological implications of this change have yet to be fully understood. The extent of the disease, the resulting land use alterations and the effect on the hydrological cycle will be discussed in Section 3.2.

3. Land Use Changes

Forests and Alpine areas cover 90% of the Canadian portion of the basin. Less than 4% is in agriculture (mainly grazing), except for the Okanagan tributary where orchards and vineyards are prominent (Schreier et al., 2008). The remaining areas are covered by glaciers, lakes, reservoirs and bare rock surfaces. A number of land use changes and intensification of use have the potential to significantly impact community water supplies. The main concerns are changes in the forest cover due to tree harvesting (Johnson et al., 2006), pine beetle infestation, increased forest fires, pressure on developing new water-based hydro-power stations, and increased intensification of recreational land use activities.

3.1 Forest Land Use Changes

Forestry is the dominant economic activity and about 55% of the productive forest area is affected by different intensities of harvesting (Table 1). The total annual allowable harvest is approximately 7.5 million m^3/y, which fluctuates, depending on the global market conditions. Over 80% of the timber harvested is exported. About 25% of the forested area is dominated by pine (mainly Lodgepole Pine and minor Ponderosa Pine) and this is the key issue for forest fires because pine beetle infestation has increased the fire risk.

Table 1. Forest statistics for the Canadian portion of the Columbia Basin

Entire Size of Columbia Basin		
Total size of basin	6,700,000 ha	USA & Canadian Portion
Statistics on Canadian Portion of River Basin		
Canadian portion	1,005,000 ha	15%
Forest & Alpine Area	9,160,000 ha	90%
Productive forest	5,000,000 ha	50%
Approx. area currently available for harvesting	2,760,000 ha	55% of productive forest
Annual available cut	7,590,000 m^3/y	
Average area dominated by pine	1,250,000 ha	25%

* Based on the following Timber Supply Areas (TSA): Okanagan, Boundary, Arrow, Kootenay Lake, Cranbrook, Golden , Invermere, Revelstoke, Robson (50%). B.C. Ministry of Forests 2010.

The numbers provided in Table 1 suggest that land use changes as a result of logging and forest management are substantial and affect the water resources in many different ways. Besides changing the snow accumulation, transpiration, and runoff pattern there is the associated effect from having to build and maintain logging roads, which is very challenging in these mountain environments. It is estimated that there are some 250,000 km of paved highways in British Columbia but over 450,000 km of unpaved resource roads (mainly logging roads and roads for mineral and natural gas extraction). Most of these resource roads are built rapidly and are not very well maintained after harvesting declines. These roads usually impact the hydrological regime and contribute to major sediment fluxes in river systems (Anderson and Potts, 1987; Bilby et al., 1989).

3.2 Pine Beetle Infestation

Very large areas in British Columbia are dominated by native stands of Lodgepole Pine and B.C. has a long history of minor infestation of pine beetles (*Dendroctonus ponderosa*). As mentioned, low temperatures in mid-winter usually results in killing most of the beetles. Since 2000 the winter night temperatures have increased most rapidly and this has resulted in the largest and most rapid outbreak of pine beetle infestation in the history of the province. This is likely accelerated because of warmer summer temperatures which stresses the trees and facilitates infestation (Hogg and Bernier, 2005). By 2009 the infestation covered a cumulative area of 16.3 million ha and infested 675 million m^3 of timber. The major infestation occurred primarily in the central part of the province (in the adjacent Fraser River Basin, where Lodgepole Pine is the dominant tree). Some 35% of the forest is now affected in that basin (Schnorbus et al., 2010). The infestation has spread rapidly to all parts of the province but is somewhat less prominent in the Columbia Basin where pine only accounts for 25% of the dominant forest cover.

This has led to a major dilemma. If the dead trees are not harvested they pose a major fire risk and if the trees are harvested within 2-3 years of infestation, the wood can still be used for commercial purposes, although with limited type of use. Infested dead trees increase the fire risk. This combined with more frequent fires and increased harvesting activities has created conditions that will have major impacts on the hydrological processes. Forest fires were perceived as a major risk to the safety of the local community, and large fires make a large contribution to the annual CO_2 emission in B.C. Since forest activities are the main economic engine in the area it was decided to log as much of the infested areas as possible in order to maintain the economic viability of the communities and to reduce the fire risk. There is also some evidence to suggest that the rapid logging of infested trees is contributing to increases in the sediment load as shown by Kreutzweiser and Capell (2001).

3.3 Forest Fires Incidences

Forest fires greatly change the vegetation cover and affect the soils and the hydrological systems in many different ways. Wild fires are a frequent occurrence in British Columbia but have increased significantly due to higher summer temperatures, the widespread pine beetle infestation, a long history of fire suppression (without reducing the fuel load), and more human encroachment into the forest activities. As noted by Westerling et al. (2006), there is evidence that climate warming is accelerating the risk of forest fires. There are no detailed specific records of forest fires in the Columbia Basin, but the annual statistics for the province provided by the B.C. Ministry of Forests show that since 1998 there are on an average 1963 wildfires/year. While the number of occurrences fluctuates wildly from year to year as a result of prevailing climatic conditions, soil moisture variations, frequency of lightning strikes, and human caused incidents, there is evidence that the area affected by fire has significantly increased in the past 12 years (Table 2). As a result the cost of fighting fires has also increased substantially since 2003.

On an average 56% of wildfires are caused by lightning strikes and the remaining 44% are caused by people. Given the complexity of potential incidence and causes of fire it is not possible to determine the contribution of

Table 2: Frequency and extent for wildfires in British Columbia during 1998-2010

Year	*No. of fires*	*Total ha burned/year*	*Total cost (million $/ year)*	*Average ha/ fire*	*Human caused in %*	*Lightning caused in %*
1998	2665	76,574	154	29	46	54
1999	1208	11,581	21	10	50	50
2000	1539	17,673	52	12	45	55
2001	1266	9,677	54	8	62	38
2002	1783	8,539	38	5	51	49
2003	2473	220,518	371	107	39	61
2004	2394	265,053	164	92	28	72
2005	976	34,588	47	35	61	39
2006	2570	139,265	154	54	40	60
2007	1606	29,440	99	18	43	57
2008	2026	13,240	82	7	42	58
2009	3064	247,419	382	81	29	71
2010	1673	330,000	220	197	41	59
Average	1941	107,967	141	50	44	56

Data Source: Wildfire Management Branch, B.C. Ministry of Forests, 2011

each of the key factors such as climate warming, lightening frequency, disease, droughts, rainfall regime, fuel load, and human activity. However, a significant positive relationship was found between mean maximum summer temperatures (June to August) and frequency of fires, and a negative relationship between frequency of fire and summer rainfall in the central part of the province. This suggests that the climate is the underlying factor that increases the wildfire risk.

There is ample evidence that post-fire sediment rates increase and it can take some 7-10 years before these impacts reach pre-fire levels (Ewing, 1996; Wondzell and King, 2003). This is of significant concern for drinking water supply management and subsequent water treatment operations.

3.4 Pressure to Increase Hydropower Development (Run-of-the-River Hydro)

Ninety-five percent of the electricity in British Columbia is generated by hydropower and 50% is generated within the Columbia basin. Most of the production comes from large hydro-power reservoirs that were constructed between 1950 and 1980. Given the many problems and environmental impacts by large hydro-dams (Scudder, 2006), and given the push for green energy, there has been a major push to promote run-of the river hydro-power stations, which are deemed to be more environmentally friendly than large hydro-dams. As of 2010 there are over 800 proposals in British Columbia (over 70 in the Columbia basin) to develop such systems and only a few have currently been approved. However, there are major concerns about such systems because most of the proposed sites in the Columbia basin are in remote mountain environments and at a long distance from the power grid and the population and industrial centres. What is of particular concern is not the operations, which under good conditions cause relatively small environmental impacts. It is the access roads that need to be developed for construction of the site, the construction of the grid connection and servicing of these systems that are of major concern in these steep mountain environments. The experience of forest logging road serves as a good example of what the extent of logging roads impacts are on the aquatic systems (Gomi et al., 2005; Anderson and Potts, 1987; Bilby et al., 1989).

3.5 Increased Summer and Winter Recreation

Next to forestry, both summer and winter recreations are the major economic activity in the Columbia basin. Most recreational activities focus around water or require substantial amounts of water. There are more than 20 major Ski areas in the basin and this puts significant pressure on water supplies during peak holiday periods like Christmas. These occur at a time of the year when river flow is at the low end. What makes this even more of concern is that most of the winter resort areas have a base elevation of less than 1200 m and will have to rely on widespread snow making activities in early winter. As shown by the experience in Europe, snow making requires large amount of water because at least 20-30% of the water sublimates during the snow making process (Vanham et al., 2009; Steiger and Mayer, 2008). This also means that large amounts of water need to be stored in late fall when water flow in most mountain streams are low.

Every mountain community has at least one golf course and there are more than 75 major golf courses operating in the basin. In fact the Okanagan tributary which has the driest climate in Canada lists 45 operating golf courses using on an average 11,000 m^3 of water annually for irrigation (Schreier et al., 2008). The majority of golf course operators rely on domestic water supplies and given the popularity of the sport and the warming trends the water demand is increasing.

There is also a very well developed sports fishing industry operating in the basin and the concerns for this activity is two-fold: 1. Will there be sufficient water for maintaining the aquatic biota given the increasing demand for water for domestic and recreational activities? and 2. Will the water temperatures in late summer be cold enough to maintain the main fish population native to the streams?

4. Community Source Water Supplies, Water Quality and Water Demand

Most communities collect their domestic water from forested catchment. The majority gets their water from streams, lakes and reservoirs and less than 30%

rely on groundwater. Since most of the communities are small (>10,000 people), the water storage capacity and the financial resources for infrastructure support is limited.

4.1 Supply and Demand Issues (Domestic Use, Seasonal Demand etc.)

Based on a reconnaissance survey in 2005 it was determined that only one of the 18 communities surveyed used water meters and until recently most residents paid a flat annual rate with no restriction to the amount of water used (Ells, 2005; Ronalds, 2005). Quantitative records are difficult to obtain since water metering is largely absent but based on the amount of water released from the various treatment plants and reservoirs, the per capita water consumption was found to be very high. This of course includes all service industry use (residential and commercial) and leakages. The obtained values are obviously a first gross estimate. As shown in Fig. 1, the mountain communities in the Columbia basin are among the highest domestic water users in the world, averaging 678 L/capita/day (extreme use 1900 L/capita/day). There are many reasons for such large water consumptions. There is a lack of information, there is the perception that water is plentiful in the mountains, there is little knowledge about the seasonal water cycle, and the cost for water is so low that there is little financial incentive for conservation.

The average cost for domestic water per family is a flat rate of $ 206 per year. Figure 2 shows the negative relationship between domestic water uses and annual cost per family. The communities that pay the most for their water consume significantly less than those that pay the least for water.

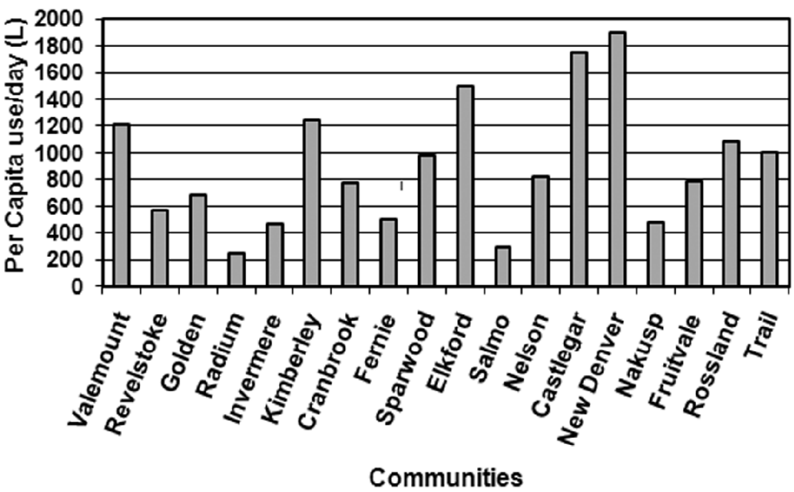

Fig. 1. Domestic water consumption in 18 communities in the Columbia basin.

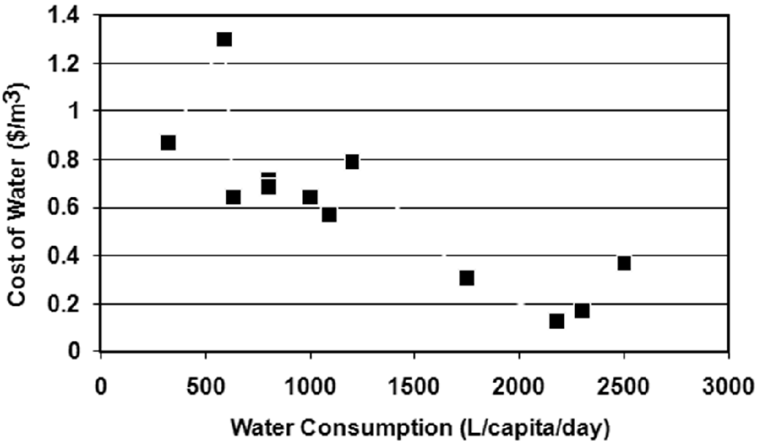

Fig. 2. Relationship between domestic water use vs. cost of water.

From the survey conducted by Ronalds (2005) it became evident that 40% of the respondents have insufficient water for their domestic needs during critical times of the year, suggesting that conservation and demand management is becoming a critical aspect of water management.

4.2 Water Quality Issues

Because many of the water supply sources are in forested mountain watershed the main water quality problems are sediments, pathogens, Fe and Mn, excess nutrients, and selected metals. The perceived pollution sources are highly variable ranging from agriculture (13%), forestry (27%), mining (13%), septic systems (17%), urban (13%) and wildlife (17%). The primary concern is pathogens and as shown in Table 3, the incidents of boil water alert clearly shows that many communities are in dire needs for improved water treatment (Prystajecky, 2009). What is particularly surprising is the fact that 45% of all boil water advisories in British Columbia are in the B.C. Interior Region (80% of the Columbia basin) and 65% have been in place for less than five years and 36% in more than 10 years. This clearly shows that a chronic water quality issue exists and source water protection is sadly neglected.

Table 3: Number of boil water advisories and how long these advisories have been in place in British Columbia and in the Columbia basin

Region	*Total number of boil water advisories*	*Numbers less than 5 years in place*	*Numbers more than 10 years in place*
British Columbia Total	275	184	64
Interior Region (80% in Columbia basin)	124	79	45

5. Water Management Adaptation Strategies

What is of major concern for the basin communities is the lack of quantitative information on both water supplies and demands. Source water protection and water conservation are clearly key issues that need to be addressed.

5.1 Adaptation Strategies for Water Supply Management

On the supply side, the main concern is source water protection and this includes protecting land use activities in the mainly forested water source areas and effective measures to retain and release water at different times of the year. The need for such measures are clearly evident as a result of increased climatic variability, dramatic changes in forest cover and management activities, and associated activities related to the development of new hydropower production. To reduce the vulnerability to domestic water supplies requires a multi-barrier approach that protects and enhances supplies and minimizes impacts on water quality.

On the quantity side the following actions could reduce the risk for communities to experience water stress during critical periods:

1. Conserve, maintain and enhance the wetlands in the source water areas. This will allow more water storage and will regulate seasonal variability in runoff.
2. Provide shading of streams in riparian corridors to reduce evaporation (Pollock et al., 2009).
3. Selectively harvest forests so as to enhance snow accumulation and minimize fire risk, excessive road construction, and soil disturbance (Rashin, 2006).
4. Enhance soil quality by maintaining organic matter, soil structure, infiltration rates and minimize soil compaction. Enhancing the infiltration of rain into soils will delay runoff and will produce more recharge to groundwater sources.
5. Determine the ground water and glacial contribution to summer low flow to establish vulnerability and sensitivity to climate change.
6. Provide more storage capacity to reduce the risk of greater and earlier peak-flow and lower summer base-flow.
7. When replanting forests select diverse tree species to increase biodiversity and plant trees that have low water requirement, are drought resistant and can survive and prosper in warmer climate (Spittlehouse, 2005; Johnson et al., 2009; Williamson et al., 2006).

On the water quality side the following source water protection strategies should be initiated:

1. Provide large well vegetated riparian buffer zones so as to absorb excess nutrients, and detain sediments before they can enter the streams (Inamdar, 2006; Dosskey et al., 2010).

2. Use wetlands as major filter systems for nutrients, pathogens and other contaminants.
3. Initiate source control measures. Only allow minimal land use in critical water supply areas and minimize the use of chemicals and animal grazing.
4. Construct sediment detention systems in fore-bays of storage reservoirs in order to minimize problems at water treatment stations.
5. Minimize forest activities, initiate forest fire prevention strategies by reducing fuel load and regularly maintain existing logging roads (Johnson et al., 2006).

5.2 Adaptation Strategies for Water Demand Management

The greatest savings can be made by having a very aggressive water conservation programme in place. This is probably the most cost effective adaptation strategy to increase climatic variability. The most effective options are:

1. Meter all domestic water use. This will not only reduce water consumption by at least 30 % (REF) but will also provide the basis for proper water accounting.
2. Require all water saving devices to be installed in new houses and convert existing facilities over a 5-10 years period. The requirement for low flush toilets alone will reduce consumption of domestic water use by a minimum of 30%.
3. Initiate household rainwater storage facilities (roof-water collection systems) because 50% of domestic water use is during summer for outdoor use (Maurer, 2009) and using harvested rainwater can reduce outdoor water use by at least 30-50%.
4. Minimize the lawn area that needs to be irrigated, or practice xeriscaping to reduce outdoor water use during the summer.
5. Having an effective leak evaluation system and leak repair system in place will be essential because it is estimated that many communities lose 30-40% of their domestic water through leakage.

6. Summary and Conclusions

The mountain communities in the Columbia Basin have most of their water supplies in forested catchments that are subject to rapid land use changes and increased climatic variability. The climate change scenarios suggest that peak-flows will be higher and earlier in the season and summer low flow will be extended. This is coupled by impacts of major land use changes due to increased disease (pine beetles), more frequent fires, increased harvesting and forest disturbance to reduce the fire risk by salvaging infested trees before the wood is no longer useful for commercial purposes. The combination of these factors means that stream-flow pattern will change and supplies will become more stressed.

On the water use side water metering is not in place, people pay very low prices for domestic water and there are no financial incentives to conserve water. As a result these communities are among the largest water users in the world. Since water protection strategies have been neglected these communities have a high preponderance of water borne pathogen problems leading to frequent and long term boil water advisories, which does not solve the problem and is also very energy consumptive. The initiative that are currently underway by the Columbia Basin Trust is to initiate a widespread adaptation strategy to reduce the vulnerability of these communities to increased climatic variability and land use changes by putting in place a water conservation programme, a source water protection strategy, and a climate change adaptation initiative. This will include protecting and enhancing the source water catchment areas, retain more snow in forest openings, improve water storage in soils, recharge groundwater sources, enhance water storage by protecting and improving wetlands, and store water in detention systems during the snowmelt and high runoff periods. This will facilitate water flow during the extended summer low flow when water demands are highest.

At the same time extended and well vegetated riparian buffer zones, source control and land use management restriction will reduce water quality deterioration problem, thus reducing the requirement for expensive treatment systems.

The greatest savings and the most effective adaptation strategy is to reduce the demand for domestic purposes by requiring all water use to be metered, requiring all residents to use water saving devices, and significantly reducing the outdoor water use. The latter can be accomplished by using roof-water collection systems, minimizing watering lawns during summer and focussing on water efficient plants.

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4

Environmental Education and Catchment Citizenship in Mountain Regions

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1. Introduction

Community participation and engagement is a key ingredient in effective mountain watershed management and one that tends to be neglected by those applied scientists whose focus is exclusively upon the physical or even economic environment. The challenge for those engaged in the technical, economic or planning and development of mountain watershed is how to engage community partners and how to spread understanding of the technical problems of applied watershed management into the community sufficiently that local communities are able to develop as informed, empowered and active catchment citizens, capable of acting as critical friends in watershed management decision making (Ewing et al., 2000). As Robert Ferrier and Alan Jenkins (2009) put it: "*Catchments are naturally leaky and thus part of the responsibility should be borne by the public ... at a grassroots level with catchment citizens and other organizations*". However, achieving this goal involves community-based environmental education and the mobilization of community stakeholder groups (Blackstock and Richards, 2007).

This chapter concerns an environmental and citizenship education training programme that, for the past ten years, has been offered in Quebec. The programme is called the Program in Environmental Education and Citizenship (PEEC). The PEEC programme is based on an educational model known as *"Action Research for Community Problem Solving"* (AR:CPS). This model leads students and learners to become actors in, for and with their communities.

Previously, the idea of catchment citizenship has been developed particularly in western regions of US. As an example, the Los Angeles & San Gabriel Rivers Watershed Council was founded, in 1996, because the five

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different water agencies managing water in this region were failing to adequately exchange information even among themselves, let alone with the public (Council for Watershed Health, 2011). Now rebranded as the Council for Watershed Health, this NGO has become the centre for practical watershed education, research and analysis in Southern California, focussing on the watersheds of the Los Angeles Basin. The Watershed Council is uniquely situated at the intersection of research and policy to drive applied research to improve policy and practice. Elsewhere, in Baltimore, American citizens use urban waterways like the Patapsco River as sources of drinking water and for a variety of activities including boating, fishing and swimming. Of course, cleaning up, restoring and sustaining the qualities of this water resource is essential to protecting the local community's health and to improving their overall quality of life. Revitalizing such urban waterways also help reconnect citizens to open spaces and their natural habitat, as well as having positive economic impacts on local businesses, tourism and property values. It could also spur private investment and job creation in these communities.

2. Programme in Environmental Education and Citizenship

Since 1993, PEEC, the Québecois Program in Environmental Education and Citizenship, has been building an effective strategy for active environmental citizenship. The PEEC citizenship concept is defined by Jane Jenson, Director of the Canadian Policy Research Network's Family Network, as both a status and a relationship between state and citizens (Jenson, 2001). Her citizenship concept has three dimensions: (1) rights and responsibilities, (2) access and (3) belonging. She also explores how citizens' formal equality can be turned into real participation.

The PEEC programme is based on an educational model known as *"Action Research for Community Problem Solving"* (AR:CPS), which encourages learners to become actors in, for and with their communities (Poudrier, 2011). The approach was developed in the United States by William B. Stapp and his students (Stapp et al., 1996; Bull et al., 1988; Wals et al., 1990), where model was often used to change the conventional school environment and to improve teaching and learning conditions in schools.

The AR:CPS approach advocates a citizenship education learning strategy that leads actors of all ages to:

- Identify a problem of concern to them in their community.
- Analyze the problem by considering its different issues.
- Identify potential solutions.
- Select the one that best fits the situation.
- Develop and implement an action plan.
- Evaluate the process and its outcome.

The AR:CPS model use thirteen steps (Table 1) for developing community projects that integrate or link to the social, physical or biophysical environment. The teacher leads the first two steps. The students then become partners in the decision-making processes and gradually take on all or part of the project management. The teacher continues to work in the role of a guide, facilitator and resource person.

Table 1: AR:CPS Thirteen Steps

1.	Process planning by the teacher, in collaboration with all concerned partners: principal, colleagues, parents, community members, etc.
2.	Diagnosis evaluation of students' abilities in solving problems, in order to spot their "deficiencies". As the project goes along, the teacher will have to try to develop required abilities through appropriate teaching and exercises.
3.	Students' awareness of community problems. An exploratory visit of immediate environment is an excellent way to discover these problems and become sensitive to them.
4.	Listing of noticed problems. The brainstorming technique is then useful. Problems may be classified and their interrelations underscored.
5.	Identification of criteria for the selection of a problematic situation to be solved.
6.	Selection of problematic situation.
7.	Search for information on this problematic situation. It may be documentary researches, interviews, observations, etc. A lot of information comes from community environment itself.
8.	Clear definition of problem inherent to the analyzed situation.
9.	Search continuation on the problem now clearly defined.
10.	Examination of possible solutions (again, brainstorming session).
11.	Development of criteria for the selection of preferred solution.
12.	Development and implementation of action plan.
13.	Evaluation of action considering expected effects and follow-up.

Throughout, the AR:CPS process leads students to take meaningful action in their communities. Its approach is geared toward solving real problems by developing and then implementing action plans. The students lead the decision making, step by step, making their way through a democratic process. Throughout, they log everything they experience in an experiential learning journal. They record their findings, thoughts and even feelings. Their journals describe what they have learnt, their new insights on their problem, changes in their awareness and understanding, their experimentation with participation strategies, and their perseverance and struggle in the face of set-backs and adversities. Through reflection on these accounts, the approach not only leads young people to solve community problems but also highlights new opportunities for the development of learning and even solutions for school-related teaching/learning problems. As Wals (1994) discovered in Detroit, while these activities may target just one environmental problem, the method actively engages both students and teachers in an interdisciplinary learning process that seeks improvement in their local biophysical and/or social environments.

Programme evaluations conducted thus far suggest that the approach is popular with students, teachers, parents and school administrators and that all are very satisfied with its application and its outcomes. Especially, it seems, learners prefer this approach to traditional teaching models. The reason is that the model opens up the community to the school. The immediate environment, as seen by the actors, becomes a source and tool for learning. The students select and develop projects based on a problem-solving approach. The students identify various problems in their school or neighbourhood, such as vandalism, vacant lots, rundown buildings, bullying, waste of energy or drinking water, etc., and take steps towards their resolution. It offers real benefits to all involved. It helps educators discover their students' potential, renews their skills and generates community goodwill. It helps learners develop self-esteem, teamwork skills and self-awareness of their individual power as agents within, for and with their community (Amegan et al., 1981). It promotes reflective practice alongside the development of critical thinking and communication skills (Sauvé, 1992). Of course, for the educational institutions as a whole, the project is valuable because it helps enhance the school-community relationship and encourages school staff to be more deeply involved with their surrounding community.

3. Discussion

The PEEC project is rooted in the Action Research process of participants solving real life problems in, with, and for their community. Currently, PEEC engages fifteen or so school boards, two private schools, Dawson College, as well as some Day Care and Seniors Centers. In 2008, there were 70 schools, some pre-schools and universities, involved in the programme. PEEC involves elementary and secondary school teachers, education consultants and also adult education and pre-school educators. The Ministry of Education in Quebec is engaging with researchers providing teacher training, while the PEEC project itself offers training for learners of all age groups from four years old upwards.

This investment is thought worthwhile because this AR:CPS model proves inspirational; its success, as observed by teachers, is due to the great motivation and perseverance that its student-citizen actors show in their efforts to improve a situation or solving a real problem that affects their families and community. In March 2005, the Canadian Policy Research Network (CPRN) published the results of an online survey of 200 or so young Canadian adults aged from 18 to 25 years (Canadian Policy Research Networks, 2005). The survey was designed to identify young adults' priorities in relation to six themes predetermined by an advisory committee made up of people of the same age.

However, the key survey finding was that young people truly want to be active citizens and to be involved in community decision making. These results are similar to those reported by an earlier CPRN, which also revealed the same hunger for participation and confirmed Canadian citizens' desire to participate in bringing about changes in their communities (Peters, 1995).

Thus far the evaluations of AR:CPS projects have demonstrated that student participation in community problem-solving strongly promotes the development of their sense of accountability and community belonging because these young people are the leaders of the projects they create, albeit in collaboration with a guide (teacher or other person) (Poudrier, 2005). This methodology contributes to developing students' sense of empowered personal responsibility towards and engagement within their communities (cf Haigh, 2009). The AR:CPS approach engages students in developing partnerships with members of their communities. They learn that collaboration, team work and coordination are critical and that, today, no actor can succeed alone (Saint-Martin, 2004). As the CPRN's Pat MacKinnon also reports, Canada's citizens are keen to play a larger role in the democratic process and welcome greater opportunities to engage with decision makers on issues that affect their collective quality of life. The PEEC project strongly supports this goal as does that of the later CPRN 'Focus on Youth' programme (2004), whose goals include the identification of effective approaches for engaging young people in their community's democratic process. One of the effective methods, this suggests, is the AR:CPS model.

Equally, the Conseil Supérieur de l'Éducation (1998) states that no citizenship education programme can yield tangible results if the students do not have real opportunities to apply the values, rights, responsibilities and civic involvement they are taught in class. This link between teaching and practical engagement is crucial for successful citizenship education and the advantages of the PEEC programme include students' gaining frequent opportunities to exercise their citizenship learning. The AR:CPS model creates multiple opportunities for students to apply their citizenship education skills because it spans an entire school year and builds skills that are key to active participation in democratic society, such as critical thinking, communication, persistence and collaboration (Poudrier, 2005). The Conseil supérieur de l'Éducation (1998) also argues that citizenship goes hand in hand with the development of community roots. The PEEC program's AR:CPS approach engages students in community service and encourages them to develop their sense of social responsibility.

4. Conclusion

The PEEC programme's AR:CPS approach is something that gives meaning to school learning, and the development of critical thinking skills and creativity as well as for citizens who apply the model. It gives learners the chance to acquire experience outside the conventional framework and in the real world contexts of their community and encourages their emergence as active democratic citizens. The key problem in the protection of mountain watersheds is finding ways of integrating the needs and perspective of the technical, scientific and economic agents in these regions with those of the community of inhabitants (Haigh, 2010). To achieve this goal, it is essential that environmental and citizenship education in these regions should work together to produce the kind of informed, engaged, effective and reflective change agents that are capable of making informed decisions for their communities. This PEEC programme and the AR:CPS model that underpins it has wider significance than just the needs of Canadian society. It is a model that should be widely applicable to other regions of the world and anywhere that seeks to involve citizens, regardless of age, in the decisions that concern them. In so doing, this empowering style of environmental and citizenship education will be able to contribute to improving the quality of life and environmental management by building not only the requisite foundations of knowledge but also, and above all, by developing the behaviours and attitudes that are key to educated citizenship.

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Part II

Stream-flow Processes in Mountain Catchments

5

Integrated Hydrological Model for Mountain Ecosystem Assessment

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1. Introduction

In Japan, more than 70% of the land surfaces are covered with forest and most of these are coniferous forest plantation for timber production. However, the timber price slump according to the economical depression and declining birthrate and growing proportion of elderly people are accelerating vast forest deterioration. Furthermore, with the global warming, many regions have been experiencing the hydrological extremes such as heavy rainfall and severe floods or droughts. Consequently, most of the farmers and foresters who lived in mountainous area had to settle to the urban area located in the lower reaches of the river basin. Then, most of these abandoned mountainous areas are becoming inadequately managed forest which might frequently cause land surface erosion or severe land slide. To make matters worse, the extreme hydrological events are aggravating the floods, soil erosion and droughts, and are projected to increase until the end of this century (Kitoh et al., 2009). Accordingly, these are damaging to forest and river ecosystems in the mountainous areas.

From the hydrological point of view, it is necessary to evaluate the amount of water consumption to clarify the amount of evapotranspiration losses from vegetation surface which is the most important factor for the potential drought risks. The disappearance of a permafrost layer, glacial recessions or change of seasonal snowfall/melt will derive a critical impact on the hydrological cycle in the cold mountainous regions. The quantification of the magnitude and frequency of the future typhoon (or tropical cyclones) are also important factors for the flood disaster prediction and mitigation. Therefore, hydrological impact of climate change has attracted considerable attention for the integrated water resources management (IWRM).

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In recent years, the global climate model, especially, the general circulation models (GCMs) based on physical principles of fluid dynamics or heat-radiation transfers are becoming the more reliable tools for projecting the impact of future climate change. By using GCMs, the changes in air temperature, the amount of sea/glacial ice, ground water dynamics, spatial distributions of the precipitation/evapotranspiration losses are projected in the global scales. However, the spatial resolution of typical GCMs (approximately 100-400 km) is too coarse to predict major hydrological and ecological processes occurred in the sub-grid scale. Thus, currently available GCMs are only suitable for predicting the hydrological impact of climate change in the relatively large watershed or continental scales (i.e. Volosmarty et al., 2000; Hirabayashi et al., 2008).

Under these circumstances, a super-high-resolution (approximately 20 km) global atmospheric general circulation model (AGCM) has been developed by the Meteorological Research Institute of Japan Meteorological Agencies (JMA) to project the changes in future weather extremes under the global warming environment, due to the availability of the recent faster super computer (Earth Simulator). This latest model (MRI-AGCM3.1/3.2S) can reproduce the actual climate conditions more accurately than the previous lower resolution models.

This paper will introduce these recent research topics and problems on climate change from a eco-hydrological point of view.

2. Background

The third phase of Japan's Science and Technology (JST) basic plan began in April 2006. One of the priority fields of the plan is research on the environment including climate change issues. As a part of this national strategy, the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) has launched a 5-year (FY2007-2011) initiative called the Innovative Program of Climate Change Projection for the 21st Century (KAKUSHIN Program), which uses the Earth Simulator to address emerging research challenges, including outcomes from MEXT's previous project (FY2002-2006) called the Research Revolution (RR) project. The RR project has made substantial contributions to the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) and the current KAKUSHIN program is attempting to contribute next AR5.

The KAKUSHIN program has the following three major themes: (a) Advancing climate modelling and projection for better simulation of physical and biochemical processes by sufficient reflection of feedbacks; (b) Quantification and reduction of uncertainty for more reliable projections of climate change using model comparisons and other methodologies; and (c) Application of regional projections to natural disaster for better assessments of natural disasters caused by extreme events using sufficiently high-resolution regional projection.

Furthermore, three teams participating in the KAKUSHIN program are covering above three themes as follows: Team 1: Long-term global change projection; Team 2: Near-term climate projection; and Team 3: Extreme event projection. Under the Team 3 of the KAKUSHIN program, the Disaster Prevention Research Institute (DPRI) of Kyoto University is conducting the risk assessment research (Prediction and evaluation of disaster environment) together with International Center for Water Hazard and Risk Management (ICHARM) of Public Works Research Institute (PWRI) using the future projection information based on a global 20 km mesh AGCM. The DPRI is performing "Integrated assessment of climate change impacts on watersheds in a disaster environment" including the following six research groups: (1) Uncertainty evaluation (dynamical/statistical downscaling); (2) storm surge and strong wind disaster; (3) landslide and soil erosion; (4) flood and drought prediction; (5) fluvial inundation; and (6) coastal disasters (including tidal wave induced by typhoon), and we are trying to integrate our progresses for proposing more appropriate future adaptation strategies.

3. Data and Method

3.1 Atmospheric General Circulation Model (MRI-AGCM)

The spatial resolution of the MRI-AGCM is the highest resolution in the world at the present time. The origin of the coordinate system is (0°E, 90°S). The difference of longitude (DLO) is constant (0.1875°). On the other hand, the difference of latitude is not evenly separated, so the definition of the latitude of each grid mesh edge is described in the control file. The elevation of each grid mesh is also described in Digital Elevation Model (DEM) outputs with the format of (1920 × 960).

The future climate projection of the model is based on sea surface temperatures (SST) derived from the IPCC's assessment report 4 (AR4), a special report on emission scenario (SRES) A1B. The data of AGCM is divided into three different time periods: 1979-2004 as the present, 2015-2039 as the near future, and 2075-2099 as the future climate condition. The meteorological factors used for the input of parameters for the hydrological model are hourly precipitation, air temperature and daily rainfall to the soil layer, snowmelt to soil layer, evaporation loss from soil layer, and transpiration loss from soil layer.

3.2 Soil-Vegetation-Atmosphere-Transfer (SVAT) Model

In order to run the hydrological model, it is necessary to prepare the input meteorological datasets, such as input rainfall to the soil layer (net rainfall + snowmelt) and water losses from the soil layer (evaporation + transpiration). As shown in Fig. 1a, all of these meteorological components are included in the AGCM. However, the amounts of evapotranspiration and snowmelt are not measured directly in most of the routine meteorological observation in Japan. Therefore, the Soil-Vegetation-Atmosphere Transfer (SVAT) model is used to obtain input rainfall and evaporation from the routine observed meteorological dataset (Fig. 1b).

The SVAT model can simulate snowfall, snow-cover and snowmelt processes. In the SVAT model, precipitation is converted to snow when the hourly air temperature is less than approximately +2°C. Snow density is set as constant (100 kg/m^3) to simplify the calculation. The amount of snowmelt is calculated by the heat balance method. The heat balance at the land surface is calculated in the process to estimate potential evaporation. The influence of nocturnal condensation in the arid-region can be negligible, and thus it is not considered in this model. Following Xu et al. (2005), potential evaporation, *Ep*, is defined as the evaporation from a continuously saturated imaginary surface. The imaginary surface include surface roughness = 0.005 m, albedo ref = 0.06, surface emissivity ε = 0.98, and evaporation efficiency β = 1. Surface temperature, sensible heat flux, and latent heat fluxes are estimated from the following energy balance equations:

$$(1 - \mathrm{ref})S^{\downarrow} + \varepsilon L^{\downarrow} + = \varepsilon\sigma Ts^4 + H + \lambda E + G \tag{1}$$

$$\mathrm{H} = c_p \rho ChU_1 \, (Ts - Ta) \tag{2}$$

$$\lambda E = \lambda\rho\beta ChU_1 \, (q_{sat}\,(Ts) - q_a) \tag{3}$$

where $S^{\downarrow}$ (W/m^2) is the solar radiation, $L^{\downarrow}$ (W/m^2) is the downward long-wave radiation flux, σ is the Stefan-Boltzman constant (5.670 × 10^{-8} W/m^2/K^4), and *Ts* (K) is the calculated surface temperature that satisfies the heat balance equations indicated above. Computational details for $S^{\downarrow}$ and $L^{\downarrow}$ have been described by Ma et al. (2003). When *Ts* is known, sensible heat flux *H* (W/m^2) and latent heat flux λ*E* (W/m^2) are computed at the same time. In this case c_p

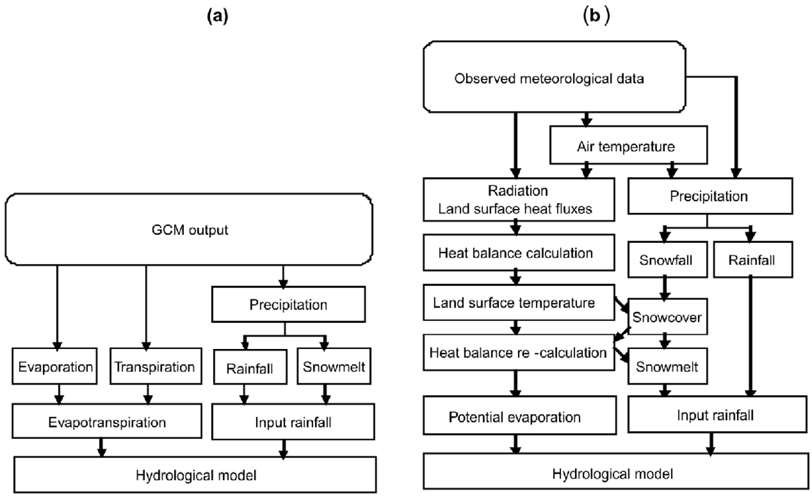

Fig. 1. Simplified procedure to obtain input data for hydrological model.

(J/kg/K) is the specific heat of air, ρ (kg/m^3) is the air density, *Ta* (K) is the air temperature, λ (J/kg) is the latent heat of vaporization, $q_{sat}(Ts)$ is the saturation specific humidity of *Ts*, and q_a is the specific humidity. ChU_1 (m/s) is the exchange speed defined as follows:

$$ChU_1 = \max\,(0.0027 + 0.0031 \times U_1, 0.0036 \times (Ts - Ta)^{\frac{1}{3}}) \tag{4}$$

The evaporation rate under these conditions is defined as the potential evaporation *Ep*. The temperature of the isothermal soil layer is assumed to be the lower boundary of the SVAT model; this layer is set at a depth of 6 m below the ground surface and is equal to the annual mean air temperature of each grid cell. Soil and snow temperature profiles are calculated using a thermal conductive model to obtain the values of soil and snow heat flux, *G* (W/m^2). The soil layer and snow pack are subdivided at 0.01 m intervals. The value of *G* (at 0.01 m beneath the land surface) is calculated as follows:

$$G = -\kappa \frac{Ts - Tg}{0.01} \tag{5}$$

where *Ts* (K) is the land surface temperature, *Tg* (K) is the temperature at 0.01 m beneath the land surface, and κ (W/m/K) is the thermal conductivity of soil or snow. The value of κ was set at 2.0 for the soil layer and 0.3 for the snow layer. Once we can calculate the vertical profiles of the soil temperature, we will be able to calculate the temperature of river channel or ground water.

3.3 Hydrological River Basin Environment Assessment Model (Hydro-BEAM)

To assess the current and future basin scale environment and water related disaster risks, a physical based distributed hydrological model (Hydrological River Basin Environment Assessment Model: Hydro-BEAM) is developed (Kojiri, 2006). The model is a kind of the cell concentrate type rainfall-runoff model which divides each grid cell into two pairs of rectangular hill slopes and one river channel (Fig. 2a). The surface flow and subsurface flow from A layer and channel flow are calculated by a kinematic wave model (Fig. 2b). The groundwater flow from B and C layers are calculated by the storage function model (Fig. 2c). The deeper seepage and long-term groundwater storage are considered in D layer.

The five land use types (forest, grassland, urban/city, paddy, water/ice) are used to determine land surface roughness of manning equation and infiltration ratio of each land use types. The angle of hill-slope and gradient of river channel are determined by DEM. The basic form of the kinematic wave equation for open channel flow is

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = qin \tag{6}$$

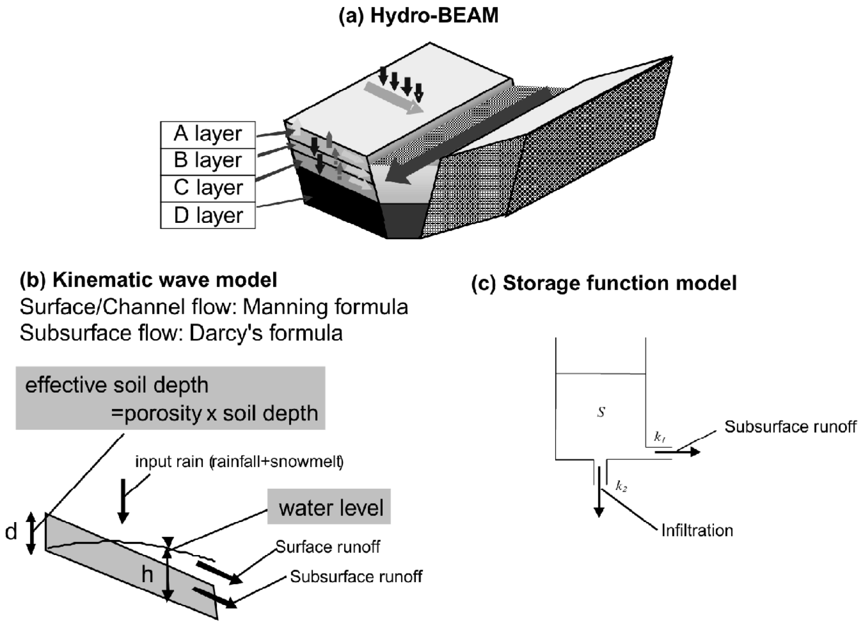

Fig. 2. Basic structure of hydro-BEAM.

$$Q = \alpha A^{\frac{4}{3}} \tag{7}$$

$$\alpha = \frac{\sqrt{sl}}{n}\left(\frac{m}{\left(2\sqrt{1+m^2}\right)^2}\right)^{\frac{1}{3}} \tag{8}$$

where A is the flow cross-sectional area (m^2), Q is the flow discharge (m^3/s), qin is the lateral inflow discharge per unit length (m^2/s), α is constant, sl is the channel slope, n is the Manning's friction coefficient (equivalent roughness) and m is the slope of river bank. The m in the mesh 'i' is defined as:

$$mi = \frac{Bi}{Hi} \tag{9}$$

where Bi is the channel width (m) of mesh i, Hi is the depth of water (m). Equation 6 represents the continuity equation and is derived from the mass conservation principle. Equation 7 is derived from Manning's law assuming flow resistance of open channel uniform flow. A catchment (each grid cell) is modelled as a set of hill slopes and runoff flow from these slopes are modelled as shallow water flow on each hill slope. The hydraulic radius of shallow flow in Manning's law can be approximated by the water depth, h (m). Then, the discharge per unit width q (m^2/s) can be expressed as:

$$q = \frac{\sqrt{hl}}{n} h^{\frac{5}{3}} \tag{10}$$

where hl is the hill slope. In the Hydro-BEAM, the channel and hill slope less than 0.001 is modified/fixed to 0.001 to solve these equations from source area to river mouth continuously.

By dividing both sides of Eq. 6 by the width of a each hill slope (m), we can obtain the following continuity equation for hill slope flow.

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = fr \tag{11}$$

where r is input rainfall intensity (m/s), and f is the direct runoff ratio (soil saturation ratio in A layer).

The kinematic wave model described in Eqs 10 and 11 can be applied to infiltration excess overland flow (Hortonian overland flow). However, Hortonian overland flow is seldom found in mountainous watersheds and it is not applicable to saturation excess overland flow, because the model does not consider such a flow in A layer. Therefore, a new kinematic wave model which considered both surface and subsurface flow is applied to the Hydro-BEAM (Fig. 2b). By integrating Manning's formula for surface flow and Darcy's formula for subsurface flow, the Eq. 10 can be rewritten as:

$$q = \alpha(h-d)^{\frac{5}{3}} + ah \; (h > d) \tag{12}$$

$$q = ah \; (h \leq d) \tag{13}$$

$$\alpha = \frac{\sqrt{\sin\theta}}{n}, a = K\frac{\sin\theta}{\lambda} \tag{14}$$

where d is the effective soil depth of A layer (m) = λD. λ is the porosity of A layer and D is the actual depth of A layer (m). θ is the angle of hill slope (radian) and K is the saturated hydraulic conductivity (=0.0001 m/s). Equation 13 is used for those cases where only subsurface flow occurs, and Eq. 13 is used for those cases where saturation excess overland flow occurs.

The kinematic wave model described above is one of the most reasonable physical based rainfall-runoff models for flood prediction. However, the model is difficult to predict the major part of the recession discharge between storm periods due to the complex mechanism of water flow under the ground (e.g. the spatial distribution of soil hydraulic conductivity or actual soil depth data cannot be obtained from current conventional field observation techniques). Thus, for the B and C layers in the Hydro-BEAM, the linear storage function model is applied to predict the base flow process more accurately. The continuity equation and dynamic equation of the linear storage function model are described as follows:

$$\frac{ds}{dt} = I - O \tag{15}$$

$$O = kS \tag{16}$$

where S is the storage of water (m), I is the inflow (m/s), O is the outflow (m/s) and k is the outlet coefficient (1/s). The runoff from paddy field is calculated to keep the desired pounding depth (m) of the paddy field. When the water deficit occurs, the irrigation water is supplied from the nearest river channel if there is enough water in the river channel. On the other hand, the residual water is directly returned to the river channel. The details of the structure and parameter settings of the model used in this study are summarized in Sato et al. (2009b).

3.4 Channel Network

In order to run a distributed hydrological model, it is necessary to prepare the basin's geographical information such as the flow direction or channel network. The basic procedure to pick up the geographical information of the selected river basin is as follows. At first, to determine the basin boundary, a digital map is used to check the actual river channel network (Fig. 3).

As an example, Fig. 3 shows the channel network of the Nagara River basin displayed by a free digital map (kashimir 3D ver8.8.2, http://www.kashimir3d.com). This digital map is compatible with most of major free DEM datasets such as Shuttle Radar Topography Mission (SRTM: http:/

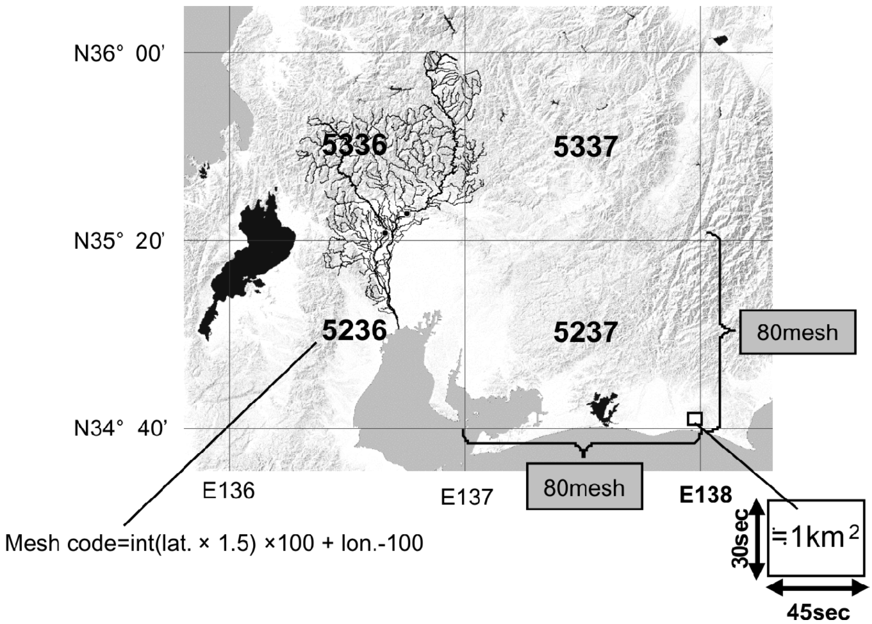

Fig. 3. Definition of Mesh Code System by Geophysical Survey Institute (GSI) and actual channel network indicated by a free digital map (kashimir 3D).

/dds.cr.usgs.gov/srtm/). Actual channel network data is obtained from the Geophysical Survey Institute in Japan (GSI: http://nlftp.mlit.go.jp/ksj/index.html).

The basin boundary, land use classification and digital elevation map datasets are provided by standard regional grid and mesh code systems. This system is based on longitude and latitude coordinates and used for statistical research in Japan. The whole of Japan is divided into more than 100 areas of primary mesh by meridian lines of 1 degree and parallel lines of 40 minutes. The primary mesh corresponds to a sheet area of 1:200,000 scale district maps. The secondary mesh is defined by dividing the primary mesh area into 8 × 8 portions corresponding to 1:25,000 scale topographic maps. Finally, the tertiary mesh is defined by dividing the secondary mesh into 10 × 10 small portions. The area of a tertiary mesh is close to 1 km^2 at the central part of Japan. Then, the direction and connection of channel and hill-slope flow are determined using 50 m DEM by the following assumptions: river channels run through the lowest part of each grid mesh and flow to the adjacent mesh of steepest slope. If the depression sink occurs before the river mouth, the elevation of the mesh is modified to flow down to the nearest mesh.

Figure 4 is a sample of a channel network, a hill slope distribution and land use type analyzed by the automatic basin information integration tool. This tool can create a database of flow direction (channel network), slope and landuse type from 50 m DEM and GSI's databases.

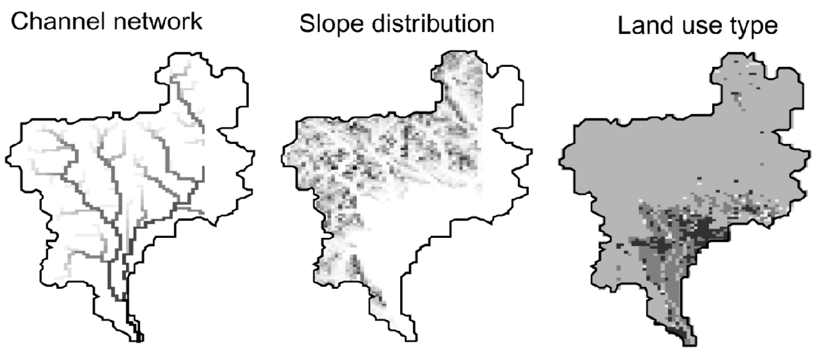

Fig. 4. Output samples of automatic basin information integration tool.

3.5 Study Area

Figure 5 shows the location of seven river basins selected as major river basins in Japan. The Ishikari River basin and Mogami River basin located in the northern part of Japan are selected as snow dominated region. The Tone, Kiso and Yodo River basins located in the central part of Japan are selected as

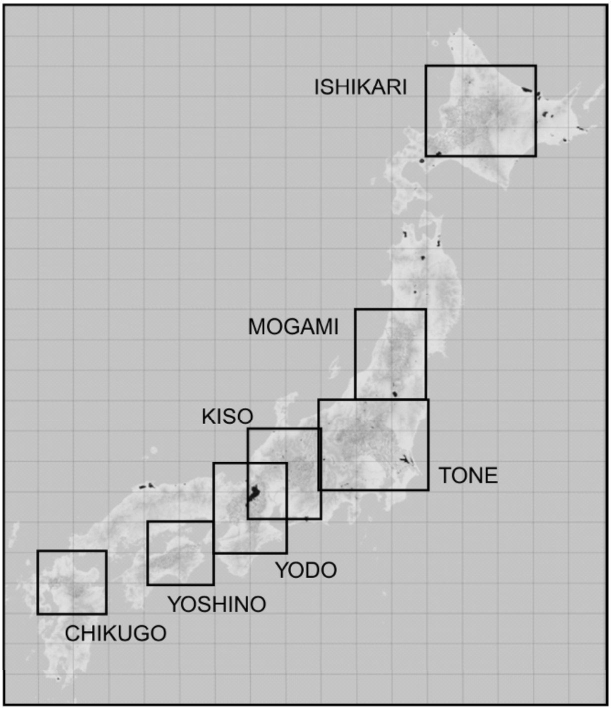

Fig. 5. Location of the study area.

the region which includes large mega cities such as Tokyo (capital city), Nagoya and Osaka. The Yoshino and Chikugo River basins located in the south-western part of Japan are selected as warm and humid region. The detailed characteristics and selected hydrological stations of each river basin as a reference point are summarized in Table 1.

Table 1: Characteristics of each river basin and hydrological station

River basin	*Total basin area (km^2)*	*Ta (C)*	*P (mm)*	*Station*	*Lon. (N)*	*Lat. (E)*	*Drainage area (km^2)*	*Qobs (m^3/s)*
Ishikari	14330	**4.8**	1151	Oohashi	141.5	43.1	12697	453.9
Mogami	7040	**8.9**	1763	Sagoshi	139.9	38.9	6497	399.5
Tone	16840	**11.6**	1396	Kurihashi	139.7	36.1	8588	234.3
Kiso	5275	**9.2**	2050	Inuyama	137.0	35.4	4684	270
Yodo	8240	**13.2**	1561	Hirakata	135.6	34.8	7281	236.4
Yoshino	3750	**11.9**	1938	Iwazu	134.2	34.1	2740	125.4
Chikugo	2863	**13.5**	2011	Arase	130.8	33.3	1440	82.3

Ta: air temperature; P: annual precipitation and Qobs: observed river discharge.

4. Results and Discussion

4.1 Impacts of Climate Change

As shown in Fig. 6, we can see the considerable changes in intra-annual variability of river flow among each river basin in Japan. In the case of Ishikari river basin, the peak will occur earlier due to early snowmelt. On the other hand, the seasonal change of river discharge will disappear in the Mogami river basin due to the earlier shift and decrease of snowfall itself with the temperature rise. In most of other basins, the river discharge will increase in winter and will decrease in the late summer. The latter is also assumed to be the increase of evapotranspiration losses due to air temperature rise.

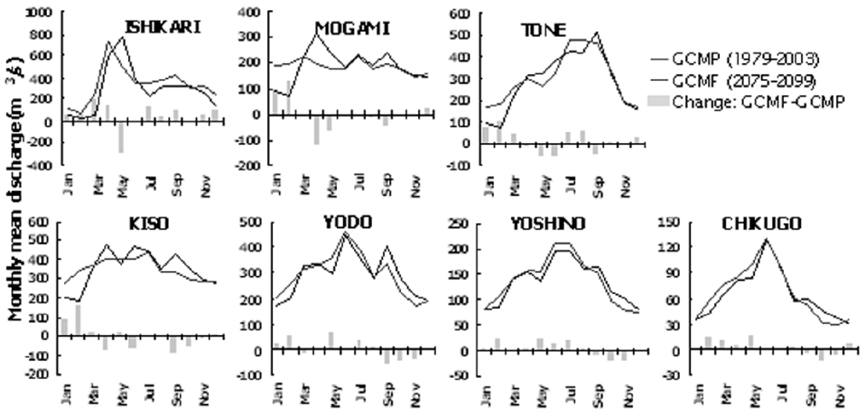

Fig. 6. Changes of seasonal variability of river flow of major river basins in Japan.

4.2 Change in Extreme Events

A flow duration curve (FDC) is a simple but powerful way of summarizing the distribution of stream flow for a given catchment. The FDC is widely used as a measure of the flow regime as it provides an easy way of displaying the complete range of flow. It can also be used to access changes in the flow regime following climate change, by considering changes in percentile flows. Therefore, we applied the FDC to detect the potential disaster risk due to the extreme event.

Figure 7 shows the daily FDC for the two periods (present and future) and their relative change in daily flow with the same percentile for each river basin. The results indicate that potential extreme flood risk (more than 'high flow': $Q_{5\%}$) will increase at Ishikari, Tone, Yodo, Yoshino and Chikugo river basins in the end of 21st century. On the other hand, the flood risk will decrease in Mogami and Kiso river basins. The extreme drought risk (less than 'low flow': $Q_{95\%}$) will increase in Yodo, Yoshino and Chikugo river

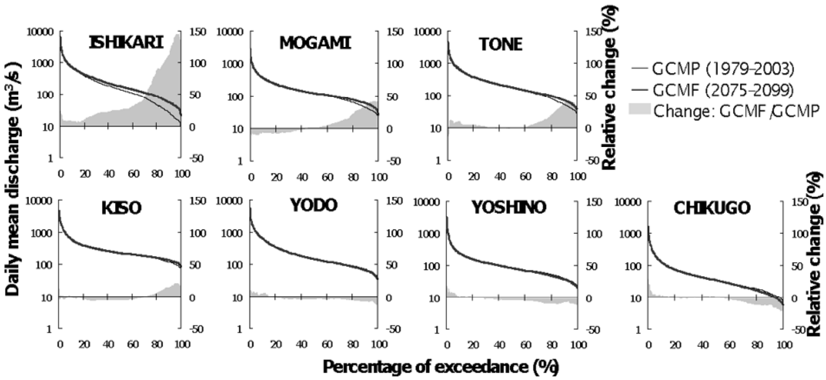

Fig. 7. Changes in flow duration curve (FDC) of major river basins in Japan.

basins. The risk of drought will decrease significantly in the Ishikari river basin. In the Mogami, Tone and Kiso river basins, the drought risk will also decrease. These regional differences of potential disaster risks by the extreme event are clearly projected by the super-high resolution AGCM.

4.3 Need for Simplification

There have been a lot of procedures proposed to quantify the hydrological impact of climate change, such as sustainability, availability, vulnerability, resiliency, sensitivity, adaptability and so on. However, the standardized procedure to clarify the potential risks seems to be discussed further. Moreover, the eco-hydrological processes are not fully understood yet, because of the lack of available information or lack of our understanding. Thus, a model must be simplified to represent the real world more reasonably. Of course, it is possible to treat some of the processes in detail and specifying their governing equations fairly fully. However, some other processes must be treated in an approximate way. The components of the eco-hydrological processes interact with each other producing feedbacks. So, the solution of these governing equations must be complex and needs a great deal of computation. There is still computational resources limitation to deal with them.

4.4 Improvement of the Model Structures

Analysis of the long-term water balance is one of the useful approaches to understand the mechanism of water cycles in the arid regions (Sato et al., 2007). If we can assume the water storage within a river basin as constant in the specific period, the available water resources can be estimated by the amount of precipitation supply minus actual evapotranspiration losses. However, the amount of evapotranspiration loss is still difficult to estimate in the watershed scale. Furthermore, the available water resources are also influenced by human activities such as reservoir operations, water intake from river channel or underground aquifers.

The artificial land use change such as afforestation, urbanization and development of irrigation areas will also make significant influence on the regional water balances. Therefore, integrated hydrological models are indispensable for better future prediction (Sato et al., 2009a). Such models will contribute for adaptation strategies or integrated water resources management (IWRM) under the climate change.

4.5 Coupling with Available New Technologies and Data

In the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), a dataset of more than 20 global coupled atmosphere-ocean general circulation models (AOGCMs) under the Coupled Modeling Intercomparison Project Phase 3 (CMIP3) are fully utilized to project future climate changes for various scenarios. The idea of ensemble simulation is important when the results of global climate models are used to estimate the possible impact of climate change in a local or regional scale.

Using remote sensing data such as normalized difference vegetation index (NDVI) or latest geographic information system (GIS) tools will also support to obtain more reliable distributed/long-term land-use information of specific watershed, and thus will contribute to better estimation of actual evapotranspiration losses.

4.6 Reduction of Uncertainties

Uncertainties included in the climate change projection mainly arise from (1) the formulation and accuracy of the GCMs itself, (2) the magnitude of anthropogenic impacts, and (3) the temporal and special impact of natural variations internal to the climate system. The uncertainty of the GCMs can be attributed to the structural set-up (e.g. choice of the grid resolution and climate processes) and variability in the internal parameterizations within a sub-grid scale. The impacts of anthropogenic uncertainty are related with the future scenario of socio-economic and human activities. The multi GCMs and multi scenario ensemble simulations are recommended for a better assessment of climate change. When we assess the regional impact of climate change, we should consider another uncertainty arising from the choice of downscaling method. Generally, there are two types of downscaling measures: dynamical downscaling and statistical downscaling. Different downscaling method with different initial and boundary conditions will produce different results.

4.7 Eco-Hydrological Assessments

The potential evaporation increase will directly correspond to the air temperature rise. However, the actual evapotranspiration often does not increase with air temperature rise because it is restricted by soil moisture content and vegetation physiology (i.e. photosynthesis activities). The spatial distributions of potential vegetation are mainly dependent on air temperature and available water in the root zone. According to warmness index and wetness index analysis, the potential vegetation will change significantly until the end of this century, and it will alter the regional water balances. On the other hand, change of the stream flow regime such as flow velocity, water level and water temperature/quality will have large influence on river ecosystems. Therefore, in order to conserve biodiversities and to clarify its potential impacts on hydrological cycle, the ecological and environmental knowledge must be collaborated with the hydrological studies more closely.

5. Conclusions

In this paper, we attempted to overview some recent research topics and problems on climate change from an eco-hydrological point of view, and attempt to discuss about the possibility of interdisciplinary research to break through the current research problems. Grasping current situation correctly and recognizing the current problems to be studied further will contribute to develop more appropriate adaptation strategies for integrated water resources management to the climate change.

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6

Investigation and Modelling of Subarctic Wetland Hydrology – A Case Study in the Deer River Watershed, Canada

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1. Introduction

Wetlands are generally defined as bogs, fens, swamps, marshes and shallow water where soil is saturated with moisture or inundated by surface or groundwater either permanently or seasonally. They provide benefits such as wildlife habitats, groundwater reservation, water purification, storage of organic carbon and adaptation to climatic change (Price et al., 2005). The subarctic region covers much of northern Canada and is often characterized by taiga forest vegetation with relatively mild winters (Petrescu et al., 2010). The taiga consists primarily of coniferous forest and is interspersed by lichen and wetland landscapes such as bog marsh and muskeg. These subarctic wetlands, which are acknowledged as an important ecotone between arctic tundra and boreal forest, span almost 3% of the Canadian landscape and offer habitats for wild lives (Price and Waddington, 2000). Recently, investigation and conservation of subarctic wetlands has been recognized as an attractive route because of their unique hydrologic features and vulnerability to climate change (Rouse et al., 1997; Woo and Young, 2003; Woo and Thorne, 2006; Ström and Christensen, 2007).

Research efforts to explore the hydrological features of subarctic wetlands have been continuing in literature. Sufficient water supplement, which comprise snowmelt, precipitation, groundwater, streamflow and inundation from lakes, is the determinant factor of the existence of wetlands (Winter and Woo, 1990; Woo and Young, 2006). Quinton and Roulet (1998) demonstrated the

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relationship between flux and water storage of a subarctic patterned wetland, conceptualizing the discharge response delay to precipitation which is attributed to large storage capacity of pools. Woo and Young (2006) also noted that reliable water supply which comprises snowmelt water, localized groundwater discharge, stream flow and besides these, water flow within northern wetlands is highly sensitive to precipitation because of particular porous soil characteristic and shallow impermeable permafrost table. Woo and Marsh (2005), based on reviewing the frozen soil and permafrost hydrology in Canada from 1999 to 2002, showed two distinctive flow mechanisms of subarctic wetland related to permafrost and permafrost table fluctuation. Hayashi et al. (2007) noted that subsurface flow is strongly dependent on permafrost table and developed a simulation method for hydrological models. Channel runoff resulted from snowmelt and rainfall is mainly delayed by lakes in the vicinity and the particular permafrost (Quinton and Roulet, 1998; Leenders and Woo, 2002). Soil features of subarctic wetlands play a key role in hydrological processes because their porosity and hydraulic conductivity dramatically decline with depth (Woo and Marsh, 2005). Quinton and Marsh (1998) stated that hydraulic conductivity declines with depth because of increasing humidification of peat and moreover, Carey and Woo (1998) also found that discontinuity between organic and mineral layers leads to the explicit vertically hydraulic reduction. Recently, variation in climatic conditions, which couples with changes in the magnitude of water supply, permafrost degradation, and even complete drying, has attracted much attention (Payette et al., 2001; Woo and Young, 2006). The temperature of subarctic regions, especially the Hudson Bay Lowlands (HBL) which is the second largest wetland in Canada, has been increasing during the past decades (Rouse et al., 1997).

To help understand the hydrological processes, hydrological models have been widely used as simplified, conceptual representations of the hydrologic cycle. Numerous models have been developed and applied for hydrology simulation, such as hydrologic engineering centre (HEC-1), semi-distributed land use-based runoff process (SLURP), precipitation-runoff modelling system (PRMS), streamflow synthesis and reservoir regulation (SSARR), snowmelt runoff model (SRM), UBC, WATFLOOD and TOPMODEL (Quick and Pipes, 1977; Beven et al., 1984; Abbott et al., 1986; Bergström, 1992; Kouwen et al., 1993; Bicknell et al., 1997; Kite, 1997; Richard and Gratton, 2001). However, only a few studies specifically targeted at modelling subarctic wetlands, particularly the HBL in northern Manitoba due to a number of knowledge gaps, such as the difficulty of considering continuous permafrost, numerous seasonal ponds, and snow sublimation as well as the complexity of simulating water linkage between surface and subsurface flows in the hummocky terrain (Mancell et al., 2000; Zhang et al., 2000; Van der Linden and Woo, 2003; Boswell and Olyphant, 2007). As one of the most unique attributes, the overlaying permafrost existing in northern Canada seasonally thaws during the summer and refreezes during the cold long winter. Its depth varies by season and location which significantly influences the generation of interflow and groundwater flow. The presence of numerous ponds and hummocky terrain also poses difficulties in recognizing the behaviour of water transfer between surface and subsurface flows due to the vast and uncertain water storage capacities of ponds and organic soil layers. However, integrated research efforts on monitoring and modelling subarctic wetlands in the Hudson Bay lowlands (HBL) has been limited due to its physical accessibility and technical difficulties such as data availability. In this study, the semi-distributed land use-based runoff processes (SLURP) model and the WATFLOOD model were targeted and tested in a Canadian subarctic wetland – the Deer River watershed in northern Manitoba. Two of the major Canadian hydrological models, SLURP and WATFLOOD, have been extensively applied in many basins ranging in size from a few hectares to million square kilometres (Haberlandt and Kite, 1998; Fassnacht et al., 1999; Su et al., 2000; Pirtroniro et al., 2006; Shin and Kim, 2007; Dibike and Coulibaly, 2007; Armstrong and Martz, 2008; Jing and Chen, 2011b). However, they have not been parallelly applied in the subarctic region and the difference of their performance in simulating wetland hydrology is still unknown. This paper examines the hydrological and vegetation characteristics of subarctic wetlands in the HBL, combining and discussing the findings from an extensive field investigation with the modelling results from both SLURP and WATFLOOD to understand the interactions between climate and hydrological processes in subarctic wetlands.

2. The Study Area

This study was conducted at the Deer River watershed, a 5048 km^2 subarctic wetland in the northern part of the HBL, Manitoba, Canada (Fig. 1). The study area is composed mostly of muskeg and peatlands, and dotted with seasonal ponds, lakes and streams. Elevation gradually descends from 232 m in the southwest to 16 m in the northeast (Jing et al., 2009). Spruce, birch alder and balsam fir dominate the headwaters as well as the adjacent areas along river channels. Shrub and tundra prevails in the hummocky terrain within the mid- and downstream regions. The primary soils are brunisolic static cryosol, brunisols, brunisolic turbic cryosol, and organo cryosol with a peat depth of 1-3 m that in parts are underlain by continuous permafrost with an active depth of approximately 1 m by late August (Mills et al., 1976; Malmer and Wallén, 1996; Christensen et al., 2004). Subsurface water content reaches its maximum equilibrium following snowmelt when surface water fully recharges the soil layers. The Deer river watershed has been categorized as a marine subarctic climate. Mean annual precipitation at nearby Churchill is 462 mm with maximum in summer and mean annual temperature is –6.5 ^{o}C (1978-2007). Winters are long and cold with average temperature varying around –20 ^{o}C from November to April. Runoff is extremely low in winters and is mainly sustained by groundwater discharge. Spring returns in early or mid

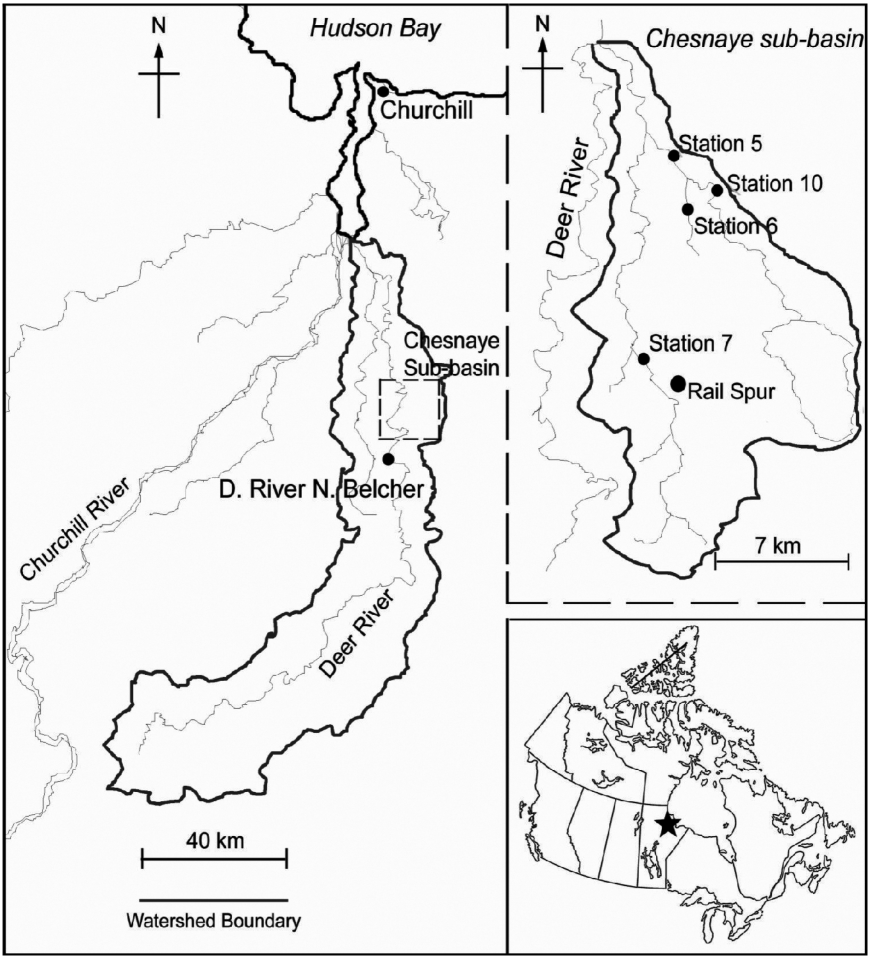

Fig. 1. Location of the Deer river watershed and the Chesnaye sub-basin (Jing and Chen, 2011b).

May when snowmelt starts and ceases by mid June which generates annual peak runoff. Soil water deficits are commonly observed in summer and fall due to the intensive evapotranspiration and lack of precipitation.

3. Methodology

3.1 Field Investigation

Due to limited accessibility, a representative sub-basin in the lower reach of the Deer river, the Chesnaye sub-basin, was selected for an extensive field investigation during the summer time from 2006 to 2008 (Fig. 1). A monitoring network of four stream gauging stations (i.e., Stations 5, 6, 7 and 10) and one automated weather station (i.e., Rail Spur) was maintained (Jing, 2009; Jing et al., 2010). Meteorological parameters such as air temperature, dew point temperature, cumulative precipitation, incident short wave radiation, relative humidity, and wind speed and direction, were obtained from the weather stations. Data were scanned by a Campbell Scientific data logger (model CR1000) and stored at hourly intervals. Evapotranspiration was estimated by the FAO-56 Penman-Monteith Equation (Allen et al., 1998). Streamflow was measured at each gauging station by HOBO® water pressure transducers and Sontek® ADV Flowtracker. Permafrost table and surface soil moisture were measured at multiple transects (2 m, 4 m, 6 m and 8 m from both banks) of each station using steel pole and SM200 soil moisture sensor. The helicopter recons were also carried out on June 20 and Oct 3, 2007 to collect the information about vegetation coverage, topographic and hydrological conditions across the watershed and particularly in the upper reach of the river.

3.2 Hydrological Modelling

3.2.1 The SLURP and WATFLOOD Hydrological Models

The SLURP model version 11 (Kite, 1997) is a semi-distributed, conceptually continuous hydrological model. This daily time-step model was originally developed for the meso- and macro-scale basins with intermediate complexity, which incorporates necessary physical processes without compromising the simplicity of calculation. It requires the watershed to be delineated into multiple HRUs aggregated simulation areas (ASAs) by TOpographic PArameteriZation (TOPAZ). Each ASA is further divided into subareas with different types of land cover based on vegetation, soil and physiographical conditions. The vertical water balance module is sequentially applied to each type of land cover within each ASA to account for precipitation, canopy interception, snowmelt, infiltration, surface runoff and groundwater outflow (Table 1). Precipitation is intercepted by canopy while the amount of precipitation that passes through canopy is counted as snow or surface storage. Snowmelt is calculated using either the degree-day method (Anderson, 1973) or the simplified energy budget method (Kustas et al., 1994). Snowmelt rate is interpolated (parabolically) between the rates in January and July. Infiltration is governed by the Philip formula (Philip, 1954). Three methods from Morton (1983), Spittlehouse (1989) and Granger (1995) are available for estimating evapotranspiration. Surface runoff appears when water remaining in the aerated soil layers after infiltration exceeds the depression storage capacity. Subsurface flow (interflow and groundwater flow) is simulated at a rate depending on the water content of the subsurface storage tanks as well as the water transfer coefficient. Manning's equation is applied to route surface and subsurface flow from each land cover to the nearest channel within each ASA. Runoff routing between ASAs is sequentially carried out by using either the hydrological storage techniques or the Muskingum-Cunge channel routing

Table 1: Summary and comparisons of the general characteristics of SLURP and WATFLOOD

	SLURP	*WATFLOOD*
Delineation approach	HRU	GRU
Snowmelt	$S_m = R_1\ (T - T_{critical})$	$S_m = R_1\ (T - T_{critical})$
(Anderson, 1973)	$R_1 = [(a-b) \times d^2 + 367\ (a-b) \times d]/33306 + (92a - b)/91$	R_1 is set to constant for each land cover
Evapotranspiration	$AET = 2WEE - PET = \dfrac{s[(2\alpha - 1)R_n + 2\alpha M] - \gamma f_A(e_a^* - e_a)}{\lambda(s+\gamma)}$	$PET = 0.0075 \times R_a \times C_t \times \delta_t^{1/2} \times T_{avg.d}$
(Hargraeves and Samani, 1982; Morton, 1983)		$AET = PET \cdot UZSI \cdot FPET2 \cdot FTALL \cdot ETP$
Rainfall-runoff response (days)	Mean: 1.44; Max: 3; Min: 1	Mean: 1.84; Max: 3; Min: 1

Note: Variables are defined in the notation.

method. The accumulated flow from the outlet of an ASA is routed to the downstream ASA and finally to the outlet of the whole watershed.

WATFLOOD, as a semi-distributed and physically based hydrological model, has been widely used to forecast flood events or simulate watersheds without sacrificing the distributed features and computational efficiency (Kouwen, 2008). As differentiated from SLURP, WATFLOOD is constructed based on the concept of grouped response units (GRU) which allows its application to large watersheds where similar vegetated areas within each grid segment are grouped as one land cover type for water balance. WATFLOOD allows hourly time increment and simulates both vertical and horizontal water balance in the natural environment, including interception, infiltration, evapotranspiration, snow accumulation and ablation, interflow, recharge, baseflow, and overland and channel routing (Table 1). Precipitation interception is computed by the Linsley's model (Linsley et al., 1949) with minor changes in regard to the interception evaporation (IET). Snowmelt is estimated by the temperature index routine which allows refreezing (Anderson, 1973) or the radiation temperature index model. In addition, snow sublimation is considered by an adjustable sublimation factor. Potential evapotranspiration is calculated using either the Priestley-Taylor (Priestly and Taylor, 1972) or the Hargreaves' equation (Hargraeves and Samani, 1982) based on input availability. The actual evapotranspiration is either presumed as the potential rate when soil moisture is at a level of saturation or reduced to a fraction of the potential rate if the soil moisture is below the saturation point. Infiltration process is governed by the Philip formula (Philip, 1954) and the Darcy's law. A groundwater depletion module is applied to diminish the base flow. Channel routing is accomplished using the storage routing technique, whereas base flow is calculated by a non-linear storage-discharge function. Moreover, routing through lakes is available using a used-specified power or polynomial function.

3.2.2 Modelling Inputs

A 3-arc-second digital elevation model (DEM) of the Deer river watershed was obtained from the National Map Seamless Server of the U.S. Geological Survey (USGS, 2008). The DEM was processed by TOPAZ which has strong capability of automated digital landscape analysis to help delineate the sub-basins and drainage network. Meteorological records (1978–1997) at the Churchill-A Climate station (ID: 5060600) were provided by Environment Canada. Streamflow data (1978–1997) were obtained from Water Survey Canada at the D. River N. Belcher station (ID: 06FD002, Fig. 1) at which modelling results were compared with historical records. Land cover datasets were obtained from the Systeme Probatoire d'Observation dela Tarre (SPOT) earth observation satellite system (SPOT Vegetation Program, 2008) and reclassified into six land cover classes, including water, impervious, marsh, shrub, coniferous trees, and deciduous trees. The helicopter recons were also carried out on June 20 and Oct. 3, 2007 to collect information about vegetation coverage, topographic and hydrological conditions across the watershed, particularly in the upper reach of the Deer river.

3.2.3 Sensitivity Analysis

To identify the most significant parameters, sensitivity analysis was conducted for the SLURP model and WATFLOOD by adjusting all the model parameters (one-factor-at-a-time) and evaluating their impacts on modelling results. The base values of the model parameters were determined in reference to the field investigation in the Chesnaye sub-basin, the manuals of both models, and other researchers' work in the HBL where the study area is located (Kite, 1997; Su et al., 2000; Metcalfe and Buttle, 2001; Kite, 2002; Thorne, 2004; Woo and Thorne, 2006). Based on the assumption of independent interrelationship, each parameter was individually adjusted by ±5%, ±15%, and ±30% while keeping all other ones at their initial values (adjustment of each parameter was made to all land covers at one time), and evaluated by the fluctuation of the 10-year (1978-1987) logarithmic Nash and Sutcliffe efficiency ($NSE_{\ln}$) and the correlation coefficient (R) to derive a limited number of influential ones. The 10-year NSE_{ln} and R were calculated by the following equations:

$$NSE_{\ln} = 1 - \frac{\sum_{i=1}^{N} \left(\ln Q_i - \ln Q_m\right)^2}{\sum_{i=1}^{N} \left(\ln Q_i - \ln Q_{average}\right)^2} \tag{1}$$

$$R = \frac{\frac{1}{N} \cdot \sum_{i=1}^{N} \left(Q_i - Q_{average}\right) * \left(Q_m - Q_{average}\right)}{\sqrt{\frac{N \cdot \sum_{i=1}^{N} Q_i^2 - \left(\sum_{i=1}^{N} Q_i\right)^2}{N \cdot (N-1)}} * \sqrt{\frac{N \cdot \sum_{i=1}^{N} Q_m^2 - \left(\sum_{i=1}^{N} Q_m\right)^2}{N \cdot (N-1)}}} \tag{2}$$

where N is the number of days; Q_i is the daily observed flow in 10 years (m^3/s); Q_m is the daily modelled flow in 10 years (m^3/s); and $Q_{average}$ is the 10-year mean observed flow (m^3/s). The NSE_{ln} describes the model performance in the case of discharge simulations during the low-flow periods. The closer it is to 1, the better performance of the model. The R statistic describes the degree of colinearity between the observed and modelled flow. It tends to the unity the more the simulated flows have the similar dynamics as the observations. The most sensitive parameters to be calibrated in SLURP are initial contents of snow store and slow store, maximum infiltration rate, retention constants for fast store and slow store, maximum capacity for fast store and slow store, precipitation factor, rain/snow division temperature, and snowmelt rates in January and July. Contrastingly, the most influential parameters in WATFLOOD include lower zone drainage function exponent, base temperature for snowmelt, porosity of the wetland or channel bank, reduction in soil evaporation due to tall vegetation, crude snow sublimation factor, melt factor and Manning's roughness coefficient.

3.2.4 Modelling Validation

To minimize the difference between observed and simulated runoff rates and compensate for errors in the measurement, a 10-year (1978-1987) calibration was conducted for the influential parameters in SLURP and WATFLOOD using their built-in optimization modules and manual adjustment. Both the NSE_{ln} criterion and the correlation coefficient (R) were used as statistical measures of the goodness of fit of the calibration results at the D. River N. Belcher station. Tables 2 and 3 summarize the final values of model parameters obtained after the calibration of SLURP and WATFLOOD, respectively. Modelling verification was performed for the subsequent 10-year period (1988-1997) to ensure that both models accurately reflect the hydrological cycle of the study area. Tables 4 and 5 show the models outputs and performance measures with the model parameters declared in Tables 2 and 3 (Jing and Chen, 2011a, 2011b).

4. Results and Discussion

4.1 Soil Properties

Soil layers became more saturated as getting closer to the stream channels. The average soil moisture contents at the left bank of Station 5 were observed as 38.2%, 24.5%, 21.8% and 17.9% with the locations varying from 2 to 8 m (2 m interval) away from the bank in 2006 (Fig. 2a). On account of the presence of extraordinarily high hydraulic conductivity (Reeve et al., 2000), near-stream locations received more infiltrated water from streams and vicinity because the extent of this infiltration process was inversely proportional to the distance from the bank. Some discrete points that disobeyed this trend could be attributed to the presence of permafrost table, soil texture and land slope. Permafrost table descends as approaching to the stream, which represents that active organic layer become deeper and infiltration occurs more easily with less resistance because the storage capacity increases. Therefore, some distant transects, if permafrost table is shallow enough, are possibly to be saturated near the ground surface, leading to higher soil moisture contents than those close to the stream. Measurements from the automated weather station at Rail Spur also disclosed the temporal and vertical distribution of soil moisture and temperature (Fig. 2b). Following the major recharge period during the snowmelt, soil moisture contents kept declining throughout the summer, mainly due to the intensive evapotranspiration. In addition, the descending permafrost table enlarged the active organic layer and dragged the water table downwards,

Table 2: Calibrated SLURP parameters for each type of land cover in the Deer river watershed

Parameters	*Unit*	*Water*	*Impervious*	*Marsh*	*Shrub*	*Coniferous*	*Deciduous*
Initial contents of snow store	(mm)	1	1	1	1	1	1
Initial contents of slow store	(%)	9.775	8.625	4.238	6.839	5.895	6.205
Maximum infiltration rate	(mm/day)	100.9	142.4	106.9	147.7	111.9	105.7
Manning roughness, *n*	(dimensionless)	0.02	0.08	0.01	0.07	0.02	0.03
Retention constant for fast store	(day)	36.97	52.62	5.447	7.480	62.89	40.45
Maximum capacity for fast store	(mm)	95.35	133.8	531.2	583.6	373.7	697.0
Retention constant for slow store	(day)	130.7	171.0	686.1	745.5	713.0	747.1
Maximum capacity for slow store	(mm)	338.7	260.6	361.6	102.9	62.19	63.22
Precipitation factor	(dimensionless)	1	1	1	1	1	1
Rain/snow division temperature	(ºC)	–0.03	–0.56	–0.99	–0.93	–0.61	–0.32
Canopy interception A	(dimensionless)	0	0.5	1	1	1	1
Canopy interception B	(dimensionless)	1	1	1	1	1	1
Land cover albedo	(dimensionless)	0	0.15	0.15	0.14	0.13	0.16
LAI in January	(dimensionless)	0	0	2	0.5	5	3
LAI in July	(dimensionless)	0	2	2	4.5	5	10
Maximum canopy capacity	(dimensionless)	0	2.8	3.8	6.2	5.6	4.3
Soil heat flux amplitude	(dimensionless)	0.15	0.15	0.15	0.15	0.15	0.15
Snowmelt rate in January	(mm/ºC/day)	0	0	0	0	0	0
Snowmelt rate in July	(mm/ºC/day)	4	4	4	3	2	2
Maximum albedo of snow	(dimensionless)	0.78	0.78	0.78	0.7	0.7	0.7
Minimum albedo of snow	(dimensionless)	0.37	0.37	0.37	0.37	0.37	0.37
Temperature lapse rate	(ºC/100 m)	0.75	0.75	0.75	0.75	0.75	0.75

Table 3: Calibrated WATFLOOD parameters for each type of land cover in the Deer river watershed

Parameter	*Description and unit*	*Deciduous*	*Coniferous*	*Shrub*	*Marsh*	*Water*	*Impervious*
AK2	Upper zone drainage resistance factor (dimensionless)	0.55	0.55	0.55	0.55	0.051	5E-10
AK2FS	Snow upper zone drainage resistance factor (dimensionless)	0.52	0.51	0.52	0.52	0.051	5E-10
AK	Soil permeability of bare ground (mm/h)	13.4	12	3	400	-0.1	0.1E-10
AKFS	Soil permeability under snow (mm/h)	1.2	1.2	3	400	-0.1	0.1E-10
Albedo	The all-wave albedo (dimensionless)	0.16	0.13	0.14	0.15	0	0.15
BASE	Base temp for snowmelt (ºC)	-0.32	-0.61	-0.93	-0.99	-0.03	-0.56
MF	Melt factor (mm/ºC/h)	0.13	0.13	0.17	0.17	0.13	0.15
NMF	Negative melt factor (mm/ºC/day)	0.10	0.10	0.10	0.10	0.10	0.10
R3	Overland flow roughness for bare area (dimensionless)	0.10	0.08	0.20	0.09	0.04	4
R3FS	Overland flow roughness for snow area (dimensionless)	0.1	0.05	0.20	0.10	0.04	4
REC	Interflow depletion coefficient (dimensionless)	0.2	0.2	0.2	0.9	0.1	0.9
RETN	Upper zone specific retention (mm)	150	150	150	140	0.1	0.1
A5	API hourly reduction value (dimensionless)	0.985	0.985	0.985	0.985	0.985	0.985
Lzf	Lower zone drainage function parameter (dimensionless)	0.1E-4	0.1E-4	0.1E-4	0.1E-4	0.1E-4	0.1E-4
Pwr	Lower zone drainage function exponent (dimensionless)	2.05	2.05	2.05	2.05	2.05	2.05
R2n	Channel Manning's roughness coefficient (dimensionless)	0.018	0.018	0.018	0.018	0.018	0.018
Ds	Depression storage for bare ground (mm)	123	120	1.2E4	1.2E10	0	1
Dsfs	Depression storage for snow covered ground (mm)	223	220	220	2.2E10	0	1
flapse	Lapse rate in per 100 m (ºC)	0.75	0.75	0.75	0.75	0.75	0.75
Fpet	IET increase for tall vegetation (dimensionless)	3	4	4	4	1	0
Ftal	Soil evaporation reduction of tall vegetation (dimensionless)	0.85	0.85	1	1.3	1	1
kcond	Conductivity of the wetland (mm/h)	0.75	0.75	0.75	0.75	0.75	0.75
Mndr	Meandering factor (dimensionless)	1	1	1	1	1	1
R1n	Flood plain Manning's roughness coefficient (dimensionless)	0.05	0.05	0.05	0.05	0.05	0.05
sublim	Crude snow sublimation factor (mm/h)	0.10	0.10	0.22	0.22	0.30	0
Theta	Porosity of the wetland or channel (dimensionless)	0.7	0.7	0.7	0.7	0.7	0.7

Table 4: Annual modelling outputs of SLURP at the D. River N. Belcher station (1978-1997)

Year	*Cumulative precipitation (mm)*	*Mean air temperature (°C)*	*Cumulative simulated AET (mm)*	*Mean observed flow (m^3/s)*	*Mean simulated flow (m^3/s)*	*NSE_{ln} (%)*	*R*
1978	532.8	–7.76	218.7	12.7	14.6	71	0.74
1979	341.9	–7.96	194.6	13.9	9.9	51	0.89
1980	484.0	–6.93	242.3	18.4	12.4	71	0.82
1981	395.4	–4.89	203.1	14.4	17.9	61	0.84
1982	605.8	–8.43	239.6	15.8	24.6	41	0.86
1983	621.0	–7.06	248.6	27.9	35.7	68	0.69
1984	413.9	–6.50	195.0	14.3	17.8	43	0.65
1985	448.5	–7.11	184.4	11.1	17.0	38	0.65
1986	500.3	–7.33	241.0	22.8	25.6	57	0.92
1987	432.7	–5.42	227.1	11.6	17.1	42	0.77
1988	441.3	–7.38	180.2	9.07	6.68	72	0.92
1989	358.5	–8.02	172.6	17.6	15.8	70	0.61
1990	485.3	–7.41	187.4	12.1	16.4	22	0.74
1991	524.9	–7.09	202.0	23.8	28.6	62	0.93
1992	402.0	–8.21	169.3	12.8	23.1	15	0.78
1993	291.5	–7.11	177.6	9.0	10.4	13	0.63
1994	345.5	–6.62	147.4	7.2	14.0	21	0.51
1995	416.4	–6.90	224.1	19.4	17.2	59	0.88
1996	424.1	–7.46	200.7	7.0	12.7	25	0.86
1997	509.7	–6.55	185.4	27.2	22.1	68	0.94
Average	448.8	-7.1	202.1	15.4	18.0	49	0.78

Table 5: Annual modelling outputs of WATFLOOD at the D. River N. Belcher station (1978-1997)

Year	*Cumulative precipitation (mm)*	*Mean air temperature (°C)*	*Cumulative simulated AET (mm)*	*Mean observed flow (m^3/s)*	*Mean simulated flow (m^3/s)*	*NSE_{ln} (%)*	*R*
1978	532.8	-7.76	403.9	12.7	24.5	8	0.38
1979	341.9	-7.96	204.4	13.9	17.0	41	0.86
1980	484.0	-6.93	332.2	18.4	13.7	66	0.70
1981	395.4	-4.89	325.2	14.4	22.5	38	0.53
1982	605.8	-8.43	527.3	15.8	35.0	20	0.82
1983	621.0	-7.06	610.2	27.9	49.6	36	0.46
1984	413.9	-6.50	235.7	14.3	26.5	20	0.49
1985	448.5	-7.11	325.4	11.1	15.4	28	0.47
1986	500.3	-7.33	431.4	22.8	30.8	49	0.74
1987	432.7	-5.42	299.6	11.6	22.5	25	0.48
1988	441.3	-7.38	207.9	9.07	13.3	48	0.56
1989	358.5	-8.02	232.9	17.6	16.6	58	0.26
1990	485.3	-7.41	320.4	12.1	15.6	41	0.77
1991	524.9	-7.09	419.9	23.8	24.5	55	0.82
1992	402.0	-8.21	401.8	12.8	26.4	13	0.57
1993	291.5	-7.11	135.1	9.0	9.9	25	0.81
1994	345.5	-6.62	186.3	7.2	6.0	52	0.95
1995	416.4	-6.90	397.3	19.4	22.4	52	0.59
1996	424.1	-7.46	233.1	7.0	16.9	7	0.72
1997	509.7	-6.55	462.5	27.2	27.8	68	0.87
Average	448.8	-7.1	334.6	15.4	21.8	38	0.64

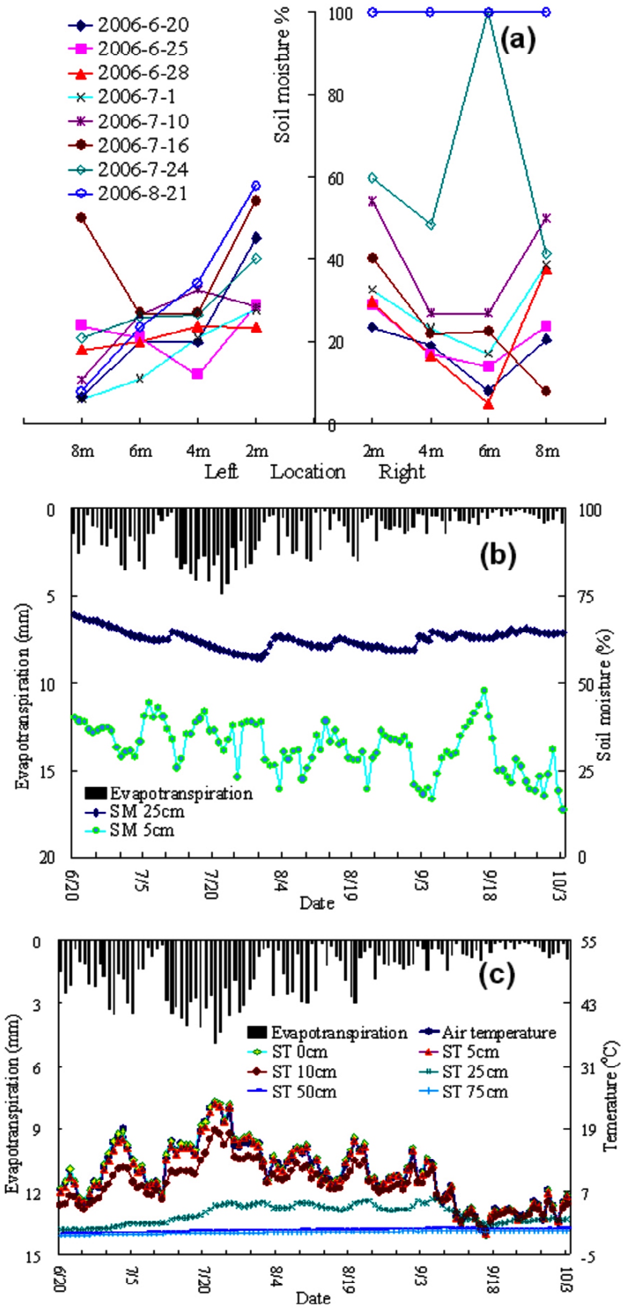

Fig. 2. (a) Soil moisture at the banks of station 5 in 2006 summer, (b) variation of daily soil moisture and evapotranspiration in 2007 summer at Rail Spur (SM: Soil Moisture) and (c) multiple soil layers temperature, air temperature and evapotranspiration in 2007 summer at Rail Spur (ST: Soil Temperature).

which reduced the water supplement. Soil temperature of the shallow layers (at 0, 5 and 10 cm depth) varied continuously and more or less agreed with air temperature (Fig. 2c), whereas soil temperature of the deep layers (50 and 75 cm) kept stable (around 0 °C) which could be attributed to the fact that permafrost lied around (Jing, 2009).

A reciprocal relationship between permafrost table and its distance to the stream channels was observed (Fig. 3a). There are a number of possible factors which may contribute to this finding, such as the effects of water contents from stream flow and subsurface flow as well as low albedo vegetations. Soil moisture tended to be higher as getting closer to the stream where porous organic layer became saturated from stream penetration and the

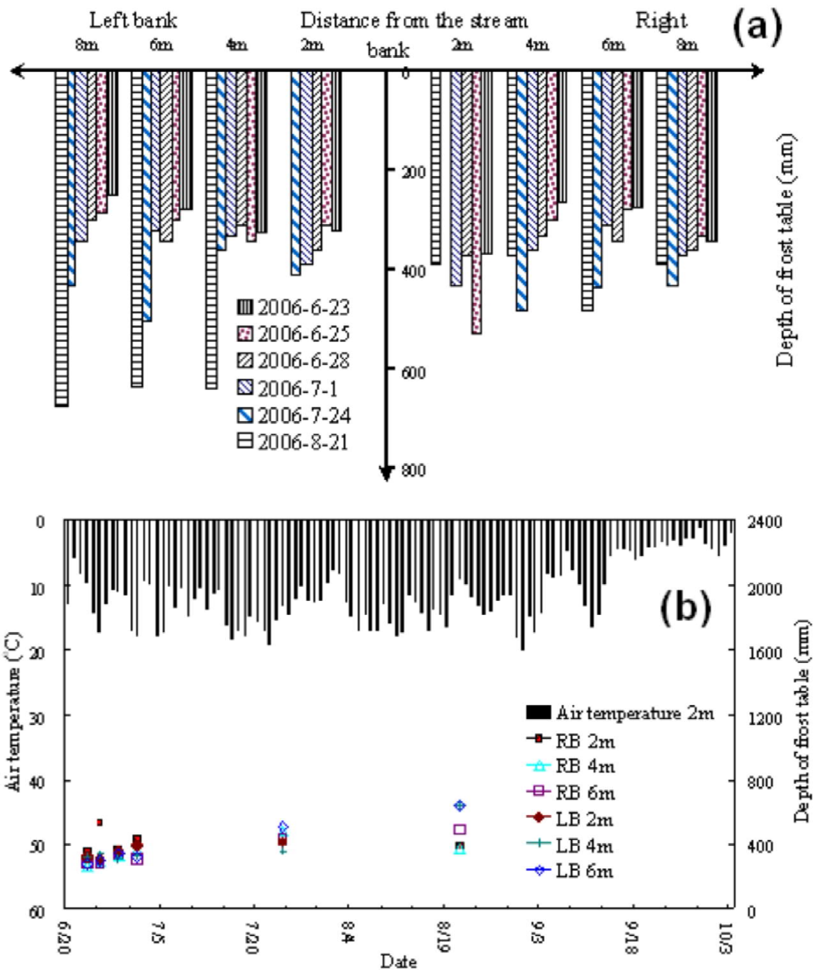

Fig. 3. (a) Permafrost table and (b) permafrost table vs. air temperature in 2006 at station 6 (RB: Right Bank; LB: Left Bank).

thaw of ice contents, which in turn accelerated the depression of the permafrost table. This melting process could be intensified by subsurface flow that moved towards the stream. Coniferous forests located along the streams have much lower albedo than the lichens/moss covered hollows which are far away from the streams. This difference may result in the absorption of more radiation energy and subsequently the acceleration of the ice thaw at the near-stream locations. Similar evidences have also been reported by previous studies (Woo and Marsh, 2005; Woo and Young, 2006). Air temperature acted as the dominant factor of the fluctuation of permafrost table as shown in Fig. 3b. For instance, permafrost table continuously descended throughout the summer of 2007 when air temperature retained at 11-23 ^{o}C. Meanwhile, the influence of precipitation on permafrost table was not as significant as that of air temperature. Permafrost table kept descending regardless at rainfall events, which mainly contributed to the fluctuation of groundwater table (Jing, 2009).

4.2 Snowmelt Runoff

Snowmelt is defined as surface runoff produced from melting snow in spring and is usually an important fraction of the annual water cycle in subarctic wetlands. The rate of snowmelt is determined by the available energy to the snowpack and is usually dominated by the net radiation. Cold snowpack has negative energy balance while warming results in the isothermal condition and additional energy starts the melt. In subarctic wetlands, snowmelt runoff usually commences in May with an increase in runoff during the melting period corresponding to the saturation of organic soil layers and a sharp decline following the snow disappearance. Fluctuations of melt rate exist due to the varying rhythm of melt responding to the seasonal trend. Saturation begins 12-18 days following the start of snowmelt infiltration, indicating that most of the snowmelt peaks occur in May or June and leads to pronounced flow maxima in streams. The most commonly used snowmelt-runoff model is the degree-day method or temperature index routine which has been successfully verified worldwide over a number of basins and climates. Due to the lack of net radiation data, it was selected for both models. While this approach has inadequate accuracy in simulating small-scale snowmelt rates, it does produce acceptable results at basin scale (Pohl et al., 2005; Jing et al., 2009). SLURP uses an increasing parabolic interpolation from values specified in January and July to determine the degree-day factor (Table 1). The later the date is, the greater melt rate. The degree-day factors of each land cover are calibrated as constants in WATFLOOD in reference to Kouwen (2008) and Stadnyk (2008) (i.e., 0.13-0.17 mm/day/^{o}C). This difference, if under the same ambient conditions (e.g. date, time, temperature, radiation) in the melting season (April-June), may result in more rapid snow depletion in SLURP. Figure 4a shows the Julian days of observed and simulated snowmelt peaks at the D. River N. Belcher station. It can be concluded that most of the simulated peaks were 2-11 days later than the observed records. This can

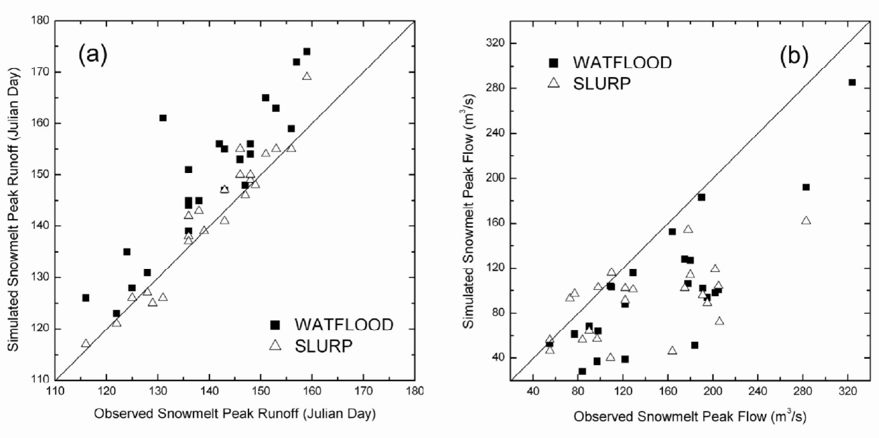

Fig. 4. (a) Days of observed and simulated snowmelt peaks and (b) observed and simulated snowmelt peak flows at the D. River N. Belcher station (1978-1997).

probably be explained by the existence of permafrost that blocked the percolation of water and therefore increased the observed runoffs. The simulation results also demonstrated that the amount of peak flows was 30% less than the historical records (Fig. 4b). Permafrost represents an over-winter surface storage of groundwater. When temperature increases and snow starts to melt, water is also released as stream runoff from the thaw of ice contents within the organic soil layers (Woo and Thorne, 2006). The numerous seasonal ponds may also contribute to melt peaks because they have a vast water equivalent storage capacity that can be discharged when air temperature rises (Jing and Chen, 2011a).

4.3 Evapotranspiration

Evapotranspiration is defined as the sum of vapourization from both vegetations and open water bodies, and plant transpiration. It is affected by a number of factors, including vegetation growth stage and maturity, percentage of soil cover, soil moisture, solar radiation, humidity, air temperature and wind speed. The 3-year summer field investigation at Rail Spur showed that the average annual cumulative evapotranspiration is 45% of the average annual cumulative precipitation, indicating that evapotranspiration also dominates the water cycle of the Deer river watershed especially in summer. A significantly proportional relationship between daily air temperature and evapotranspiration in the summer was also observed; meanwhile, precipitation played an important role in elevating the evapotranspiration with an average lag of one day (Jing, 2009; Jing et al., 2009). For example, according to the FAO-56 Penman-Monteith Equation (Allen et al., 1998), daily evapotranspiration reached its local bottom (0.2 mm/day) on July 11, 2007 along with the local minimum daily temperature (6.5 ºC) (Fig. 5a). Heavy rainfalls occurred on July 10 and 11 (6.1 and 3.8

mm/day, respectively) along with the gradually increasing temperature; consequently, the daily evapotranspiration rose up to 4.4 mm/day one day after its local lowest point (0.7 mm/day) on July 11 (Fig. 5b). This demonstrated that air temperature is one of the dominant factors of summer-time evapotranspiration in subarctic wetlands. Meanwhile, precipitation also influenced evapotranspiration process because it increased water availability and air humidity. For example, daily evapotranspiration reached its local bottom (0.2 mm/day) on July 11th, 2007. With the gradually increasing temperature, heavy rainfalls occurred on July 10th and 11th, 2007 (6.1 and 3.8 mm/day, respectively); consequently, the daily evapotranspiration increased up to 2.8 mm on July 12th, 2007 (Fig. 5b).

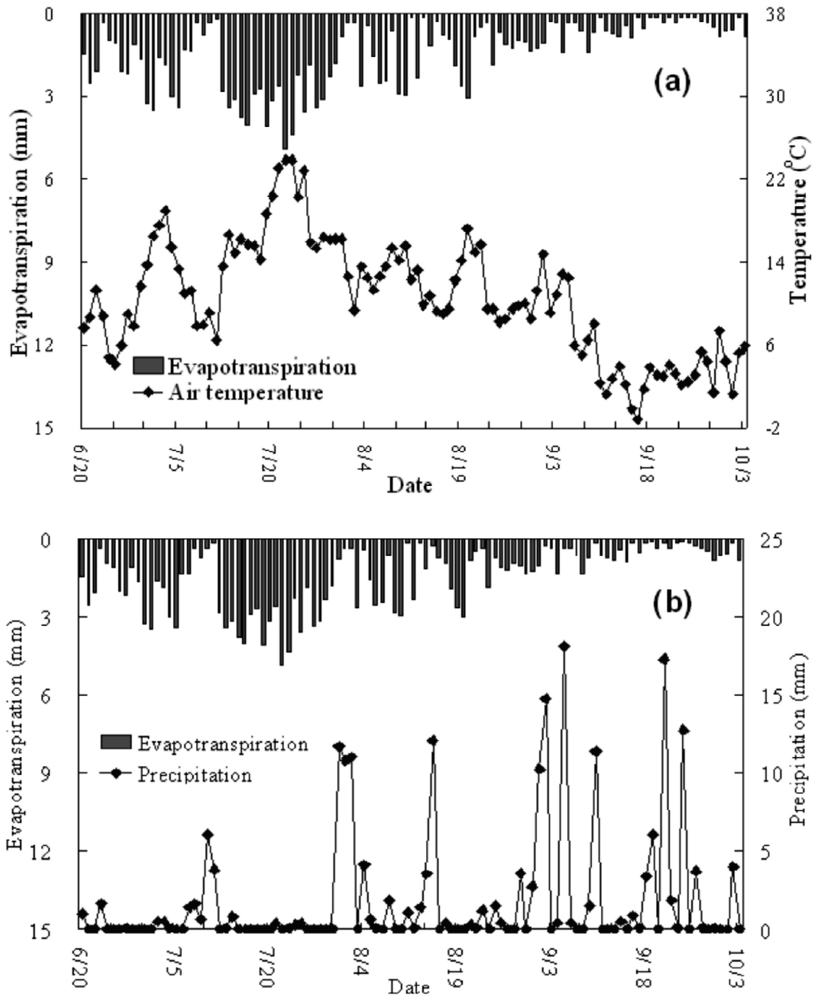

Fig. 5. Variation of daily evapotranspiration and (a) air temperature, and (b) precipitation at Rail Spur in 2007.

In hydrological models, the Penman equation has been widely used to estimate potential evapotranspiration (PET) which specifies the maximum evapotranspiration capacity if there were abundant water available (Penman, 1948). However, PET is a theoretical concept and is unlikely to be achieved in most scenarios. Many hydrological models calculate actual evapotranspiration (AET) from reducing PET because some water will be lost due to infiltration and surface runoff. In this study, the Morton complementary relationship areal evapotranspiration (CRAE) model was selected to calculate AET in SLURP (Morton, 1983) due to the lack of sunshine hours and soil heat flux. As a modification of the Penman equation, it computes PET by replacing the wind function with a vapour transfer coefficient in order to solve the energy balance and aerodynamic equations. On the other hand, the Hargreaves equation was applied in WATFLOOD to empirically estimate PET from daily air temperature due to the absence of hourly radiation data (Table 1). It is a lumped empirical estimation that may not accurately reflect the real conditions depending on the location of the study area. Nonetheless, this equation consistently produces accurate evapotranspiration approximations in an increasing number of documented studies in spite of not considering dew point temperature, vapour pressure and wind conditions (Hargraeves and Samani, 1982; Mohan, 1991). The average annual AET estimated by SLURP and WATFLOOD during the modelling period were 202.1 and 334.6 mm, respectively. Rouse (1998) estimated the water balance of a hummocky sedge fen in the northern HBL and reported an annual actual evapotranspiration rate of 269 mm. It can be concluded that SLURP may underestimate AET while WATFLOOD may overestimate it. Summer-time AET estimated by the Hargreaves equation was dramatically higher than that from the Morton CRAE method. Take August 1995 as an example. The monthly cumulative AET were 128 and 51 mm for WATFLOOD and SLURP, respectively. This difference may be attributed to a number of possible reasons. Firstly, inputs for PET computations were not the same. SLURP uses a modified version of the Penman equation whereas WATFLOOD only estimates by temperature, location on the earth as well as the Julian day. Secondly, PET calculated by both models may be subject to inaccuracy due to the lack of applications and experiences in subarctic wetlands, such as the lack of soil wilting points, soil water contents, net radian flux, water depth in the canopy and saturated vapour pressure. Thirdly, the reduction rates of PET in both models were different. WATFLOOD appears to have a more realistic concept because it employs soil moisture feedback and land cover effects. However, these extra factors may cause arbitrary uncertainties during the calibration process (Jing and Chen, 2011a, 2011b).

4.4 Rainfall-runoff Response

Streamflows had a descending trend before September 2007 and an ascending one after (Fig. 6a). Most of the small or moderate rainfall events during the summer barely generated noticeable runoff. This phenomenon was due to the descending permafrost table, high soil porosity and intensive evapotranspiration. Rainfall events occurring in the fall resulted in relatively high volume of runoff because the evapotranspiration was alleviated by low temperature and net radiation. A lag of 1-2 days between the peaks of streamflows and rainfall events was found at most of the monitoring stations due to the effect of runoff concentration (Fig. 6b). These findings were in line with some observations previously reported by other researchers (Quinton and Roulet, 1998; Carey and Woo, 1999; Carey and Woo, 2001; Woo and Marsh, 2005; Woo and Young, 2006; Jing, 2009; Jing et al., 2009).

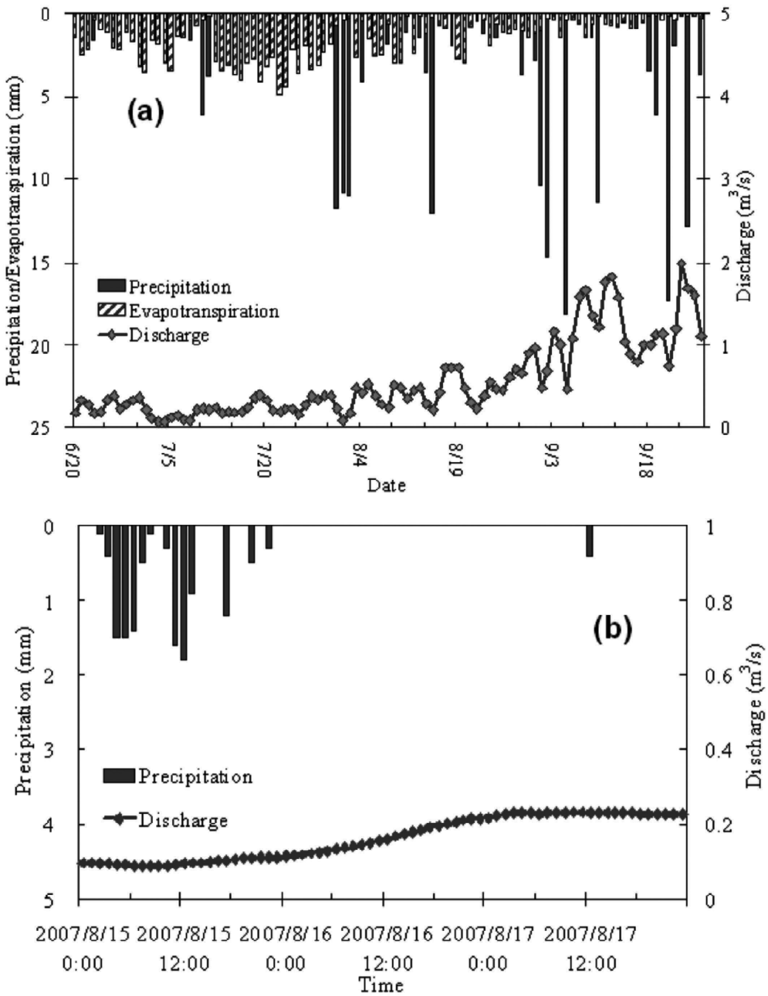

Fig. 6. (a) Plot of evapotranspiration, precipitation and water discharge in 2007 summer at station 5 and (b) response of hourly water discharge to precipitation at station 10 (August 15-17, 2007).

Both historical records and model results showed that most light and moderate rainfall events in summer (July-September) were not able to generate notable runoff due to the combined effects from interception, depression and subsurface storage, permafrost, and evapotranspiration. Many lichens, mosses, small shrubs and conifers flourish in the summer. They have considerable capacities to intercept a great amount of precipitation and lead to non-negligible water loss for the drainage basin caused by evaporation. Depression storage is mainly referred to the numerous seasonally connected ponds that behave as runoff buffers due to their fluctuating water storage capacities. Highly porous soil and descending frost table allows more water to penetrate into deep soil layers in the summer. These distinguished features of subarctic wetlands not only affect snowmelt runoff, but also alleviate peak streamflows and extend runoff concentration after rainfall events. Precipitation is retained in soil layers and ponds for a longer period and more likely to be released as evapotranspiration or groundwater flow rather than surface runoff. As the most significant natural means of cycling water back into the atmosphere, evapotranspiration also tends to be intensified due to higher air temperature and longer daylight period in the summer and therefore further reduces surface runoff. These combined factors resulted in the fact that only heavy or continuous rainfall events were able to generate countable runoff (Jing and Chen, 2011b).

A high-intensity rainfall event brought large amount of water to the wetland in a short period. After the surface soil layer was saturated, excess water generated flashy runoff, resulting in quicker runoff response. To quantitatively assess the rainfall-runoff response in subarctic wetlands, 44 summer heavy storms (daily amount is more than or equal to 20 mm) occurred during 1978-1997 were analyzed. The observed streamflow records at the D. River N. Belcher station indicated an average time lag of 3-6 days between the peaks of rainfall and runoff in summer. The modelling results showed that this delay was only 1-3 days which could be attributed to some unique features of subarctic wetlands (Fig. 7). The variation of permafrost depth, soil water storage capacity and seasonal pond level can prolong the runoff concentration. Lack of consideration of these buffering effects in both models resulted in more rapid runoff response. The mean values and standard deviations of rainfall-runoff response in SLURP (1.44 and 0.74 days) and WATFLOOD (1.84 and 0.72 days) indicated that WATFLOOD has relatively longer runoff concentration time which may be attributed to its depression storage subroutine (Jing and Chen, 2011a).

5. Conclusions

This research presents an integrated study of the hydrology of subarctic wetlands through field investigation and hydrological modelling. An extensive field investigation of the Deer River watershed near Churchill, Manitoba, was conducted in the summer time from 2006 to 2008. A monitoring network was

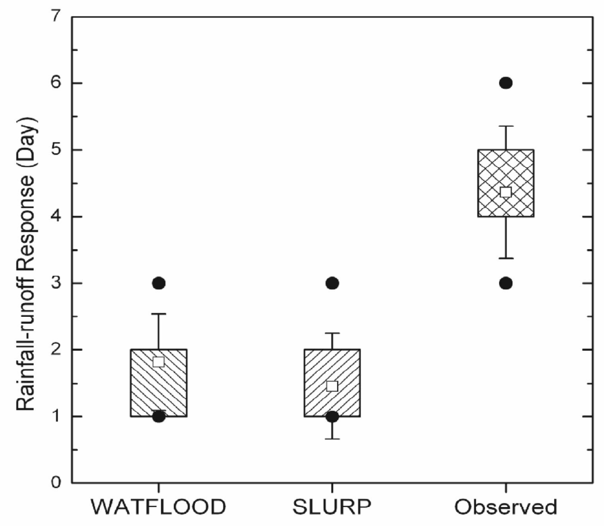

Fig. 7. Rainfall-runoff response of high intensity rainfall events in observed records, SLURP and WATFLOOD at the D. River N. Belcher station (squares show mean values; bottom and top of the boxes describe the 25th and 75th percentiles; circles represent the minimum and maximum values; error bars indicate standard deviations; 36 rainfall events in total during 1978-1997 where cumulative daily precipitation exceeds 20 mm).

established to collect hydrological and meteorological data for the in-depth understanding of the sub-arctic wetland attributes. Air temperature appeared to be the primary driving force for wetland evapotranspiration while precipitation had limited influences. Surface soil moisture became more saturated as getting closer to the stream which could be attributed to the extraordinarily high hydraulic conductivity and the descending permafrost. Permafrost table kept descending in the summer and released extra frozen soil layers due to the increasing temperature. In addition, low albedo vegetation and subsurface flow determined a reciprocal relationship between permafrost table and its distance to the streams. These findings could explain the fact that summer rainfall events were not able to generate noticeable runoff. To quantitatively confirm these findings, two hydrological models, SLURP and WATFLOOD, were applied to simulate wetland hydrology in the typical subarctic region of the Hudson Bay Lowlands. They were further compared from the aspects of formulations, and parameters, as well as simulation performance in order to evaluate their feasibility and effectiveness in modelling subarctic wetlands. The modelling results indicated that snowmelt in the spring season is the major water replenishment and constitutes approximately 50% of the annual runoff in the Deer river watershed. The degree-day snowmelt method is embedded in both models except that SLURP uses a date-varying snowmelt rate which may cause snow depletion to be accelerated. Simulated snowmelt peak flows from both models were less than the historical records in average which could be attributed to the effects of permafrost. The shallow permafrost could act as an effective barrier for infiltration and therefore amplify the spring runoff. The average annual cumulative evapotranspiration was 45% of the average annual cumulative precipitation, indicating the significance of evapotranspiration to the Deer river watershed especially in the summer months. The modelling results indicated that the Morton CRAE method in SLURP had lower evapotranspiration outputs than those from WATFLOOD. Runoff of rain water during summer only occurred after occasional intense precipitation events. Contrastingly, rainfall events that occurred in fall produced more surface runoff because the decreasing temperature and net radiation alleviated the intensity of evapotranspiration. The modelling results also showed a lag of 2-8 days between peaks of rainfall and runoff during summer and fall, demonstrating a considerable water storage capacity of the organic soil layers and buffering effect of the ponds. It also noted that the lack of considering the existence of permafrost and ponds as well as their interactions in both models appeared to be one of the main reasons for rainfall-runoff modelling inaccuracy. Modifications to both models, such as snowmelt algorithm, permafrost layer and wetland routing are recommended for both models to handle these uncertainties and further improve their performance in simulating subarctic wetlands. The findings of this study will be helpful in understanding the hydrologic features of subarctic wetlands and supporting wetland conservation particularly under climatic change context.

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7

Flash Floods in Alpine Basins

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1. Introduction

Flash floods are a very hazardous natural process causing major economic damage and fatalities under different climates (Douben, 2006). The potential for flash flood casualties and damage is also increasing in many regions due to the social and economic development increasing pressure on land use. Flash floods are characterised by rapid hydrological response, with discharges attaining the peak within less than one hour to a few hours. The fast time response of flash floods, which causes major concerns in the forecast of these processes and in the management of associated risks, is due to the small size of affected catchments (usually up to a few hundreds of square kilometres), as well as to the activation of rapid runoff processes. Flash floods are common also in alpine regions, where, due to the large availability of loose debris and to steep slopes, their occurrence is often associated to debris flows and shallow landslides on soil-mantled slopes. This results in the simultaneous occurrence of different types of hazards, which require different control measures.

In the last years, increasing attention has been paid to the study of flash floods in Europe. Amongst the studies at supranational scale, we mention a catalogue of major floods and associated damage (Barredo, 2007), the analysis of basic characteristics of flash floods based on basic data (date and location of occurrence, watershed area, peak discharge) carried out by Gaume et al. (2009), and a study depicting the long-term regimes of intense precipitation and floods across the Alpine-Carpathian range (Parajka et al., 2010).

This paper describes basic features of selected flash floods in alpine catchments, which have been investigated in the context of a wider project encompassing various geographical regions of Europe.

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2. Methods

Study methods include the collection of hydrometeorological and geographical data for a sample of major flash floods, their validation by means of a rainfall-runoff model, and the analysis of basic variables describing the climatic context of the events and flood response.

The compilation of rainfall data aims at a spatially-detailed representation of the rainstorms that caused flash floods. In order to achieve a representation of rainfall distribution using all available data, a methodology for rainfall estimation with use of radar and raingauge data (Bouilloud et al., 2010) was applied.

Discharge data is derived from both streamgauge monitoring network and indirect estimation from post-flood surveys. Streamgauge data were sometimes available, more frequently for the largest catchments. However, flash floods occur at space and time scales that make it difficult for effective sampling by means of streamgauge networks (Borga et al., 2008). This requires assessing peak discharge by means of post-flood surveys. Standardised procedures for post-flood analysis (Gaume and Borga, 2008; Borga et al., 2008; Marchi et al., 2009) were used in the study. The assessment of peak discharge in post-flood surveys generally encompasses the following steps: identification of the flow process (which was categorised into the following classes: liquid flow, hyperconcentrated flow, debris flow), identification of high-water marks, survey of channel geometry, and application of appropriate hydraulic methods for peak flood computation (Costa and Jarrett, 2008; Marchi et al., 2009). Together with peak discharge values, post-flood analysis methods were used also to derive time of the raising flow, flood peak time, and rate of recession.

Post-flood surveys, in addition to documenting flood response, aim at the characterization of geomorphic processes often associated to flash floods. The survey of geomorphic response, in addition to mapping the slope instability processes, makes it possible to recognise the type of flow processes in minor streams, enabling distinction between water floods and debris flows. This is an important prerequisite for the correct evaluation of peak flows and should be carried out before conducting peak discharge estimates. Debris flows are non-Newtonian (Costa, 1988; Iverson, 2003), and using Newtonian-based relations for debris flows can lead to gross overestimates of discharges (Jarrett, 1994). The identification of flow processes in mountain streams is usually straightforward because debris flows leave deposits distinctively different from those of water floods (Costa, 1984; Costa, 1988; Pierson, 2005). With regard to the classification of the flow process, only water floods were considered in this study.

In forested catchments, field surveys include observations on large wood entrained and transported by the flood. Source of woody material and location of deposits are mapped; the recognition of the remnants of temporary channel obstructions caused by tree and logs, whose breaching and collapse release flood surges which can attain extremely high flow discharges, unrelated to the rainfall-runoff dynamics.

Interviews to witnesses of the flood and collection of digital pictures and videos play a major role in post-event documentation of flash floods. Accounts and videos recorded by witnesses are of utmost importance especially for assessing the timing of flood occurrence (start of flooding, time of the highest water levels, etc.).

A distributed rainfall-runoff model has been applied to check the consistency of hydrometeorological data, both in terms of rainfall and runoff volumes, and in terms of timing of the runoff response. The model required raster information of catchment topography and of the soil and vegetation properties. In the model, the SCS-Curve Number (SCS-CN) procedure (Ponce and Hawkins, 1996) is applied on a grid-by-grid way for the spatially distributed representation of runoff generating processes, and runoff propagation is represented by means of a simple description of the drainage system response (Da Ros and Borga, 1997; Giannoni et al., 2003).

3. Selected Flash Floods

A sample of flash floods in the Alpine region, for which detailed hydrometeorological and geographical data are available has been collected and analysed (Table 1). Figure 1 shows the location of the studied flash floods (yellow dots) on a map reporting the Köppen-Geiger climate classification.

Although winter precipitation occur predominantly as snowfall in most of the studied catchments, the contribution of snowmelt to runoff formation is likely null for most of the studied flash floods, which occurred in summer or autumn (Table 1). For the event of October 2006 in the Isarco river system, ice-melt was observed. However, its contribution to the runoff was negligible (Norbiato et al., 2009).

Flash floods in the Alps have been subdivided into two classes: Alpine-mediterranean and Alpine. The first class includes floods that occurred in the Alpine regions more directly exposed to the influence of Mediterranean rainstorms. The class of Alpine flash floods includes events in the inner and northern parts of the Alpine range (Fig. 1).

4. Results

Data analysis targets three major topics relevant for the characterisation of flash floods: the climatic context in which they have occurred, the relations between peak discharge and watershed area, and the event runoff coefficients.

Table 1: Basic features of studied flash floods

Region /river basin impacted	*Date of flood peak*	*Country*	*Climatic region*	*No. of studied watersheds*	*Range in watershed area (km^2)*	*Range in average elevation (m)*	*Storm duration (h)*
Posina River	September 20, 1999	Italy	Alpine-Mediterranean	1	116	1045	24
Sesia River	June 5, 2002	Italy	Alpine-Mediterranean	5	75 – 983	494 – 1512	22
Fella River	August 29, 2003	Italy	Alpine-Mediterranean	4	23.9 – 623	1172 – 1370	12
Selška Sora River	September 18, 2007	Slovenia	Alpine-Mediterranean	3	31.9 – 212	847 – 992	16.5
Trisanna River	August 23, 2005	Austria	Alpine	1	122	2409	25
Isarco and Passirio Rivers	October 3-4, 2006	Italy	Alpine	6	12 – 342	1809 – 2863	12.5

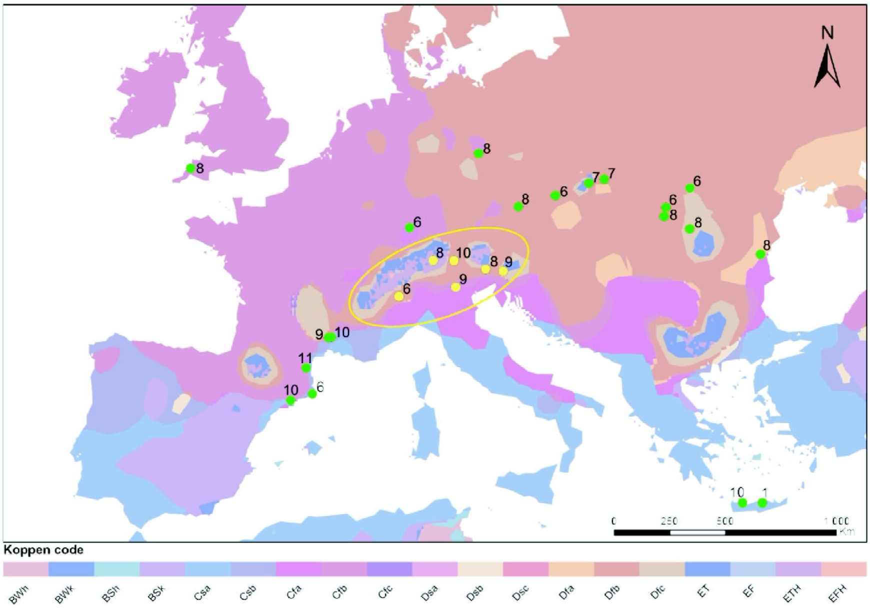

Fig. 1. Location and months of occurrence of studied flash floods in the Alps (yellow dots); flash floods analysed in the Hydrate project in other climatic regions (green dots) are also reported (map of Köppen-Geiger climate classification from Peel et al., 2007).

4.1 Climatic Context and Water Balance

Flash floods in alpine catchments have been related to climatic conditions by means of the Köeppen-Geiger classification and the Budyko diagram (Budyko, 1974). As a consequence of the wide range in elevation, the studied watersheds encompass various climates of the Köeppen-Geiger classification (Peel et al., 2007), from the temperate rainy climate *Cfb* to polar climates *ET* or *EF* at the highest elevations (Fig. 1). The Budyko plot (Fig. 2) expresses *E/P*, the ratio of average annual evapotranspiration (*E*) to average annual precipitation (*P*) as a function of *EP/P*, the ratio of average annual potential evapotranspiration (*EP*) to average annual precipitation. Actual evapotranspiration (*E*) for each catchment was derived as the long-term difference between *P* and *R* (runoff) for the basins. The ratio *Ep/P* is a measure of the climate, and is called the dryness index (or index of dryness). Large *Ep/P (>1)* represents dry climate (water limited conditions), while small *Ep/P (<1)* represents a wet climate (energy limited conditions).

Each point in Fig. 2, which permits comparison of alpine flash floods with other climatic regions of Europe, represents a flash flood event. The climatic control on annual water balance, expressed by the Budyko plot, outlines that both Alpine and Alpine-Mediterranean flash floods occur under

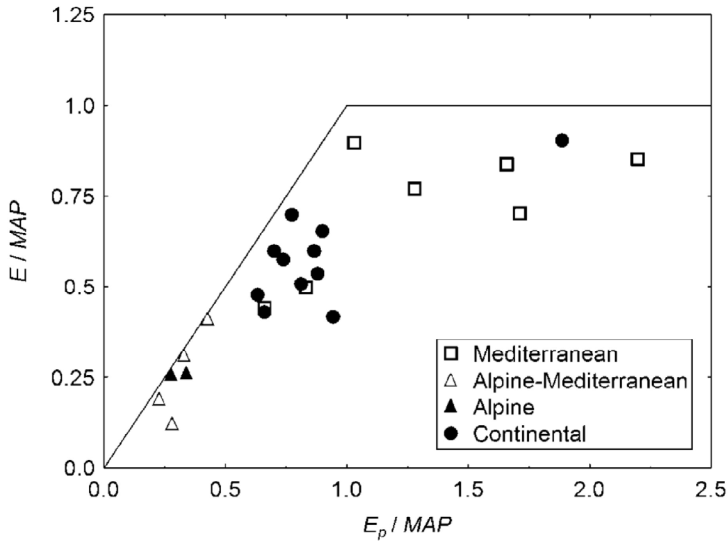

Fig. 2. Budyko plot comparing flash floods in the Alps with other regions of Europe.

wet (energy-limited) climatic conditions, with values of actual evaporation *E* close to potential evaporation *Ep*. In the case of Alpine-Mediterranean flash floods this marks a remarkable difference from neighbouring Mediterranean flash floods, which generally occur under dry, water-limited conditions.

4.2 Unit Peak-discharges

The relationship between the catchment area and the unit peak discharge (i.e., the ratio of peak discharge to upstream catchment area) was analysed to compare peak-discharge of flash floods in the alpine range with other morphoclimatic regions of Europe. The dependence of unit peak discharge on catchment area is clearly visible in Fig. 3; the upper envelope (solid line in Fig. 3) is defined by the equation:

$$Q_u = 97.0 \cdot A^{-0.4} \tag{1}$$

where Q_u is the unit peak discharge ($m^3s^{-1}km^{-2}$) and A is the upstream area in km^2.

The highest unit peak discharges correspond to events from the Mediterranean region; the second highest values of unit peak discharge over a wide range of catchment areas belong to Alpine-Mediterranean flash floods, whereas flash floods in the inner part of the Alpine range mark significantly lower values. The higher values of unit peak discharge of Alpine-Mediterranean flash floods can probably be ascribed to the type of flood-generating storm events, which are generally characterised by larger rainfall amounts than flash floods sampled in the inner part of the alpine range.

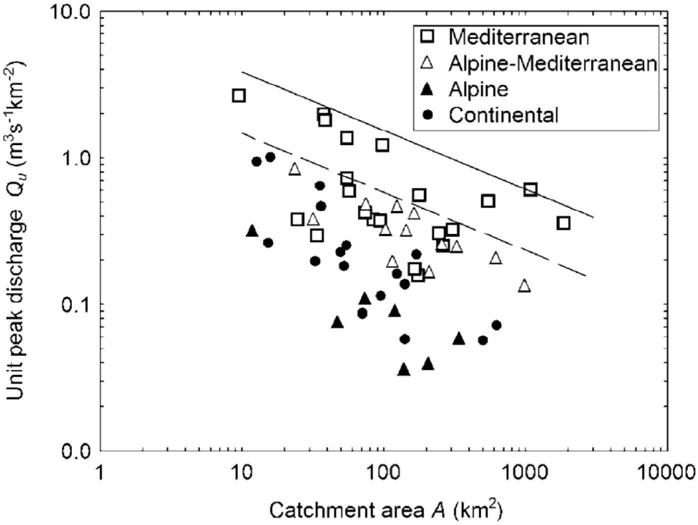

Fig. 3. Relation between catchment area and unit peak discharge. Solid line: upper envelope for the whole dataset; dashed line: upper envelope for flash floods in the Alps.

The upper envelope of unit peak discharge for Alpine-Mediterranean flash floods (dashed line in Fig. 3) can be represented by the equation

$$Q_u = 37.0 \cdot A^{-0.4} \tag{2}$$

Equation (2) keeps the same exponent as eq. (1), which has been proved to be adequate for a number of datasets of flash floods in various parts of Europe (Gaume et al., 2009).

4.3 Runoff Coefficient

Event runoff coefficient, corresponding to the ratio of direct runoff volume to event rainfall volume, have been computed for the studied flash floods. The assessment of direct runoff volume requires the separation of the event hydrograph into the two components baseflow and event flow, and then the determination of starting time and end time of event flow. Details on the methods used for such hydrograph analysis are described in Marchi et al. (2010). Table 2 reports basic statistics on event runoff coefficient for flash floods in the alpine region.

Table 2: Summary statistics on runoff coefficients for flash floods in alpine catchments

Climatic region	*No. of cases*	*Mean*	*Standard deviation*	*Median*	*Interquartile range*
Alpine-Mediterranean	13	0.32	0.13	0.40	0.19–0.43
Alpine	7	0.22	0.12	0.20	0.12–0.30

The values of runoff coefficients for flash floods in the Alps are generally low, indicating relevant losses in rainfall-runoff transformation also for these major floods. Low values of runoff coefficients agree well with the results obtained by Merz and Blöschl (2003) flash floods in Austria. These authors reported that, based on their data from Austria, runoff coefficients are smallest for flash floods, and they increase, in that order, for short rain floods, long rain floods, rain-on-snow floods and snowmelt floods.

Runoff coefficient shows higher values in Alpine-Mediterranean catchments than in catchments located in the inner part of Alps: this can be referred to higher amounts of rainfall causing flash floods in the outer parts of the alpine range, more exposed to the inflow of wet air masses from the Mediterranean. It can also be reminded that flash floods in Alpine-Mediterranean catchments display values of runoff coefficient approximately intermediate between Mediterranean catchments, with an average value of 0.41 (Marchi et al., 2010) and catchments in the inner part of the Alps. Similarly to the differences observed in the values of unit peak discharge, also the higher runoff coefficients of Alpine-Mediterranean flash floods can probably be referred to the characteristics of storm events that generate flash floods. In order to confirm these results, the analysis of a larger number of flash floods, especially in the northern part of the Alps would be advisable.

5. Conclusions

The analysis has depicted a different position of Alpine-Mediterranean catchments (Italian and Slovenian Alps) with regard to average hydrological conditions and flash floods. Annual water balance, expressed by the Budyko diagram (Fig. 2) portrays, for Alpine-Mediterranean watersheds, conditions similar to those of watersheds located in the inner part of the alpine range (energy-limited systems characterised by abundant precipitation and actual evaporation close to potential evaporation). By contrast, unit peak discharges are closer to those of Mediterranean watersheds (Fig. 3). The different hydrological behaviour in ordinary conditions, and on the occurrence of intense rainstorms associated to Mediterranean air masses is a distinctive characteristic of Alpine-Mediterranean watersheds, that differentiate them from other flash-flood basins in Europe.

Runoff coefficients for flash floods in alpine catchments show generally low values, even if with remarkable differences between the inner part of the alpine range and the southern side of the Alps, the latter having higher values of runoff coefficients. Low values of runoff coefficient are a common feature of flash floods in different climatic regions of Europe: an average value of 0.35 has been obtained for a sample of 60 catchments in Mediterranean, Alpine, and Continental regions (Marchi et al., 2010).

The study by Marchi et al. (2010) has also outlined the influence of antecedent moisture conditions on runoff coefficients of flash floods for a sample of European flash floods including events occurred under different climates. This has important implications for the assessment of flash flood response and for forecasting and managing related hazards. Extending the analysis to a larger number of flash floods could permit better exploring this relation in the alpine region.

In the first section of this paper, it has been mentioned that rainstorms which cause flash floods in Alpine watersheds trigger also debris flows and shallow landslides. On one hand, this implies that post-event documentation must take into account the recognition of different processes occurring in the stream network. On the other hand, the study of hydrological processes leading to flash flood occurrence may permit also refining the understanding of hydrological conditions leading to debris-flow triggering. A promising perspective, which would permit including the study of alpine flash floods in a wider frame of rainfall-related natural hazards, is the characterisation of rainstorms and soil moisture conditions with regard to the occurrence of water floods, debris flows or both classes of processes.

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8

Peak Discharge Prediction in Torrential Catchments of the French Pyrenees: The ANETO Method

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1. Introduction

In the mountains, torrential runoff and torrential rivers have considerable potential for damage. They are liable to seriously threaten the physical integrity of the individuals and property exposed, as demonstrated by the 23rd June 1875 disaster in Verdun sur Ariège (71 victims) or, more recently, the 14th July 1987 event at Le Grand-Bornand (23 victims). In France, about 4500 communes are concerned by the torrential risk. Prevention of and protection against these phenomena are therefore a crucial problem, requiring continuous improvements to our understanding of the various processes involved.

The ANETO method, a French acronym standing for "naturalistic and statistical approach to estimating peak discharges in Pyrenean torrential basins", was created by the RTM. It is more particularly aimed at non-specialist hydrology practitioners wishing to obtain a rapid realistic value for the characteristic peak discharges of torrential watercourses draining the Pyrenean mountain range and its piedmont plain. It applies to the catchment basins of the French Pyrenees mountain range which cover an area between 4 and 500 km² and in which the terrain comprises a negligible karstic component.

After reviewing the main hydrological characteristics of the range and the predictive approaches usually applied, the purpose of this article is to present

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the principle of the ANETO method. This method is based on the statistical analysis of hydrometric and rainfall measurements. It also has the particularity of taking into account the factors linked to the climatological environment and the geomorphology of the basins. The satisfactory performance of this approach and the level of interest it has aroused in the Pyrenees constitute an incentive for now testing its feasibility in the French Alps. This range is an area in which the density of the assets and populations exposed to torrential hazards is very high.

2. Geographical Context

2.1 Relief

With a length of 435 km running from the mouth of the Bidassoa in the West, to Cape Creus in the East, the Pyrenees culminate at the Pic d'Aneto at a height of 3404 m (Val d'Aran, Spain). Of the 270 km separating the Pic d'Anie (Pyrenees Atlantiques) from the Canigou (Pyrenees Orientales), the ridge running along the border never descends below 1600 m. This situation enhances the impression of a mountainous barrier, a feature that characterises the Pyrenees when observed from the plain of the Aquitaine basin.

The distribution of the Pyrenean relief shows a well-marked North-South dissymmetry. The French side contrasts significantly with the Spanish side, being far shorter and steeper than the latter. There is a similar contrast between the West and East ends of the range. The western Pyrenees slope down to the Atlantic Ocean more gradually than the eastern Pyrenees to the Mediterranean Sea.

2.2 Hydrography

Figure 1 shows that the Pyrenees mountain range comprises five main hydrographic units:

- the coastal rivers of the Basque country, which in particular comprise the Bidassoa and the Nivelle,
- the Adour and its major Pyrenean tributaries, including the Nive, the Bidouze, the Saison, the Gave d'Aspe, the Gave d'Ossau and the Gave de Pau,
- the Garonne and its mountainous tributaries such as the Neste d'Aure, the Pique, the Salat, the Ariège or the Hers Vif,
- the Aude and its tributaries from the Corbières hills, the main one being the Orbieu, and
- the coastal rivers of the Roussillon region, such as the Agly, the Têt, the Tech or the Baillaury on the Vermeille Coast.

In the central part of the mountain range, most of the valleys run South-North, defined by the main secondary geological features. At the ends of the

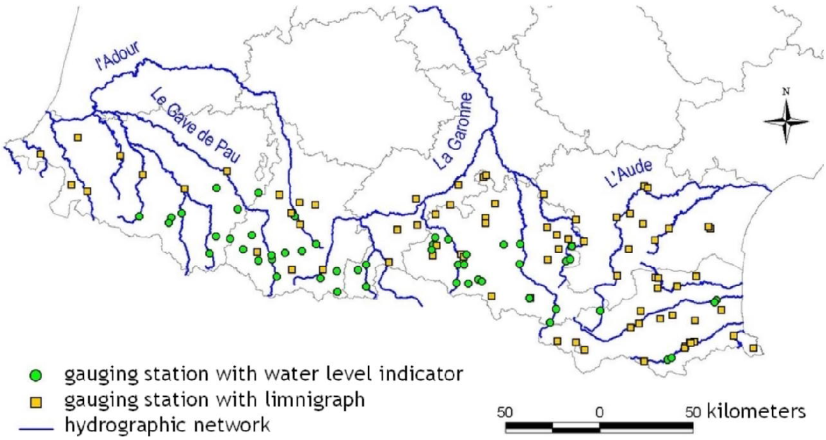


Fig. 1. Location of the main Pyrenean hydrographic units and the hydrometry stations selected for production of a hydrological summary of the torrential watercourses of the French part of the range.

range, the coastal valleys are on the contrary oriented parallel to the general axis of the range.

Before the 1960s, the hydrometric monitoring of these watercourses was generally based on daily observations of water level gauges. After this period, the installation of continuous recording devices became virtually systematic. It we take as the sampling criteria a minimum observation period of 15 years and a basin area of less than 500 km², 77 stations equipped with a water level recorder and 52 stations with only a level gauge could be counted in 2005 in the HYDRO data bank of the MEEDDAT (Ministry for ecology, energy, sustainable development and planning). Only a small number of stations provide instantaneous discharge measurements in the central part of the high mountain range (Fig. 1).

2.3 Rainfall Conditions

In 2005, the rainfall measurement network managed by Météo France comprised 169 rainfall gauges at 10 recording rain gauges. In the central and western parts of the Pyrenees, these recording rain gauges are generally located on the piedmont plain and along the hillsides (Fig. 2).

The data from the network managed by Météo France show that the French Pyrenees are under the influence of three distinct climatic zones:

- mild, humid oceanic climate, to the West,
- cool and relatively wet mountainous climate, in the central part of the range, and
- warm and dry Mediterranean climate, to the East.

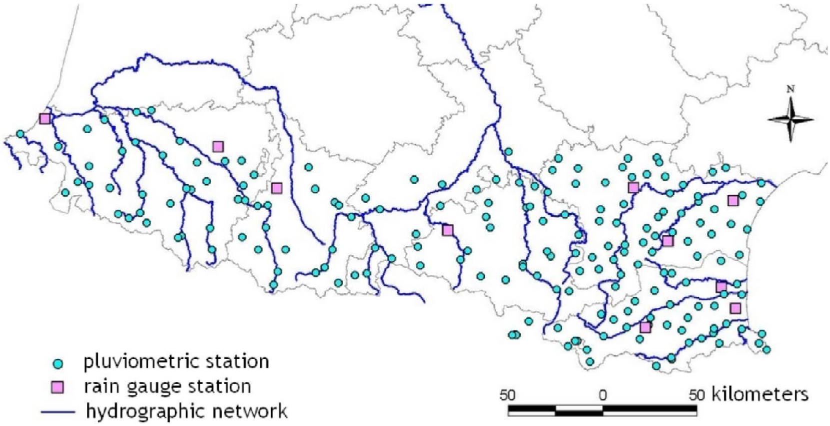


Fig. 2. map of locations of rainfall gauges and recording rain gauges in the Météo France network on the French Pyrenees range, showing the low density of measurement points for rapid runoff of rainwater.

The rainfall distribution shows that there is a West-East gradient for the annual average rainfall, as well as a significant contrast between the high range and the coastal sectors for the ten-year return period daily rainfall (Table 1). With a time step of one day, for example, this shows that the high areas in the immediate proximity of the coastal zones are far more exposed to intense rainfall than the central areas of the range. This contrast is particularly marked in the eastern part of the range.

This complex situation obviously leads to the existence of numerous local transitional areas subject to a wide variety of climatic influences.

Table 1: Data from a few stations in the French Pyrenees showing a widely differing rainfall situation from one end of the range to the other

Rainfall station	*Altitude (m)*	*Ten-year return period daily rainfall (mm)*	*Mean annual rainfall (mm)*
Port Vendres (66)	82	146	700
La Tour de France (66)	110	160	650
Ax les Thermes (09)	570	74	940
Lourdes (65)	410	82	1170
Banca (64)	256	103	1830

Source: Météo France.

2.4 Showers at the Origin of the Main Significant Discharge

Using the typology established by Pardé (1935, 1941), it is possible to distinguish at least five categories of showers that are at the origin of remarkable flooding in Pyrenean water courses:

- Mediterranean showers, which usually occur in the autumn and are the result of warm, wet winds from the Mediterranean. They cause very spectacular floods, especially in the watercourses of the Roussillon mountains and the watercourses draining into the small coastal basins.
- "Extensive" Mediterranean showers, which correspond to hot disturbances from the South-East and which affect the Western Pyrenees and the entire border range with Spain, often after the first autumn snows.
- Conventional oceanic showers, more frequent in autumn and winter, caused by disturbances primarily from the West.
- Pyrenean oceanic showers, which correspond to a typically Pyrenean version of the oceanic showers and which affect the range essentially in the spring. The disturbances behind these showers follow North-West to North-North-West flows. They affect the Pyrenees from the high range to the piedmont plain and extend from the upper Adour to the Aude basin.
- Storm showers, whether or not localised, which take place between spring and autumn and which are liable to affect all areas in the range. They generally lead to intensities often exceeding 100 mm/h for a duration of a few minutes to a few hours.

3. Predicting the Peak Discharge

3.1 Stakes

Understanding torrential basin peak discharges is an issue that concerns many operational applications:

- definition of hazards linked to flooding of torrential rivers and torrents in the Hazard Prevention Plans,
- assessment of the rarity of a torrential event prior to declaring a natural disaster or for the purpose of experience feedback,
- functional sizing and design of hydraulic crossing structures and hydraulic protection or safety barriers against flash floods, and
- estimation of the catchment basin solid material transport management plan prior to a river management contract.

This is thus a problem of interest for many public and private stakeholders liable to be involved in the torrential hazard management field: State services (DDT, DREAL, etc.), General Councils, Catchment basin management committee, ONF-RTM, METEO FRANCE, EDF, design offices, etc.

Hydrometric data concerning mountain catchment basins are however relatively rare, in particular because of the considerable mobility of torrential beds and the frequent destruction of equipment in periods of flooding. Consequently, prediction methods are virtually always used in hydrological studies concerning watercourse flash floods.

3.2 Brief Reminder of the Methods Usually Applied to an Ungauged Site

At present, these methods do not really vary much between plain and mountain catchments. By referring to a typology proposed by Lang et al. (2007), the approaches most commonly used by the hydrologists in an ungauged site context consist in exploiting any discharge measurements available close to the site studied, in implementing pre-configured hydrological models (rational method, SCS, etc.) or in applying rough formulations resulting from multiple regressions (Crupedix, Socose, etc.).

3.3 Limits in Applications to the Pyrenean Torrential Context

All of these approaches nonetheless comprise uncertainties and obvious limitations, linked to numerous factors. The first, which is not specific to the Pyrenees, is due to the fact that certain particularities of mountain hydrology are hard to take into consideration, even though they are crucial in the response of a torrential catchment to a rainfall event. Without attempting to be exhaustive, this for example includes the small surface of the catchment areas, the influence of the relief on the nature and intensity of precipitation, the density and the structure of the basin hydrographic network, its orientation in relation to the prevailing disturbances, etc. Furthermore, in the Pyrenees, the calibration of hydrological models based on transforming a design rainfall into a flood discharge is generally made highly uncertain by the low density of the hydrometric and above all rain-gauge measurement networks. Moreover, the formulations resulting from multiple regressions give a poor representation of the context of the Pyrenean torrential catchments because they are generally calibrated for a national scale and for far large catchment areas. Finally, no regionalisation and no refinement of the population of calibration catchments have ever been carried out on the Pyrenees mountain range, unlike the Alps (Faure et al., 1991).

This last point is particularly prejudicial, because even if the formulations resulting from multiple regressions are at first sight relatively simplistic, they are in fact extremely useful for practitioners in the prediction studies. Furthermore, more than a quarter of a century of additional data having been registered since the publication of this work, it would seem fair to raise a certain number of questions, in particular:

- What confidence can today be given to these formulas, given the wealth of new information available?
- Is there any point in updating and regionalising these approaches?
- How does one take account of the specific features of torrential catchments to limit the margin of uncertainty in these estimation methods?

In an attempt to provide some answers for the questions concerning the reliability of these formulas and the possible need for updating, the performance of the "national" Crupedix approach was reassessed on the basis of a data set

Table 2: Probability that an estimation given by the national Crupédix method encompasses the "true" value according to the confidence interval and the data sets considered

Data set used	*Confidence interval*	
	[Q/2 ; 2.Q]	*[2.Q/3 ; 3.Q/2]*
Calibration data in the national summary of floods in small catchments (1980)	90%	70%
Data updated in 2005 for Pyrenean torrential catchments	86%	60%

updated in 2005 and specific to Pyrenean torrential catchments. Table 2 thus shows that the probability of encompassing the true value using the historical formulation in this approach drops, especially when the data used are updated and concern a restricted portion of the territory initially studied.

4. The ANETO Method

4.1 Foundations

The findings of Table 2 encouraged the RTM to begin a hydrological summary of the torrential catchments of the French Pyrenees (Adam, 2003; Carladous, 2005). The main aim of this work was to develop a method for estimating the characteristic peak discharges of ungauged catchments, offering a significant gain in precision over approaches of the same type, by incorporating new data and adapting to the specific context of the Pyrenees.

The approach is targeted more at an audience of natural hazards practitioners with limited experience of hydrology, so it needs to be simple and pragmatic. Consequently, it should preferably use a relatively small number of easily accessible explanatory variables.

Owing to its practicality, basing an approach built on the calibration of formulations taken from multiple regressions, such as the Crupedix method, seemed in principle to be suited to these constraints. The creation of a calibration sample, which was sufficiently large and comprised updated hydrological data concerning the Pyrenean torrential catchments, confirmed the feasibility of such an approach.

In order to take into account the influence of the climatological environment and the geomorphology of the catchments on flood hydrology, several key factors were defined and then fed into the analysis approach. The performance of this approach was evaluated in order to assess its advantages with respect to existing methods.

4.2 Criteria of Sampling the Hydrological Data

The sampling of hydrometric data for producing this summary was based primarily on four criteria:

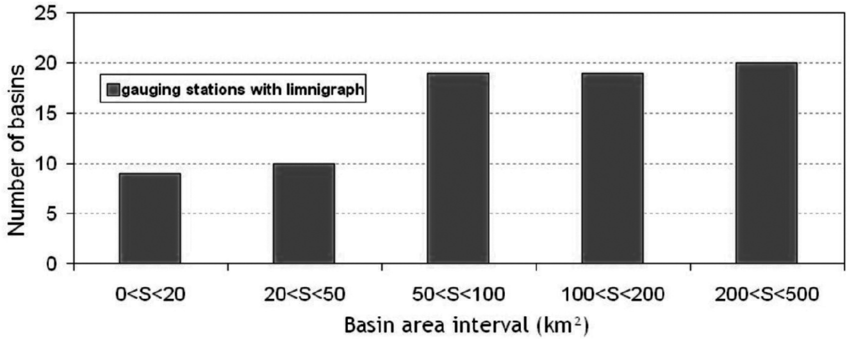


Fig. 3. Graph showing the distribution of Pyrenean catchments equipped with hydrometric measurement stations with water stage recorder, per surface area class.

- hydrometric stations with instantaneous discharge measurements,
- elimination of stations from which the measurements are liable to be significantly disrupted during flood periods by the hydraulic structures situated upstream,
- minimum observation period of 15 years, and
- catchment surface area of less than 500 km².

Based on the data published in 2005 in the MEEDDAT's HYDRO data bank, these criteria were used to create a sample of 77 stations equipped with a water stage recorder (Fig. 3). Only nine catchments of less than 20 km² were equipped with a water stage recorder. The smallest catchment has a surface area of about 4 km². The very small gauged catchments are thus under-represented in the sample.

The sample of rainfall data was supplied by Météo France. The stations with at least 10 years of suitable observations were chosen (Fig. 2). A map of daily rainfall with a ten-year return period was produced, with a regular 2 km mesh, based on a kriging interpolation method.

4.3 Main Hydrological Units Selected in the Pyrenees

On the French side of the Pyrenees, six zones considered to be hydrologically homogeneous were identified. The breakdown proposed in Fig. 4 takes into account, inter alia, the geographical distribution of extreme precipitation, the maximum intensity of the specific discharges at various points along the range and the spatial extension of the remarkable showers and resulting floods. However, no geology-related criterion was adopted. This factor proved not to be discriminating (Adam, 2003), apart of course from the predominantly karstic catchments.

In order to assess the degree of exposure of the catchments to the weather disturbances, about twenty events were analysed using the RTM's "Events" database, the MEEDDAT's HYDRO data bank and the summary maps

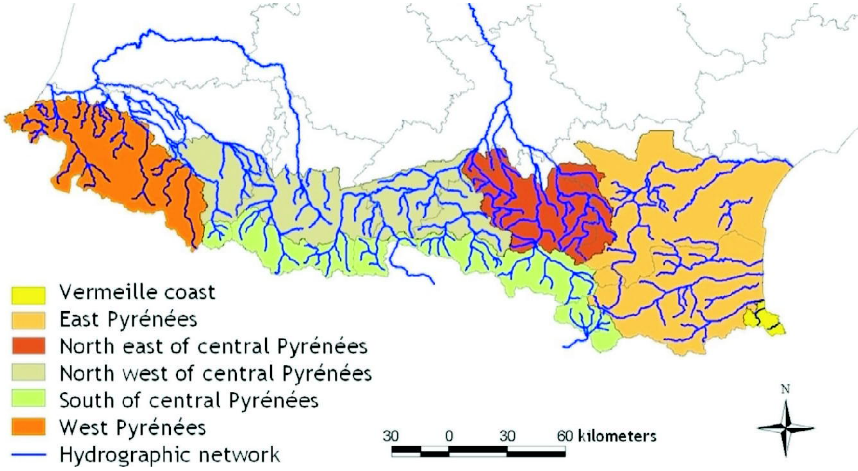
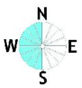
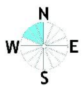
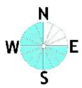
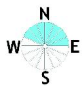
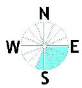


Fig. 4. Breakdown of the French Pyrenees into six hydrologically homogeneous zones.

Table 3: Geographical origin (in colour) of the disturbances causing the largest floods in the various hydrologically homogeneous zones of the French Pyrenees

Western Pyrenees	*North-Western central Pyrenees*	*Southern central Pyrenees*	*North-Eastern central Pyrenees*	*Eastern Pyrenees and Vermeille Coast*
				

published by Météo France (2001), concerning the extreme rainfall episodes observed between 1958 and 2000 in Southern France.

Table 3 shows the main geographical orientations of the showers causing the largest floods in each of the six zones defined as a result of this geographical and historical analysis. The situations would appear to be relatively contrasted, in particular in the various sectors of the central part of the Pyrenees. The contrast is considerably less marked over the entire Eastern part.

4.4 Principle of the Method

Calibration of regional formulas taken from multi-variable statistical regressions

Several physical and rainfall characteristics of the catchments were quantified from a geographical information system. They in particular concern:

- the surface area drained at the location of the hydrometric station,
- the perimeter of the basin, and
- the mean ten-year return period daily rainfall.

The choice of the ten-year daily rainfall does not mean that the ten-year rainfall causes the ten-year flood or that the daily rainfall is that which generates the heaviest flooding in the basins of the sample. This variable should be considered to be a rainfall parameter that can be regionalised and is easily accessible, unlike the rainfall data observed with a shorter time step.

The maximum instantaneous discharges corresponding to return periods of 2, 5, 10 and 20 years, were also extracted from the HYDRO bank. For information, these quantiles are calculated by fitting a Gumbel distribution to the annual maxima. The quality of the fits published for each of the catchments within the study perimeter was first of all reviewed, mainly by checking the dispersion of the processed data around the fitted line.

To remain consistent with the Crupedix approach, application of multiple regression methods allowed the definition of formulas linking the ten-year peak discharges (Qi_{10} in m^3/s), the catchment surface area (S in km²) and the ten-year daily rainfall (Pj_{10} in mm). Several formulas can then be proposed for each of the homogeneous regions previously defined (Table 4).

Table 4: Regional formulas taken from statistical regressions, linking the ten-year return period peak discharge (Qi_{10} in m^3/s), the catchment surface area (S in km²) and the ten-year return period daily rainfall (Pj_{10} in mm). r^2 is the regression determination coefficient

N°	*Hydrological zone*	*Formula*	*r^2*	*Sample size*
(1)	Eastern Pyrenees	$Qi_{10} = 0.64 \,.\, S^{0.93}.\left(\frac{Pj_{10}}{85}\right)^{1,97}$	0.75	29
(2)	Vermeille coast	$Qi_{10} = 1.28 \,.\, S^{0.93}.\left(\frac{Pj_{10}}{85}\right)^{1,97}$	0.75	2
(3)	Southern central Pyrenees	$Qi_{10} = 1.62 \,.\, S^{0.72}.\left(\frac{Pj_{10}}{85}\right)^{0,37}$	0.80	11
(4)	North-Eastern and North-Western central Pyrenees	$Qi_{10} = 1.82 \,.\, S^{0.78}.\left(\frac{Pj_{10}}{85}\right)^{0,56}$	0.61	29
(5)	Western Pyrenees	$Qi_{10} = 1.22 \,.\, S^{0.95}$	0.82	6

In Table 4, it should be noted that:

- Formula (1) is calibrated on a data set containing the catchment basins of the Eastern Pyrenees and the Vermeille coast.
- Formula (2) is not the result of calibration based on data specific to the Vermeille Coast but is the result of an increase of formula (1) by a factor of 2 in order, for an equivalent drained surface, to take account of specific discharges which are appreciably higher by comparison with the other basins in the Eastern Pyrenees.

- A more satisfactory level of correlation was obtained by combining the data from the North-Eastern and North-Western central parts, rather than by dealing with these two samples separately (formula 4).
- In the Western Pyrenees, a simple relationship between the ten-year return period peak discharge and the drained surface was finally adopted (formula 5). Introducing the "ten-year daily rainfall" variable did not lead to any appreciably greater precision.

For all the stations, the performance of these formulas was assessed by comparing the values estimated in the HYDRO ($Q_{Est.}$) bank with the values calculated ($Q_{Calc.}$) from these formulas. The quality of the results is on the whole satisfactory, with a correlation coefficient (r^2) of 0.76 and a straight line leading coefficient indicating an average under-estimation of 5% (Fig. 5). The interval [Q/2; 2Q] also represents a confidence interval with a 93% probability of encompassing the estimated value. Interval [2Q/3; 3Q/2] corresponds to a probability of 71%.

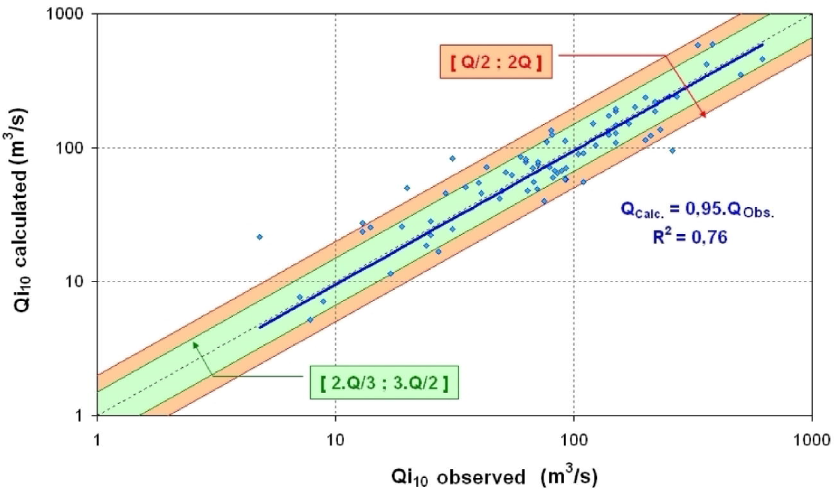


Fig. 5. Reconstitution of ten-year return period peak discharges from formulas (1) to (5).

4.5 Additional Naturalistic Analysis

A naturalistic analysis of the sites making up the calibration sample was then carried out. The aim is to determine the geographical features common to three catchment categories defined, such that the calculated discharge is either over-estimated, or conforming, or under-estimated in relation to the estimated value taken from the HYDRO data bank.

Firstly, a qualitative comparison of the catchments is able to identify factors which would seem to aggravate or mitigate the value of the ten-year return period discharge. Table 5 summarises the results of this preliminary

Table 5: Main factors aggravating or mitigating the ten-year return period discharge value

Factor		*Influence*
Number of main tributaries[1]	3 tributaries or more	++
	2 tributaries	+
	1 single tributary	–
Compactness of the basin[2]	Low	–
	High	+
Presence of a long reach before the final discharge		–
Floods mainly caused by localised storms[3]		+
Orientation of the basins in relation to disturbances causing the flooding	Upwind	+
	Downwind	–

The following convention was adopted: ++ heavily aggravating factor; + aggravating factor; – mitigating factor.

[1] A tributary can be considered main if the ratio between the area of its catchment basin and the total area drained at the final discharge is at least 30% if two main tributaries are counted, 20% if three main tributaries are counted and 15% if main four tributaries are counted.

[2] The compactness of a catchment can be considered high if the value of the Gravelius compactness coefficient (Kg) is less than 1.55. For information, Kg is equal to 0.28. $\frac{P}{\sqrt{S}}$, where S is the drained surface area in km² and P the perimeter of the catchment in km.

[3] The nature of the showers causing the known historical floods in a given catchment can be identified using the RTM's "Events" database, checking any correspondence with the floods observed on neighbouring water courses. There is thus every chance that an isolated event will have been caused by a localised storm.

analysis, giving the list of these factors and an assessment of their respective degrees of influence.

Depending on the various combinations of factors observed on the 77 previously sampled catchment basins, this analysis allows a definition of the direction and scale of the correction to be made to the standard ten-year peak discharge value calculated with formulas (1) to (5), in order to approximate the value estimated from the HYDRO bank. This comparative work concerned the basins linked to the same geographical zone and within the same surface area range.

It led to the definition of a naturalistic classification key for the catchments according to their geomorphology and their climatic environment. A determination key for the correction factor (Fc) associated with this preliminary classification was also calibrated. Figures 6, 7 and 8 show that depending on the characteristic elements of the catchment considered, the value of Fc is within an extreme range of 0.35 to 1.65.

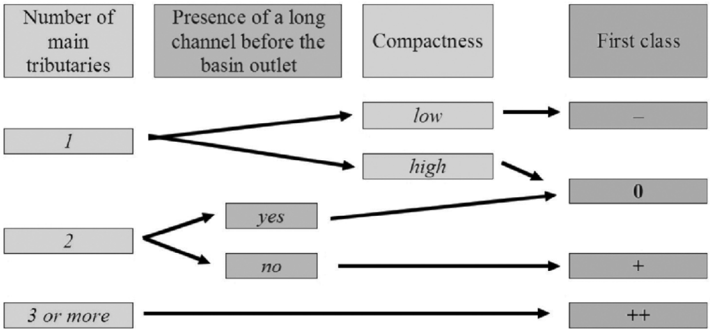


Fig. 6. Catchments first naturalistic classification key according to their geomorphology.

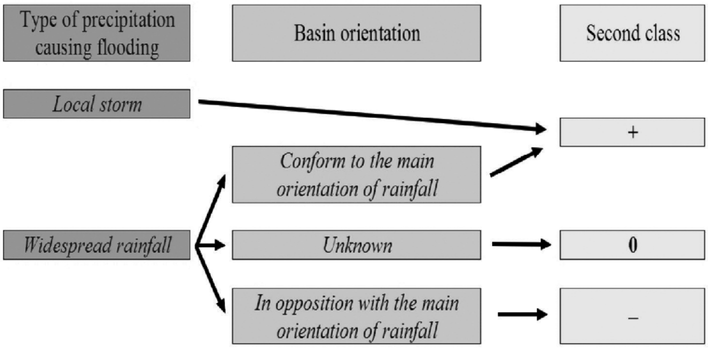


Fig. 7. Catchments second naturalistic classification key concerning their climatic environment.

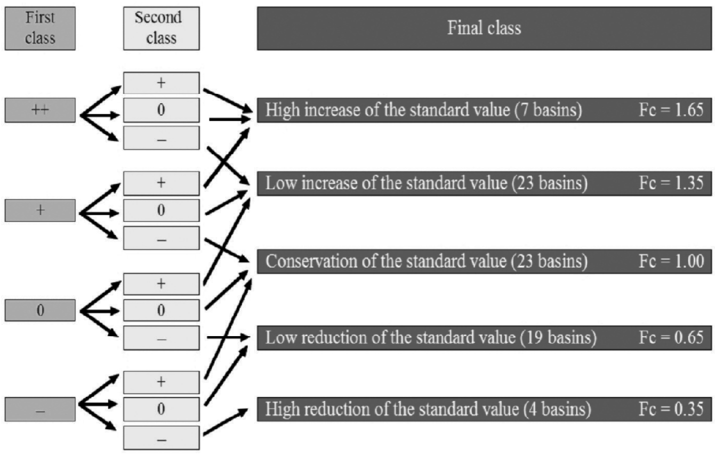


Fig. 8. *Fc* determination key to be applied to the standard ten-year discharge value calculated from formulas (1) to (5), according to the catchment classification. The final breakdown of catchments in the calibration sample (*bv*) is given between parentheses for information.

4.6 Performance of the ANETO Method

As compared with simply applying formulas (1) to (5), the increased precision offered by the ANETO method, combining application of statistical formulas and a naturalistic analysis of the catchment basin, is significant.

Figure 9 shows that this gain is reflected by a correlation coefficient (r^2) equal to 0.88. Moreover the regression straight line leading coefficient indicates on an average a zero deviation between the calculated values ($Q_{Calc.}$) and the estimated values ($Q_{Est.}$) taken from the HYDRO data bank. Finally, the interval [Q/2; 2Q] corresponds to a confidence interval with a 95% probability of encompassing the estimated value. Interval [2Q/3; 3Q/2] represents an 80% probability.

For information, the use of formulas (1) to (5) alone enabled results of 93% and 71% respectively to be obtained. Consequently, the naturalistic analysis significantly improves how uncertainties are factored in, particularly with regard to estimating the interval [2Q/3; 3Q/2].

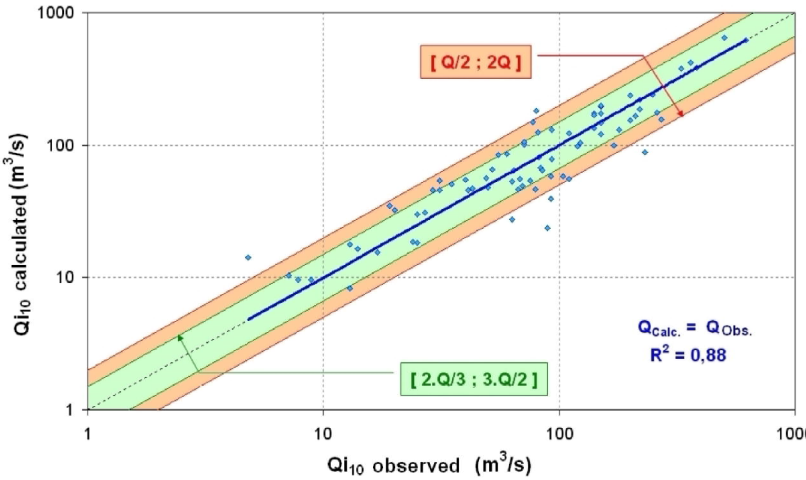


Fig. 9. Reconstitution of the ten-year return period peak discharges using the ANETO method.

4.7 Extrapolation to Other Return Periods

For engineering purpose, data concerning the ten-year return period peak discharge alone is often insufficient, especially when the hundred-year return period reference peak has to be defined in a hazard prevention plan to define hazard zoning. To obtain an order of magnitude for other reference discharges of a catchment, one approach could be to multiply the estimated value of the ten-year return period peak discharge by a coefficient adapted to a region, a catchment category and a given return period. For the French Pyrenees, the hydrological summary produced means that we can recommend the following coefficients:

$$Qi_{20} = 1.20 \cdot Qi_{10} \qquad (r^2 = 0.996)$$
$$Qi_{5} = 0.80 \cdot Qi_{10} \qquad (r^2 = 0.996)$$

(r^2 is the correlation coefficient between the discharges estimated by this multiplication coefficient and the discharges resulting from the Gumbel fit extracted from HYDRO)

For two-year return period discharges, the following distinction is also proposed:

for the Eastern Pyrenees and the Vermeille Coast:

$$Qi_{2} = 0.45 \cdot Qi_{10} \qquad (r^2 = 0.986)$$

for all the other sectors:

$$Qi_{2} = 0.60 \cdot Qi_{10} \qquad (r^2 = 0.975)$$

These ratios are very similar to those proposed by Galéa and Prudhomme (1997) for the Soyans model. This model is more representative of catchments with a small rainfall storage capacity and high surface run-off. In these conditions, for rare return periods, it would seem legitimate to retain the characteristic ratios of this same model, that is:

$$Qi_{50} = 1.70 \cdot Qi_{10}$$
$$Qi_{100} = 2.25 \cdot Qi_{10}$$

4.8 Experience Feedback and Outlook

Since it was produced in 2005, the various RTM departments in the Pyrenees have tested and applied the ANETO method to more than fifty torrential catchments, either for the drafting of Hazard Prevention Plans, or for studies prior to the creation of protection works, or surveys for individual town planning recommendations. EDF recently used this approach for a hydro-electric development project concerning an ungauged torrential tributary of the Aude river.

As an illustration, Fig. 10 presents an ANETO application on the Valentin torrent. This torrent is a tributary on the right bank of the Gave d'Ossau, in the commune of Eaux-Bonnes in the Pyrenees Atlantiques *département*.

Initial feedback confirms the benefits of this approach. It enables practitioners who are not hydrology specialists but who are familiar with the terrain and the historical working of the catchment, to obtain a realistic order of magnitude for the reference discharges of a catchment, relatively rapidly. The ANETO method can also be used to assess the sensitivity of an estimate to the intrinsic and extrinsic geographical characteristics of the catchment.

It should however be remembered that there are a certain number of limits:

- Owing to the hydrometric data available, the scope of application only concerns catchments with a surface area between 4 and 500 km². Many torrents are often far smaller.

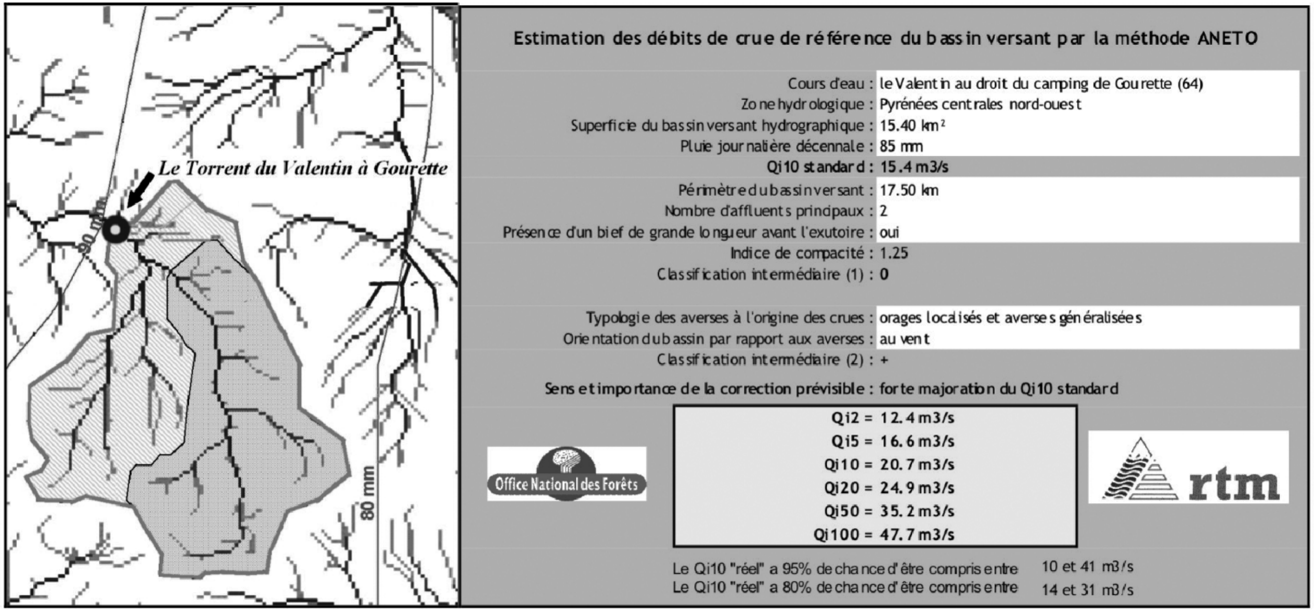


Fig. 10. Example of application of the ANETO method to the Valentin torrential catchment in Eaux Bonnes (Gourette campsite), in the Pyrenees Atlantiques département.

- The choice made on the HYDRO data bank to estimate the quantiles from a Gumbel distribution was not called into question, even though more reliable estimates could probably have been obtained with the Renewal theory.
- As currently developed, ANETO cannot evaluate the volumes of liquid flow during flood periods. In torrential catchments, this variable partly determines the intensity of the solid matter transport phenomenon.
- The proposed method for extrapolation of discharges to more rare return periods is particularly approximate. The results presented here must thus be used carefully, particularly in sectors where the rainfall hazard is liable to be very significantly aggravated at the extremes (case of the Eastern part of the Pyrenees in particular).

All of the above mean that we can now test the feasibility of this approach on the French Alps. This range is an area in which the density of the catchments exposed to torrential hazards is very high. This application to the French Alps also aims to investigate further the points left outstanding by this initial study, in particular the estimation of flood volumes. This project started at the beginning of 2009 under a collaborative agreement by the RTM, the Cemagref, the MEEDDAT, EDF and Météo France, and is also being financed by the Pôle Grenoblois Risques Naturels (Grenoble Natural Hazards Centre).

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Part III

Water Chemistry and Biota in Mountain Streams and Lakes

9

Measurement of Stream Bed Stability Characteristics Relevant to Lotic Ecosystems

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1. Introduction

Climate change and anthropogenic pressure have led to significant impacts on rivers and streams in most parts of the world (Wohl, 2006; Vörösmarty et al., 2000). Changes in rainfall patterns and altered land use may affect the flow regime, catchment erosion and thus sediment supply to river systems. Human influence via damming, water abstraction and channel modification additionally impacts on flow regime and sediment dynamics (Wang et al., 2001). These alterations directly affect stream bed stability which is a key habitat parameter for lotic ecosystems (Jowett, 2003). As a response to changes in substrate stability the species composition and functionality of these ecosystems may adjust. Thus it is important for ecologists to be able to identify relevant characteristics of stream bed stability and to quantify them.

Stream bed stability is in this respect defined as the disruption of a stable state by various processes such as erosion, transport, deposition of substrate as well as abrasion by suspended or rolling particles. These processes are driven by shear forces exerted on the stream bed by flowing water and other means (e.g. fording stock or vehicles). The likelihood of natural disruption is controlled by intrinsic properties of the stream bed such as slope, imbrication of particles and substrate assemblage as well as extrinsic factors like flow regime, sediment supply or lithology.

Response of ecosystems to changing habitat conditions can be characterised in various ways, for instance by taxonomic shifts in community composition or alterations in productivity at different levels (Resh et al., 1988; Lake, 2000). However, assessment of these characteristics at an ecosystem level is laborious and thus often key groups of organisms are selected to represent the

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ecosystem. In lotic environments the effects of floods on substrate stability have been linked to composition of periphyton (Biggs et al., 1999), invertebrate (Cobb et al., 1992; Death and Winterbourn, 1995; Holomuzki and Biggs, 2000), bryophyte (Suren and Duncan, 1999) and macrophyte communities (Riis et al., 2008). However, different groups of biota respond to different characteristics of bed stability on a range of scales. For instance, sessile organisms might be affected in different ways than more mobile groups of biota (Downes, 1990; Englund, 1991; Holomuzki and Biggs, 2000; McAuliffe, 1984). Consequently the relationship between different groups of biota and stream bed stability varies with the method employed to measure the latter (Duncan et al., 1999; Schwendel et al., 2011a). Benthic invertebrates are often employed to indicate the environmental characteristics of rivers, in particular water quality (Boothroyd and Stark, 2000; Hynes, 1994). Their wide range of mobility, key position in the food web, important functional role in decomposition of organic matter and high sensitivity to habitat variables on a wide range of spatial and temporal scales makes them good representatives of lotic ecosystems (Rosenberg and Resh, 1993).

2. Measurement of Stream Bed Stability

In order to link changes in ecosystem structure and function to habitat parameters such as substrate stability, a sensible measure needs to be identified. Schwendel et al. (2010) reviewed methods previously used to assess stream bed stability in relation to invertebrate community metrics including calculation of critical shear stress (Newbury, 1984; Cobb et al., 1992; Death and Winterbourn, 1995), FST-hemispheres (Dittrich and Schmedtje, 1995; Merigoux and Doledec, 2004), scour chains (Palmer et al., 1992; Matthaei and Townsend, 2000; Effenberger et al., 2006), scour plates (Palmer et al., 1992), tracer stones (Death and Winterbourn, 1994; Townsend et al., 1997; Death and Zimmermann, 2005; Barquin and Death, 2006), morphological budgeting (Schwendel et al., 2011a) and the Pfankuch Stability Index (Pfankuch, 1975; Death and Winterbourn, 1995; Townsend et al., 1997; Death, 2002). However, each of these methods assesses only a distinct set of bed stability characteristics and the strength of the relationship with invertebrate diversity and community composition varies (Schwendel et al., 2011a). The need of site specific calibration (e.g. bedload transport formulae and acoustics sensors) and interference with the substrate (e.g. scour plates and bedload traps) can constrain application for multi site studies and concomitant invertebrate sampling respectively (Schwendel et al., 2010). Insufficient spatial (e.g. bedload samplers) or temporal coverage (e.g. FST-hemispheres) for reach-wide, long-term bed stability assessment and potential observer bias (Pfankuch Index) can be additional problems (Schwendel et al., 2011b).

This paper presents three approaches to measure stream bed stability characteristics that are relevant to benthic stream invertebrate communities.

The first approach is an enhanced tracer technique that has been shown to be well correlated to diversity and composition of invertebrate communities (Schwendel et al., 2011a) and that also served to calibrate the other two methods. Since application of this first approach is quite time- and labour-intensive the second approach was designed to be a straightforward, time- and cost-efficient semi-visual survey with minimal instrumentation. It serves ecological studies that cannot afford elaborate measurement of each individual habitat parameter but still need a relevant measure of stream bed stability. The third approach measures direct taxonomic response of the invertebrate community to changes in stream bed stability and other correlated habitat parameters. These approaches should provide stream ecologists and environmental authorities with the tools to assess stream bed stability and facilitate inclusion of the habitat parameter stream bed stability in more ecological studies, thus improving the understanding of habitat-biota relationships in a (variable) fluvial environment.

3. In situ Marked Tracer Stones

Tracers reflect the movement of individual particles of known characteristics and thus are well suited for the stochastic and variable nature of bedload transport (Wilcock, 1997). They have been used to assess step length of movement (e.g. Habersack, 2001), proportion of the bed surface entrained (e.g. Laronne & Duncan, 1992), transport behaviour (e.g. Gottesfeld and Tunnicliffe, 2003) and transport rate (e.g. Ergenzinger and Conrady, 1982), or as an indicator of bed stability (e.g. Townsend et al., 1997). However, painted tracers or other visually detected tracers (e.g. of different lithology than the natural substrate) suffer from low recovery rates as only particles on the stream bed surface can be identified (Schwendel et al., 2010). To derive meaningful results a large number of tracers needs to be employed. Recovery rate can be improved by inserting metal bars (e.g. Schmidt and Ergenzinger, 1992) or magnets (e.g. Ferguson and Wathen, 1998) into the stones and using metal detectors or magnetometers respectively for relocation. However, placing tracers on the stream bed provides no information about actual bed stability and entrainment of particles because shear forces are not related to the local surface layer and properties such as embeddedness are not accounted for. In particular when the bed surface is armoured in situ marked particles may provide a better estimate of bed stability than unembedded tracers (Downes et al., 1998; Matthaei et al., 1999).

To overcome this and the problem of low recovery Schwendel et al. (2010b) glued small-sized (23 mm) radio frequency identification (RFID) tags with the help of wet-curing epoxy concrete in situ on stones of the surface layer. This technique allows contactless detection of tracers buried under up to 0.6 m of gravel using a portable antenna and datalogger with an average recovery rate of 77% (54 New Zealand streams, A. Schwendel unpublished data). Furthermore, each marked stone can be identified individually by its uniquely coded tag and thus the transported distance can be related to individual particle properties. The combination of high recovery and unique identification allows relatively low numbers of tracers to be employed (e.g. 15 per reach) which offsets the time-intensive marking process and cost of RFID tags and recovery equipment. This comparatively low number might not be sufficient to account for the full spatial variability of bedload transport in a reach but can provide a meaningful estimate of ecological relevant stream bed stability (Death and Zimmermann, 2005; Schwendel et al., 2011a). The tracer technique requires monitoring of the distance travelled by the marked stones over a certain time period whereby length and frequency of surveys depend on site characteristics (e.g. flood frequency, surface armour).

An index of bed stability derived from the mean transported distance, weighted by relative particle size, of tracers monitored over six months has been shown to be highly correlated with invertebrate community evenness and taxonomic richness. This is in contrast to other established techniques to assess stream bed stability such as the volume of fill derived from morphological budgeting or a flow competence calculation adapted to mountain streams (Schwendel et al., 2011a). However, the latter method could relate the percentage area of a reach subject to entrainment to bryophyte cover (Duncan et al., 1999) while the relationship with periphyton biomass is ambiguous (Biggs et al., 1999; Schwendel et al., 2011a).

The index based on tracer stones correlated very well with a distinctive axis of community composition (Schwendel et al., 2011a; 2011b) and diversity ($r_S = -0.54$, $df = 53$, $p < 0.001$; Fig. 1). Thus the described tracer technique qualifies as a relevant measure of stream bed stability for invertebrate communities and in a wider sense also for lotic ecosystems.

4. Stream Bed Stability Survey

Ecological studies that require a meaningful measure of stream bed stability but cannot afford regular site visits or a relative time and cost-intensive tracer technique, may apply the Stream Bed Stability for Invertebrates (SBSI) protocol (Schwendel et al., 2011b). It does not measure any single aspect of bed stability per se but determines a characteristic response of invertebrate community composition to a combination of bed stability characteristics. This distinguishes it from other approaches which aim to measure characteristics of bed stability per se but often are not very well related to responses of different groups of biota.

It was calibrated on a distinctive non-metric multidimensional scaling axis of invertebrate community composition that was highly related to stream bed stability (Schwendel et al., 2011b). Other habitat factors that may influence community composition such as physico-chemical water quality could not be entirely excluded. They were monitored and influence beyond a natural range was minimised by choosing calibration and validation sites in upland catchments with low anthropogenic impact. The SBSI survey consists of 13 parameters that cover aspects of sediment supply from banks, transport capacity and substrate erodibility as well as effects of particle transport on channel bottom structures, substrate assemblage and single grains.

The strong relationship of the SBSI score with taxonomic response to substrate disturbance enables the SBSI protocol also to predict effects on ecological characteristics of communities such as diversity (Brillouin Index) (r_S = –0.69, df = 53, p < 0.001). At sites not used for its development SBSI site scores show a similar or stronger connection with community diversity metrics (Fig. 1) than more traditional bed stability measures such as in situ marked tracer stones and the bottom component of the Pfankuch Index. The latter approach is purely visual and uses only a low number of parameters for evaluation. Although correlations with metrics of lotic invertebrate and bryophyte communities have been found (Death and Winterbourn, 1995; Suren, 1996; Townsend et al., 1997; Duncan et al., 1999; Death, 2002), large differences between multiple evaluations of a stream reach within a short time by the same observer may occur due to weather and surface conditions of the substrate (wet or dry) (Schwendel et al., 2011a; 2011b). The SBSI protocol might suffer less from this problem because parameters are assessed not only visually but observer bias potentially can be a problem. Additionally Schwendel et al. (2011b) recommend adjustments which allows the SBSI method to

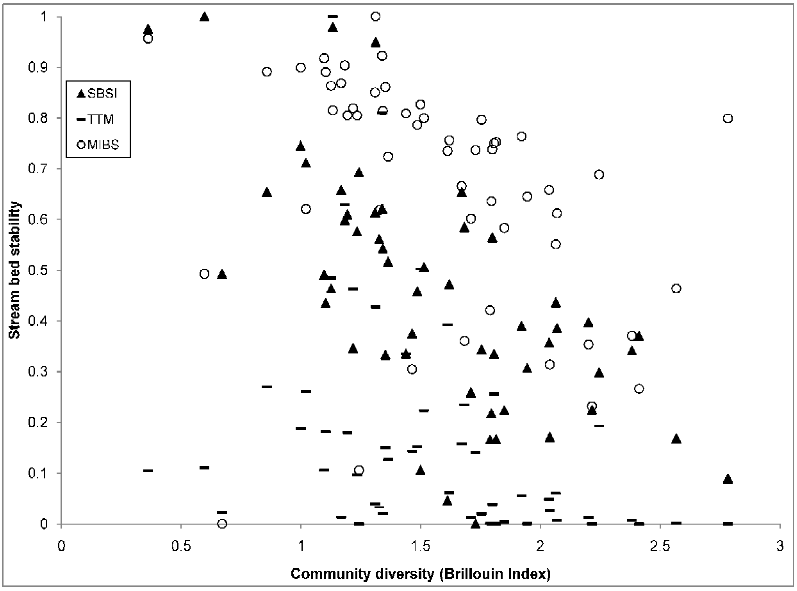

Fig. 1. Relationship between stream bed stability measured with three techniques (tracer stones (TTM), SBSI protocol and MIBS index) and benthic invertebrate community diversity (Brillouin Index). Bed stability measurements were normalised and converted to a scale where high values indicate high instability.

account for variation in particle surface constitution and angularity due to different lithologies.

In combination with the field sheet provided by Schwendel et al. (2011b) a pocket calculator and an Abney level may assist application of the SBSI protocol but are not obligatory. Interference with the substrate is low which facilitates concomitant sampling of biota and the stability score can be calculated on-site. Thus this technique combines the uncomplicated application of a visual approach with the strengths of an elaborate measure of stream bed stability.

Beside scientific studies of disturbance-diversity relationships or measurement of habitat variables the SBSI protocol may be applied for efficient and ecologically relevant monitoring of human disturbance of stream beds, e.g. by gravel mining or fording. It can be also employed to assess the potentially confounding effects of bed instability on invertebrate community composition when the latter is employed to determine water quality or environmental status of a stream.

5. Macroinvertebrate Index of Bed Stability

Assessment of habitat characteristics using biotic indices is common (Rosenberg and Resh, 1993; Hynes, 1994). In contrast to indicator species approaches where presence or abundance of individual species characterise habitat conditions, biotic community indices indicate the latter based on the composition of the entire community (every taxon scores). Community indices employ the indicator species concept without placing undue emphasis on uncommon species (Winterbourn, 1981). An index to assess stream bed stability relevant for stream macroinvertebrate communities of stony riffles (MIBS) was presented by Schwendel et al. (2011c). Although, due to endemism of taxa, its application is restricted to New Zealand, the methodology is transferable to other parts of the world. The MIBS requires collection and identification of a representative invertebrate community sample for a stream reach. It measures taxonomic response to variation in substrate stability and other intercorrelated habitat variables such as periphyton biomass (Death, 2002; Schwendel et al., 2011b).

The MIBS was developed on a dataset from 46 upland streams in New Zealand's North Island. Bed stability was assessed with in situ marked tracer stones and invertebrates were sampled from riffles. After exclusion of uncommon taxa the remaining taxa underwent a Indicator Species Analysis which accounted for abundance and faithfulness of taxa to a particular bed stability class. Taxa were then arranged along the bed stability gradient according to their indicator values and assigned an index score (Schwendel et al., 2011c). The latter ranges in theory between –10, indicating unstable substrate, and 10 at stable sites. However, the lowest score assigned was –6.5 (*Hydrobiosis umbripennis*) because no taxon appeared to be well adapted to unstable conditions. Taxa with a low score might be tolerant of unstable substrate and prefer habitat characteristics or ecological conditions (such as low competition or low number of predators) common at unstable sites. Thus low bed stability is better indicated by the composition of the entire community, e.g. by absence of high scoring taxa. Under these circumstances the application of a biotic community index is of advantage (Schwendel et al., 2011c).

MIBS site scores showed a strong correlation with invertebrate community diversity ($r_S = 0.54$, $df = 53$, $p < 0.001$). They also compare well to traditional measures of bed stability and SBSI site scores (Fig. 1) and its inclusion in the pool of variables improved modelling stream bed stability (Schwendel et al., 2011c). The MIBS score has the advantage over direct one-off measurements of bed stability that it can indicate typical habitat conditions over longer time-scales (e.g. an invertebrate life cycle) and thus encompass short-term fluctuations in bedload transport, for example as a result of variation in sediment supply from the catchment (Wathen and Hoey, 1998). Utilisation of the entire community may help assess finer gradations in bed stability, in particular at intermediate levels of substrate stability when the influence of other habitat parameters might be more pronounced (Lancaster and Downes, 2010).

Biological assessment of stream bed stability with the MIBS is particularly efficient when the invertebrate community has already been sampled for other analysis such as biological monitoring of water quality. Since many biotic indices for a habitat variable require community composition to be a function of that variable only (e.g. MCI; Stark, 1985), the MIBS can widen their applicability by assessing the confounding effects of substrate stability on community composition. However, since the MIBS was developed on a regional dataset it needs to be tested in other parts of New Zealand and, if necessary, taxon scores might need to be added or adjusted.

6. Conclusions

Sustainable management of rivers and their catchments requires ecologically meaningful information about habitat parameters because these play a crucial role for structure and function of lotic ecosystems. Large-scale environmental changes and human impacts may transfer to stream communities via local habitat characteristics. Substrate stability is a key factor influencing benthic communities but ecologically relevant assessment is difficult and thus neglected in many studies. This paper highlights three reach-scale approaches that are relevant and serve different requirements in terms of data collection and interpretation.

In situ marked tracer stones are an elaborate and accurate measure of entrainment and transport of substrate particles, two characteristics of stream bed stability that are influential on lotic communities. The SBSI protocol offers a quick and efficient means to assess a combination of bed stability characteristics specifically relevant to stream invertebrate communities. In contrast, the MIBS is a biotic community index which determines the taxonomic response of stream invertebrates to fluctuations in substrate stability.

Both, the SBSI protocol and MIBS index are calibrated on regional dataset from mountain streams and might need adjustment for application on lowland rivers and, in case of the MIBS index, also for other regions of New Zealand. Thus the author would like to encourage application of these techniques and, if necessary, further development as well as the adaptation of the MIBS to other parts of the world.

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10

Stream Habitat Fragmentation Caused by Road Networks in Spanish Low-order Forest Catchments

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1. Introduction

Designing and maintaining optimal road networks is one of the most crucial factors in forest management influencing cost-effective timber harvesting, fire control and safety, forest inventory and monitoring, game control, residential access and recreational use in mountain watersheds (Lugo and Gucinski, 2000; Janowsky and Becker, 2003; Demir et al., 2009). Planning for multi-functional road networks with minimum environmental impacts is an essential aim of forest management nowadays (Gumus et al., 2008; Eastaugh and Molina, 2011). However, forest roads continue to be a major source of impact on natural ecosystems (Spelleberg, 1998; Trombulak and Frissell, 2000; Seiler, 2001). In the United States, around one fifth of its surface area is ecologically impacted by roads (Forman and Alexander, 1998). Forest managers need an improved understanding about the potential environmental impact of road networks in different settings on which to base appropriate planning, maintenance and decommissioning of roads. In this sense, studying the impact of roads on stream ecosystems is a good compromise solution. Streams are especially suitable indicators of environmental change because they are extremely sensitive systems that integrate changes occurring over the entire catchment area (Williamson et al., 2008).

Roads affect stream ecosystems in a variety of ways including alteration of hydrologic regimes (King and Tennyson, 1984; LaMarche and Lettenmaier, 2001) and increased sediment supply to streams (Luce and Black, 1999; Jones et al., 2000). Habitat fragmentation caused by road-stream crossings is a

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subject of major concern and a priority in restoration and conservation management (Zwick, 1992; Roni et al., 2002; Gibson et al., 2005). Roads and streams share many characteristics; both compose long, linear networks conveying material and organisms across landscapes. This constrained linear nature increases their susceptibility to blockage, while increasing the frequency of intersections. Further, the steep topography of mountain watersheds often forces road delineation to occur near water courses, thereby increasing the number of crossings (Roni et al., 2002).

Stream barriers commonly occur when culverts are used instead of bridges (Warren and Pardew, 1998; Benton et al., 2008). This is common in forest roads because culverts are more cost-effective (Gibson et al., 2005). Hydraulic efficiency and road protection guide normal culvert design criteria (Norman et al., 2001). However, culverts based purely on engineering criteria can severely impair stream ecosystems by blocking the passage of aquatic organisms and altering or limiting important stream processes such as the movement of sediment, woody debris, organic carbon and nutrients (Bates et al., 2003; Bates et al., 2008). Poorly designed culverts are typically narrower than the width of the natural channel, have a skewed alignment with the stream, are improperly graded or present steep slopes and smooth interior surfaces to increase drainage capacity (Fig. 1). Undersized and poorly aligned

Fig. 1. Examples of common culvert barriers (photos J. García Molinos): (A) large volumes of sediment and debris accumulated upstream of an undersized culvert, (B) poorly graded corrugated pipe culvert creating a depth barrier, and (C) multi-box culvert with perched outlet.

culverts are often responsible for abrupt stream-to-culvert transitions. Depending on flow conditions, this can create excessive flow velocities and turbulence at the culvert entrance or obstruct the flow producing a backwater effect that favours the deposition of sediment and woody debris. Poorly graded culverts, steep slopes and smooth surfaces create problems related to the hydraulic conditions (velocity and depth) inside the culvert barrel. A very common related issue is downstream streambed scouring resulting in culverts with perched outlets.

Studies carried out in North America demonstrate that the barrier problem associated with culvert crossings is ubiquitous and dramatic (Table 1). Millions of culvert crossings block the passage of resident and anadromous fish to highly valuable headwater stream habitats in mountain watersheds. Beechie et al. (1994) found, for example, that 13% of historical salmon habitat was blocked by culverts in a large river catchment in Washington. This was estimated to account for a 30-58% reduction in smolt production. This wealth of information is lacking in European countries where, though awareness of the problem exists (Glen, 2002; Larinier, 2002; García Molinos et al., 2004), its extent and implications remain largely unknown.

Here, the author reports on the results of a field study carried out to (i) investigate the number and type of road-stream crossings, in relation to both road and stream typology, in small low-order forest catchments in northern Spain, (ii) identify the proportion of culvert barriers along roads and describe their causes, (iii) quantify the amount of stream habitat above culverts that is fragmented from the principal water course, and (iv) outline possible best management practices and mitigation measures in the context of current advances in the field.

Table 1: Literature citations on the proportion of culverts limiting or blocking the passage of fish (salmonids) for different North American studies

Reference	*Location*	*Number of culverts*	*Percentage of barriers*
(Taylor, 2001)	California	28	46
(Chesnut, 2002)	British Columbia	31	85-90
(Taylor et al., 2002)	California	51	90-98
(Tchir et al., 2004)	Alberta	142	61-74
(Gibson et al., 2005)	Labrador	47	53
(Lang, 2005)	California	312	92
(Cahoon et al., 2005)	Montana	47	81
(Park et al., 2008)	Alberta	374	50*
(Poplar-Jeffers et al., 2009)	Virginia	120	97
(Price et al., 2010)	Washington	77	30

* Only perched culverts surveyed as barriers.

2. Methods

2.1 Study Area

This study was conducted over an area draining a small forest sub-catchment (6842 ha) comprising the upper-middle part of the Arga River (upstream/downstream co-ordinates ED50 42.936585N, –1.502509W; 42.851971N, –1.583426W) in the Spanish region of Navarra (Fig. 2). The river system is composed of the main stem, the Arga River, and a tributary network comprising several high-gradient (2-16.7%) small first-to-second-order streams. The ecological status of the Arga River within the study area has been recently classified as "good" following the criteria set by the Water Framework Directive (Castiella Muruzábal et al., 2007). These water courses are classified as mixed salmonid waters hosting cool water (mean annual temperature < 15 °C) fish communities, dominated by brown trout (*Salmo trutta*), stone loach (*Noemacheilus barbatulus*) and minnows (*Phoxinus phoxinus*). Land use is represented predominantly by pine (*Pinus sylvestris*) reforestations alternated with natural oak woods and pasture land. Urban development in the area is restricted to several small villages scattered along the valley of the Arga River. However, human activity is high due to the proximity of the city of Pamplona.

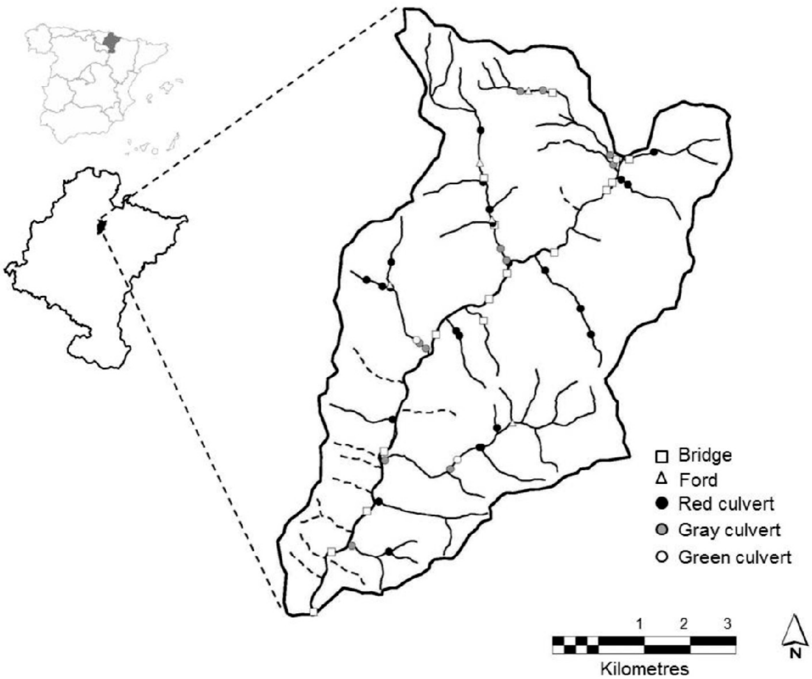

Fig. 2. Map of study area showing crossing locations by barrier status. Dotted lines indicate dried stream channels that were not included in the survey.

2.2 Survey Design and Barrier Analysis

Road-stream intersections within the study area were initially located on a 1:25,000-scale georeferenced topographic map using geographic information system tools (gvSIG 1.11.0). The georeferenced cartographic material was provided by the Geographic Information National Centre, Spanish Ministry of Infrastructures (Centro Nacional de Información Geográfica, Ministerio de Fomento), which can be downloaded at http://centrodedescargas.cnig.es/CentroDescargas/index.jsp. All crossings were visited during April 2010 under normal flow conditions. Upon locating sites in the field, crossings were classified according to their typology and grouped by stream order and road category. Roads were divided into three categories depending on the costs associated with road construction: class I included paved roads with or without associated road-side drainage elements; class II grouped unpaved roads with compacted platforms with or without drainage elements; and class III comprised unpaved minor roads with uncompacted platforms and no drainage elements. Crossings located on dried channels or on non-water courses (e.g., ditches or cross drains) were excluded at this stage.

Physical information was collected at each culvert crossing to be used later for barrier classification. Most data were obtained from a longitudinal survey of the culvert and the adjacent stream channel (Fig. 3) and included the collection of data at several specific points with a surveying optical automatic level (Nikon AX-2S, Japan). In addition to the longitudinal survey, other culvert-specific information included barrel size (diameter or width), construction material and typology (e.g., pipe, open arch, box). Finally, the average active channel width ($n = 5$) was measured upstream away from the zone of influence of the culvert.

To analyse the barrier status of each culvert crossing the author used the fish passage ranking protocol developed by Taylor and Love (2003). This protocol was developed to assess the passage status for resident salmonids at

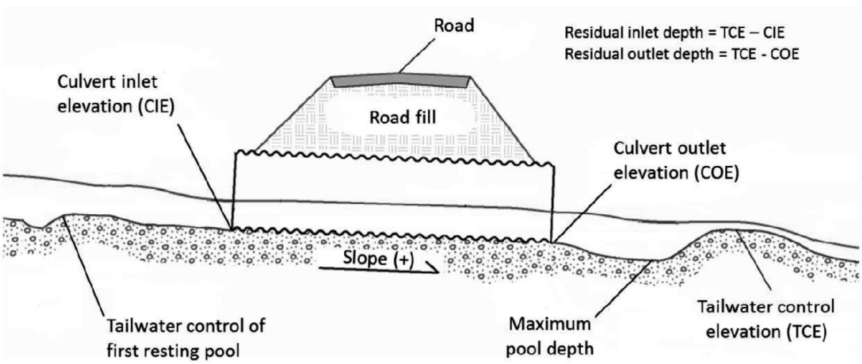

Fig. 3. Schematic longitudinal view of a culvert crossing showing the principal surveyed points used in the barrier classification criteria.

Table 2: Classification criteria to identify the barrier status of culvert crossings, as determined by resident salmonid passage, in the study

Category	*Status*	*Criteria*
Green	No barrier. Passage of all salmonid species and life stages.	Streambed substrate throughout culvert AND Inlet width ≥ active channel width OR no outlet drop AND residual inlet depth ≥ 0.15 m
Gray	Potential barrier. Passage likely to be impeded. In-depth analysis required.	All other intermediate cases
Red	Barrier. Culvert fails to meet minimum passage criteria.	Outlet drop ≥ 0.61 m OR barrel slope > 3% AND contains no waffles AND streambed substrate throughout culvert absent

After Taylor and Love 2003.

culvert crossings and it compares culvert-specific physical characteristics with fish passage criteria, classifying culverts into one of three passage type categories (Table 2). Residual inlet and outlet depths are used respectively as descriptors of the minimum water depth throughout the culvert and the existence of perched outlets (negative values) at very low flow conditions (Fig. 3). In more exhaustive studies (Taylor, 2001; Lang, 2005), this method is used normally as a first classification filter to reduce the number of crossings (Gray culverts) which need to be assessed through more sophisticated and time-consuming analyses. However, it is considered an appropriate approach for the purposes of this study because it gives an easy-to-interpret classification by placing culvert crossings along a barrier gradient (green to red). It is important to note that the Red category does not necessarily define culverts blocking passage in an absolute manner, but rather culverts failing to meet minimum fish passage criteria requirements as outlined by Californian fish regulations. Passage criteria for this protocol are selected to accommodate passage of the weaker swimming individuals within each species and life stage of resident and anadromous salmonids in accordance with these regulations (Taylor and Love, 2003).

2.3 Habitat Fragmentation Assessment

The proportion of fragmented habitat upstream of culvert barriers (Gray and Red culverts) was calculated through GIS analysis by dividing the total stream length from the barriers to their sources by the total length of streams surveyed. In those cases, where more than one culvert crossing blocked access to the same stream, the most downstream barrier was selected for calculations.

3. Results

3.1 Crossing Density and Typology

A total of 69 stream crossings were initially identified on the map. Subsequent site visits reduced this number to 57, as 12 crossings occurred on dried channels or on non-water courses and were not considered in this survey. Culverts (37/57 or one culvert every 1.97 km of stream) were by far the most abundant crossing structures (Fig. 4A). The majority were concrete (98%), circular (62%) culverts. Other frequent types included box (22%) and open arc (11%) culverts. Bridges (26%) and stream fords (9%) were other crossing structures present in the study area. However, proportions varied considerably when categorising crossings by road typology (Fig. 4A). Concentrated over the Arga River, bridges were most frequently used in paved roads (class I), accounting for 73% of the total numbers of these type of crossings. At the other extreme, stream fords occurred invariably in unpaved minor forest roads (class III).

3.2 Barrier Status

Only 8% (3/37) of the surveyed culverts were found to meet the minimum criteria to guarantee resident salmonid fish passage for all species and life-stages (Green). Among the rest, 30% crossings were classified as potential (Gray) barriers and 62% as complete (Red) barriers. A continuous layer of natural stream bed substrate throughout the culvert barrel was only found in three culverts, representing the passage criterion most frequently violated (92%; Fig. 4B), followed by undersized culverts (89%), excessive slope (60%), insufficient residual inlet depth (57%), and existence of perched outlets (51%; 30% over 0.6 m). Further, 97% of the culverts failed to meet two or more criteria. Barrier status differed significantly between stream orders (Mann-Whitney $U = 72$, $n_1 = 16$, $n_2 = 21$, $p = 0.001$). Second-order streams (Fig. 4D) accumulated all Green crossings and had much larger Gray-to-Red barrier ratios as compared to first-order streams. No significant differences ($p > 0.05$) in barrier proportions were found between road classes (Fig. 4C), though paved roads (class I) had higher proportions of Green culverts and lower proportions of Gray and Red culverts than unpaved minor forest roads (class III).

The accumulated frequency curves of the different culvert physical characteristics followed distinctive and contrasting patterns (Fig. 5). The accumulated curve of the inlet-active channel width ratio (0.31-1.14), which should be ≥1 to avoid constriction of the natural channel, presented a sigmoid pattern with a high frequency of values around 0.57-0.67. On the contrary, the culvert slope (1.1-14.3%; Fig. 5B) followed an exponential curve tailing off at values above the slope limit (3%). Finally, the outlet drop (0-1.18 m) curve displayed a more linear pattern with several small frequency breaks (Fig. 5C).

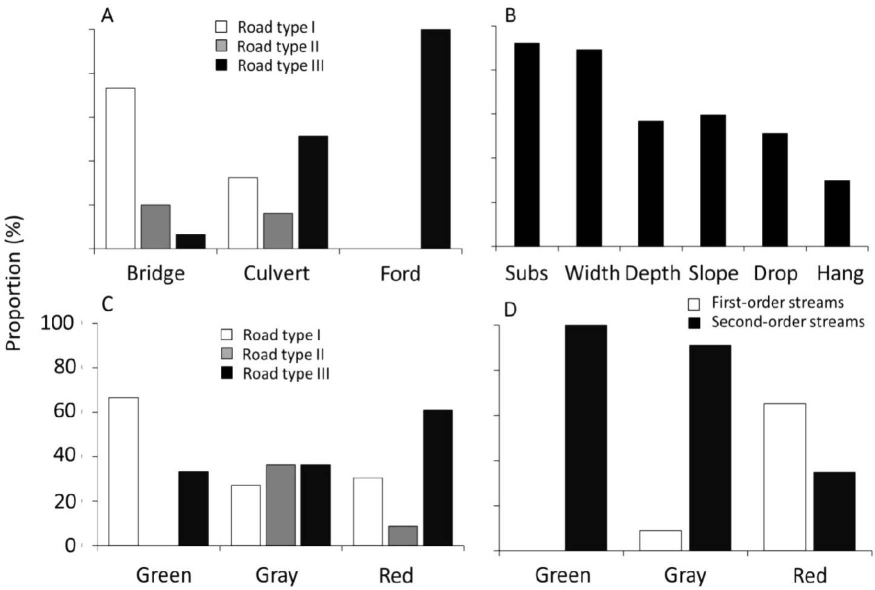

Fig. 4. Proportions of (A) road crossings grouped by crossing type and road class, (B) culverts failing to meet different fish passage criteria (Subs: no continuous streambed substrate; Width: culvert inlet width < active channel width; Depth: residual inlet depth < 0.15 m; Slope: barrel slope > 3%; Drop: existence of outlet drop; Hang: drop ≥ 0.61 m), (C) culverts grouped by barrier status and road class, and (D) culverts grouped by barrier status and stream order.

3.3 Habitat Fragmentation

The study area comprised 72.8 km of stream, of which 13.8 km corresponded to the Arga River and 59 km to the tributary network comprising first- and second-order streams. Of these, 53.8 km (74% of the total stream length or 91% of the tributary network) were located upstream of barrier (Gray or Red) crossings, isolated from the main stem. Because the main road in the study area (N-135) runs across the valley, parallel to the Arga River, almost all tributaries were affected by a crossing near their mouths (Fig. 2). Of these (13), two were bridges, one was classified as an open crossing (Green) and five as potential (Gray) culvert barriers, while the remaining five were categorized as complete (Red) barriers. However, fragmented stream habitat was characterised by a high degree of overlap among culvert barriers resulting in only a 9% of the tributary network accessible from the main stem (Fig. 2). Despite the high degree of fragmentation overlap among culvert barriers, some culverts were responsible for a significant proportion of the fragmented habitat. Seven culverts (19%) accounted for 29% of the fragmented stream habitat.

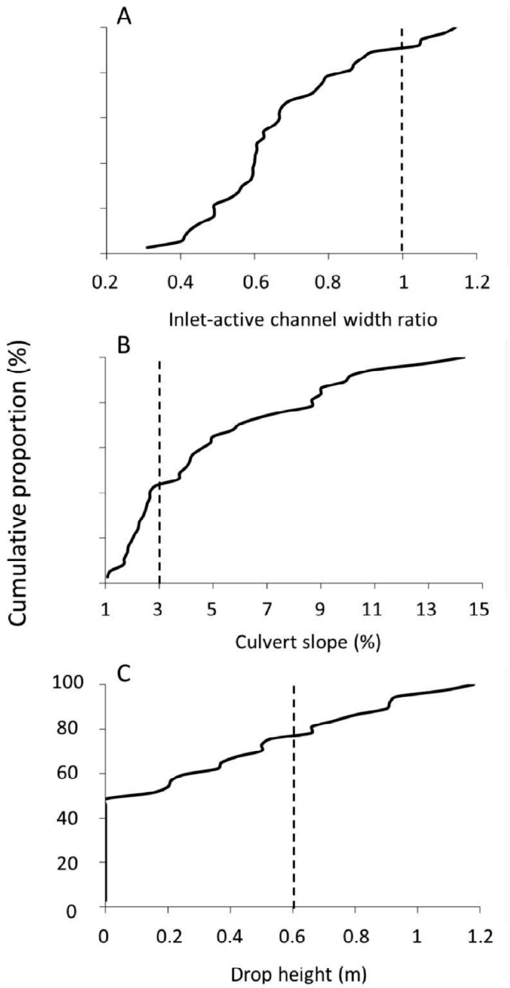

Fig. 5. Accumulated frequency distribution of (a) culvert inlet-channel width ratios, (b) outlet drop, and (c) culvert slope. Broken vertical bars indicate maximum limits set by fish passage criteria.

4. Discussion

This study represents the first published account of the extent, typology and potential consequences of culvert barriers associated with forest road networks in Spain. Culvert crossings within the study area were associated predominantly with low-order streams and low-category roads reflecting the advantages provided by these structures in relation to cost and ease of installation as compared to bridges. Surprisingly, culvert density in the study area (one culvert every 1.97 linear km of stream) appeared to be much higher than that reported in other studies (e.g., Tchir et al., 2004; Poplar-Jeffers et al., 2009).

However, this could be a consequence of our surveyed stream network, mainly comprising high-gradient (70% of the culverts placed in stream reaches above 3% of slope) first- and second-order streams. The extremely high proportion of potential culvert barriers is clearly symptomatic of poor environmental design and lax installation practices. Poorly graded, undersized, steep culvert barrels were commonplace, as appears to be the case elsewhere (e.g., Gibson et al., 2005; Park et al., 2008; Poplar-Jeffers et al., 2009). Excessive slope was, however, the barrier criteria associated to Red crossings most frequently violated within the study area, well above (+30%) excessive (>0.6 m) drop height. This situation is common in steep gradients when culverts are installed following the natural stream gradient (Poplar-Jeffers et al., 2009). Further, whereas the significant differences in culvert barrier status found between first- and second-order streams may also reflect certain degree of design relaxation associated to stream size, the absence of significant differences between road categories apparently indicate no road budgeting constraints associated to barrier generation.

The profusion of culvert crossings and the associated, disproportionately high, frequency of barriers made the proportion of tributary stream habitat potentially isolated from the main stem watercourse to be strikingly high (91%). Though the tributary network within the study area is composed exclusively of small low-order streams, this situation is likely to hinder significantly aquatic communities within the Arga River watershed. Streams are extremely sensitive to habitat fragmentation because they are highly dynamic ecosystems with strong longitudinal hierarchical dependence with regard to movements of aquatic biota and materials (Vannote et al., 1980).

Small headwater streams play an often overlooked, but highly important, multi-scale role within the watershed (Gomi et al., 2002). Forested headwater streams receive a predominant input of allochthonous organic material (e.g., leaf litter and woody debris) that is often accumulated and retained in headwater channels for long periods of time, allowing for the gradual decomposition of coarse particulate matter deposits to smaller particles that are then exported downstream to higher order streams (Wallace et al., 1991; Kiffney et al., 2000). A productive and distinctive macroinvertebrate community inhabits these banks of organic matter (Wallace et al., 1997), representing an important source of food for the salmonids that often spawn and nurse in these streams (Erkinaro and Gibson, 1997; Klemetsen et al., 2003). Isolation of these stream habitats from foraging grounds in larger rivers and lakes can lead to strong reductions in fish production (Beechie et al., 1994; Petty et al., 2005).

Despite the alarming nature of the figures, barrier estimation in this study might well be conservative. The protocol used to assess culvert barrier status was developed for the passage of resident salmonids in Californian streams, based on current fish passage regulations (Taylor and Love, 2003). State, regional and local regulations directing the design of water-crossing structures for roads normally include provision for fish passage (Moore et al., 1999).

However, enforced passage criteria commonly focus on salmonid species because of the migratory behaviour characteristic of these species and their economic relevance. Passage conditions for other fish species with weaker swimming and leaping capacities are thus often neglected. Further, in principle, habitat fragmentation can have deleterious effects on any aquatic species (Zwick, 1992; Vaughan, 2002) or even terrestrial fauna using stream corridors (Yanes et al., 1995). Movement is an essential mechanism to most aquatic organisms (Jackson, 2003). Animals disperse over different ranges and at varying times during their lives to fulfill life-history and metabolic needs such as reproduction, nursing, growth, feeding, over-wintering, dispersal and colonization. Movements are also important avoidance mechanisms in response to changes in habitat conditions caused by natural or anthropogenic disturbances (Schlosser and Angermeier, 1995). Preserving the connectivity of a stream network is also crucial for maintaining genetically diverse populations (Neraas and Spruell, 2001). Fragmented populations are more vulnerable to inbreeding and genetic drift, which decrease population fitness and evolutionary adaptability (Lande, 1988; Woodruff, 1990). Given the narrow, linear nature of stream ecosystems, unrestricted movement is critical for maintaining viable populations (Morita and Yokota, 2002).

Management approaches to allow unrestricted movement should start from avoiding construction or removal of crossings. Where permanent crossings are necessary, culverts may be replaced by less-problematic structures such as bridges. Culvert barrier replacement has been shown to be a very effective measure. Recolonization and spawning in isolated reaches usually occur shortly after replacement (Shrimpton et al., 2008), though the magnitude of the response is intimately linked with the quality of the restored habitat (Pess et al., 2005). If a culvert is to be constructed, stream simulation currently directs adequate design criteria for environment-friendly culvert crossings and should be the first choice (Bates et al., 2003; Bates et al., 2008). This relatively new methodology is based on ecosystem-based criteria seeking to mimic the morphological characteristics of the stream channel inside the culvert to guarantee free and unrestricted passage to all aquatic species and to maintain fundamental ecosystem functions such as sediment and debris transport. The diversity and complexity of the natural channel is replicated by matching the culvert to the full channel width and creating a continuous and stable substrate layer throughout the culvert, following the morphology and gradient of the natural channel. In this way, constriction of the natural channel is avoided, while retaining flow depths and velocities inside the culvert similar to those encountered in the stream.

Dispersal barriers are a major cause of fish population decline (Jager et al., 2001; Roni et al., 2002; Gibson et al., 2005), altered ecosystem functioning (Layman et al., 2007) and represent a global threat to biodiversity (Zwick, 1992; Dynesius and Nilsso, 1994). Though regulations enforcing aquatic passage criteria for water-crossing structures are uncommon in Europe, there is a growing interest on the subject amongst managers and policy-makers. A principal motivation behind this interest is the importance of preserving and restoring stream connectivity as a necessary step to achieve the 2015 "Good Ecological Status/Potential" objective for surface water bodies required by all EU Member States through the European Union Water Framework Directive (Directive 2000/60/EC). Numerous assessment protocols and guidance documents for fish passage at road-stream crossings have appeared over the last decade in Europe (Ministerio de Medio Ambiente, 2006; Kemp et al., 2008; Ministerio de Medio Ambiente y Medio Rural y Marino, 2008; Balkham et al., 2010). However, experience has shown the limitations of similar documents that were previously enforced to prevent this situation (Price et al., 2010).

A holistic, multidisciplinary approach involves improved ecosystem-based design, construction compliance, and long-term management planning. Management plans need to be founded on an exhaustive inventory to assess the condition of existing crossings and analyse their environmental implications at the catchment-scale. This information will allow the establishment of prioritization protocols directing the decommissioning and correction of barriers and the implementation of appropriate maintenance practices. Detailed information on existing crossings and sensitive areas will also aid to conceive a long-term road network that minimises environmental impacts and associated costs. Stream restoration and conservation require active incorporation of the multi-scale continuum concept into management (Fausch et al., 2002). Reconnecting fragmented habitat means restoring stream ecological function and should, consequently, be a primary management objective (Bradshaw, 1996; Gibson et al., 2005).

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Mountain Watershed in Lesotho: Water Quality, Anthropogenic Impacts and Challenges

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1. Introduction

The Kingdom of Lesotho is divided into four agro-ecological zones (AEZ): the Lowland, Senqu River valley, Foot-Hills and Mountains (Table 1). Approximately two thirds of the country is formed by rangelands and permanent pastures. Most soils show low levels of organic carbon, available phosphorus, and pH (≤ 3.5). The highest population pressure is in the lowland AEZ (Table 1), where the arable land is facing mainly problems of soil erosion and land degradation. Multi-resource management of Lesotho mountain wetlands claims the support of livestock-pastures, production of several important medicinal plants, and the source of water flow in the Senqu/Orange River. However, in wetlands of Lesotho, degradation processes are also evident, particularly following the extend overgrazing.

Table 1. Agro-ecological zones in Lesotho

Agro-ecological zones	*Altitude (m) above sea level*	*Topography*	*Mean annual rainfall (mm)*	*Mean annual temperature (ºC)*
Lowland	<1800	Flat to gentle	600-900	–11 to 38
Senqu river valley	1000-2000	Steep sloping	450-600	–5 to 36
Foot-hills	1800-2000	Steep rolling	900-1000	–8 to 30
Mountains	2000-3,484	Very steep bare rock and gentle rolling valleys	1000-1300	–8 to 30

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2. Mountain Wetlands in Lesotho

In Lesotho, wetlands are registered in categories of Palustrine, Lacustrine and Riverine. In mountain watersheds, Palustrine wetlands dominate namely with mires (bogs and fens) including high altitudes, heads of valley, and upper reaches of rivers. Generally, wetlands found in Lesotho (Plate 1) are unique by their flora and structural composition.

Plate 1: A watershed in the Highland AEZ of Lesotho.

Recent problems of wetlands in Lesotho include:

a. Increase in population pressure: Lesotho has witnessed considerable internal migration in recent years (Lesotho Demographic Survey, 2001). This pattern of migration has, in large part, been from the rural to urban areas and from the Mountains AEZ to the Lowland AEZ. This internal migration is influenced by factors such as unemployment and increasing population pressure on agricultural lands in the rural areas. Despite having only one-quarter of the total land area, the Lowlands, Foot-Hills and Senqu River valley AEZs contain more than three-quarters of the total population (Fig. 1). From the data presented below, it could be observed that the Lowland AEZ contains more human population and livestock density (i.e. cattle, sheep and goats) per km^2 compared to other AEZs. The six districts (i.e. Butha-Buthe, Leribe, Berea, Mafeteng, Mohale Hoek and Quthing) belong to the Foot-Hills and Senqu River Valley AEZ. There is a close relationship between increase in population density (i.e. of human and livestock) and degradation of natural resources (especially agricultural land, watershed and wetlands).

Ownership of all land in Lesotho is vested in the paramount chief for the people and no land is privately owned. In practice, administration of the land is delegated to local chiefs or wardens who grant the right to cultivate to either individuals or groups, but all Basothos have the right to graze their cattle on hill sides. The only protected area in Lesotho is the Sehlabathaebe national park; apart from this site, other wetland areas are subjected to increased grazing and fines which are becoming more intense as the climate is changing. The effect of these anthropogenic pressures is that ecology of these bogs and

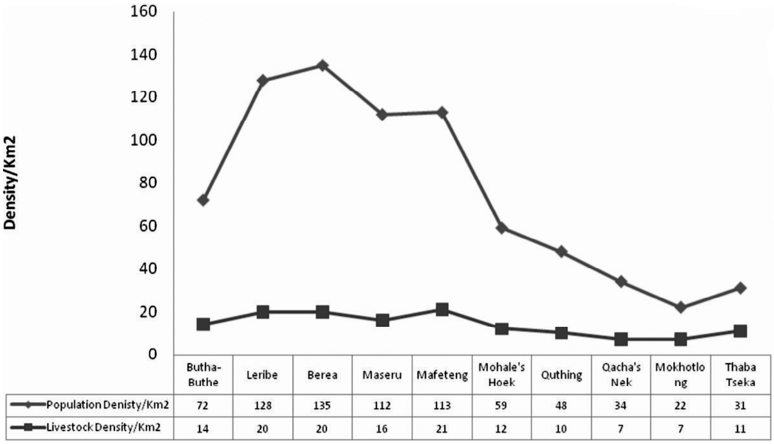

Fig 1. Population density (human and livestock) in each of the ten districts of Lesotho (Source: Lesotho Demographic Survey, 2001).

sponges are being disturbed thereby reducing the ability to store water and regulate floods. A study was conducted at Ha-Thetsane (latitude 29°S, longitude 28°E, altitude 1510 m), a riverine wetlands located in industrial areas in Maseru, Lesotho. Results showed an increase in anthropogenic activities due to direct discharge of untreated pollutants. Most of this ends up in other river downstream. Results showed increased discharge of pollutants into the riverine wetlands (Tables 2 and 3).

b. Change in rainfall distribution: Rainfall in Lesotho varies based on location within the country. The northern farming areas of the country receive the largest amount of rain. However, the rainfall over Lesotho is highly variable (Fig. 2). In addition, the chart of cumulative sums of precipitation is based on

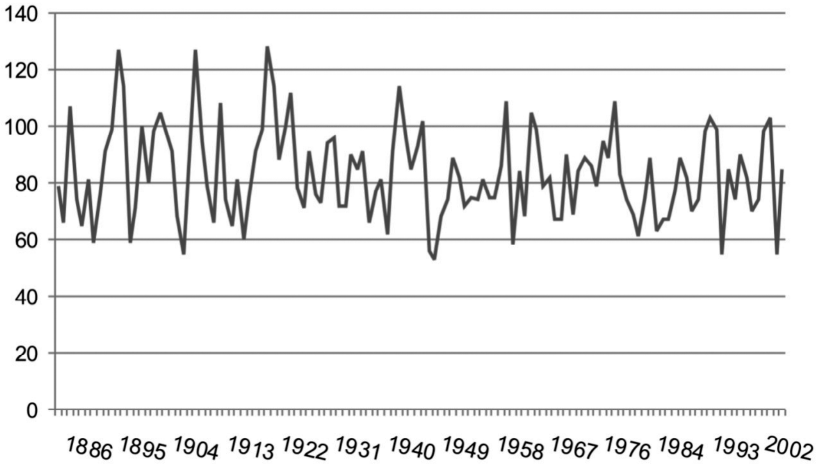

Fig. 2. The coefficient of variation of rainfall in Lesotho (1886-2006).

Table 2. Mean monthly water quality in Riverine Wetland, Lesotho (2008-2010)

Time of Sampling	*mg/L*														*mms/cm*
	pHw	*As*	*Cd*	*Cr*	*Cu*	*Fe*	*Mn*	*Pb*	*Zn*	PO_4^{2-}	*Na*	*Ca*	*Mg*	*K*	*EC*
Jan	7.79	0.00	**0.03**	0.00	0.05	0.05	0.41	**0.04**	0.00	0.00	103.05	68.99	18.07	61.46	1.56
Feb	7.84	0.02	**0.01**	0.00	0.04	0.71	0.09	**0.04**	0.00	0.00	77.15	34.24	11.00	47.32	1.22
March	8.18	0.01	**0.01**	0.00	0.04	0.04	0.04	**0.06**	0.00	0.00	49.77	35.31	10.60	39.97	1.05
April	8.00	**0.03**	**0.01**	0.00	0.04	0.05	0.06	**0.04**	0.21	0.00	71.77	35.30	12.26	46.87	1.04
May	5.82	**0.06**	**0.01**	0.00	0.03	3.51	0.32	**0.08**	0.57	0.00	37.86	53.81	17.57	34.67	0.91
June	7.55	**0.07**	**0.02**	**0.46**	0.05	1.53	0.27	**0.08**	0.09	0.12	51.39	57.17	18.10	152.49	1.18
July	7.41	**0.06**	**0.01**	0.00	0.03	0.05	0.03	**0.07**	0.11	0.51	37.32	71.89	28.24	122.91	1.97
LSD	0.86	0.040	0.008	0.43	0.008	4.12	0.35	0.049	0.61	0.11	20.72	6.85	3.05	23.78	0.36
WHO standard	6.5-9.2	0.01	0.0103	0.05	2.00	0.3	0.5	0.01	5.00	5	200	100	150	12	1.5

Table 3. Mean monthly water quality in Riverine Wetland, Lesotho across sampling points (2008-2010)

Position	*mg/L*														*mms/cm*
	pHw	*As*	*Cd*	*Cr*	*Cu*	*Fe*	*Mn*	*Pb*	*Zn*	*AvP*	*AvNa*	*Ca*	*Mg*	*AvK*	*EC*
Upper stream	7.69	0.05	0.01	0.14	0.04	0.56	0.07	0.05	0.25	0.07	63.27	49.38	14.54	66.14	1.10
Middle Stream	7.39	0.03	0.01	0.01	0.04	1.54	0.26	0.08	0.10	0.12	52.26	50.37	18.48	76.92	1.21
Down Stream	7.51	0.04	0.01	0.09	0.04	0.30	0.11	0.06	0.08	0.17	56.88	50.03	16.35	86.51	1.61
WHO standard	6.5-9.2	0.01	0.003	0.05	2	0.3	0.5	0.01	5.00	5	200	100	150	12	1.5

the technique of Tam (2009). Figure 3 shows a decreasing trend (Olaleye and Sekaleli, 2011).

Therefore, mountain and highland watersheds in Lesotho are gradually loosing their runoff potential.

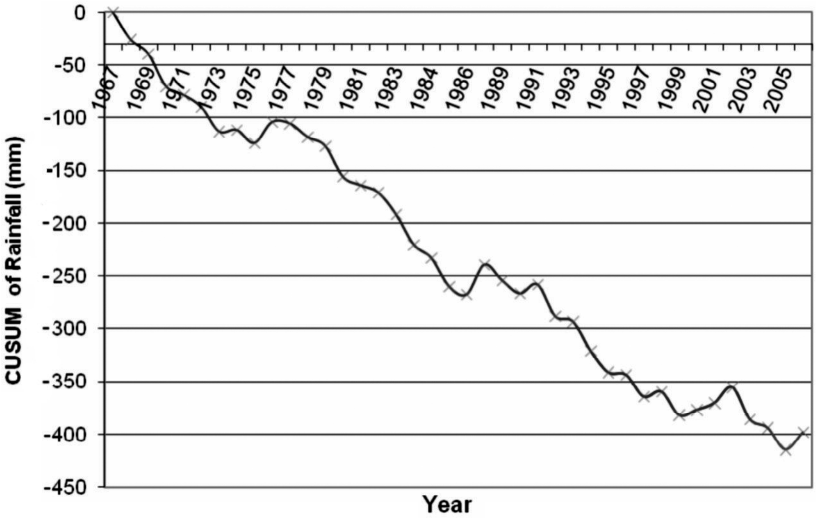

Fig. 3. Cumulative sum of rainfall between 1967 and 2006 in Lesotho.

c. Anthropogenic impacts on stream water quality: From selected points identified by the Lesotho Highland Development Authority (LHDA), water samples were collected (Highlands and Lowlands AEZs) and analyzed for some water quality variables (Table 4). Data of five sampling points are presented in Figs 4-7. From the results of the watersheds situated in the Lowland and Highlands AEZs of the country, it could be observed that the water quality parameters were still within the Minimum Permissible Levels (MPL) of the World Health Organisation (WHO), but comparing the watersheds

Table 4. Coordinates of sampling points along Senqu-River Basin in Lesotho

Sampling Points	*Locations*	*Coordinates (UTM)*
	Highlands	
Malibamtso River – Point A		72496.92;314255.709
Malibamtso River– Point B		636434.31;3139576.46
Malibamtso River – Point C		724973.27;3132771.24
Matsoku River – Point A		718822.12;2582157.84
Matsoku River – Point B		713972.22;3137201.39
	Lowlands	
Nqoe Stream – Point A		643475.61;3129531.25
Nqoe Stream – Point B		626080.29;3127117.35
Hololo River – Point A		64129.20;3126058.66
Hololo River – Point B		651290.20;3127058.66

situated in the Highlands with that of the Lowlands, results of the mean separation showed that most water quality variables were higher (especially N and P) in both the Lowlands and Highlands AEZs (Table 5) suggesting increase in anthropogenic impact in these rivers.

Table 5. Mean comparison of water quality in the watersheds in the Highlands and Lowlands Agro-ecological Zones of Lesotho

Water quality parameter	*Highland*	*Lowland*	*WHO standard*
Temperature (°C)	13.06	15.52	No guideline
pH	7.74	7.90	6.5-9.2
Dissolved oxygen (mg/L)	6.28	7.72	No guideline
Electrical conductivity (mS/m)	11.34	13.38	1.5
	(mg/L)		
Alkalinity	52.28	60.86	No guideline
Hardness	51.60	59.42	No guideline
Total dissolved solids	61.14	73.46	500
Ca	13.72	15.10	100
Mg	5.60	6.10	150
K	0.80	1.10	12
Na	2.66	3.88	200
Bicarbonate	63.42	73.98	No guideline
Sulphate	4.92	7.34	No guideline
Nitrate-N	0.74	1.72	50
NH_4-N	126.08	134.52	No guideline
P	87.02	68.84	No guideline
PO_4^{2-}	14.72	14.50	5
Dissolved organic carbon	4.08	3.12	No guideline
Fe	0.62	0.40	0.3
Silicon	7.06	8.00	No guideline

3. Constraints and Threats to Wetlands in Lesotho

The major threats identified as affecting wetland ecosystem and wetland management seems to be dominated by the following:

1. Lack of co-ordination of development efforts in areas in which wetlands are located.
2. Conflict of interests among land users on wetland ecosystem in terms of grazing, crop production, are not planned in an integrated manner to optimize the health of the ecosystem but to maximize interest group benefit.
3. Weak administrative structures at community level to effectively address the apparent negative effects of land use practices.
4. Inadequate education/knowledge on and low level appreciation of importance of wetland ecosystems and their need for special care in each of the districts of Lesotho.

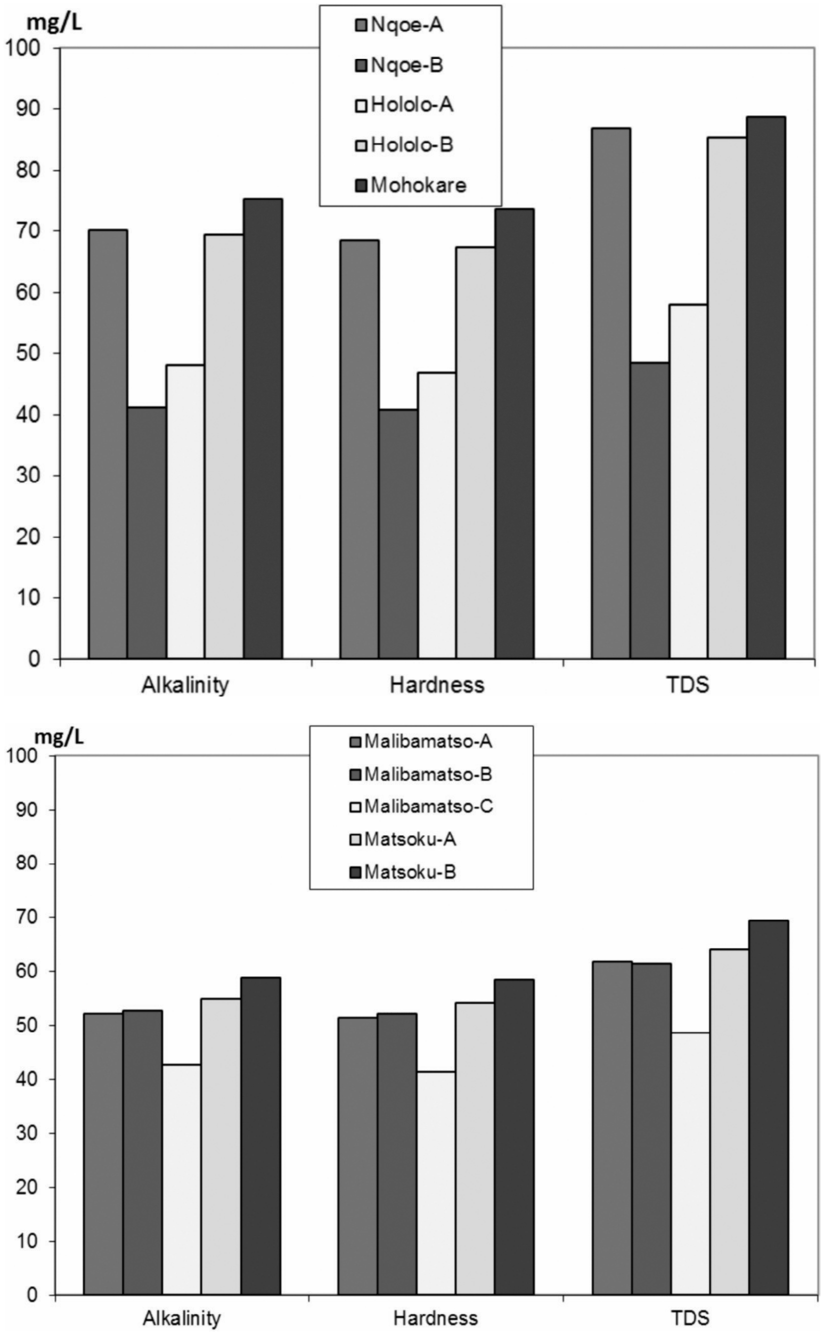

Fig. 4. Alkanity, hardness and total dissolved solids (TDS) in watershed catchments.

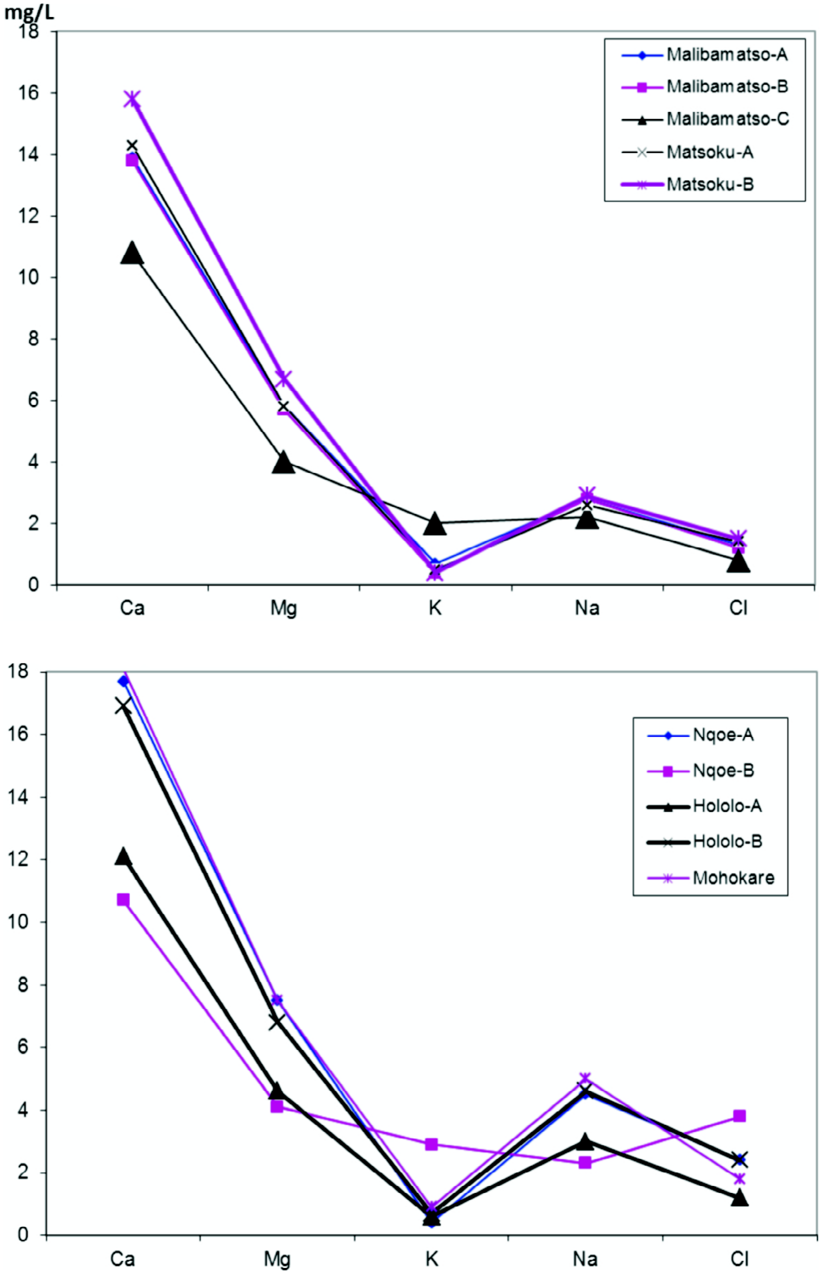

Fig. 5. Cations and chloride contents in watershed catchments.

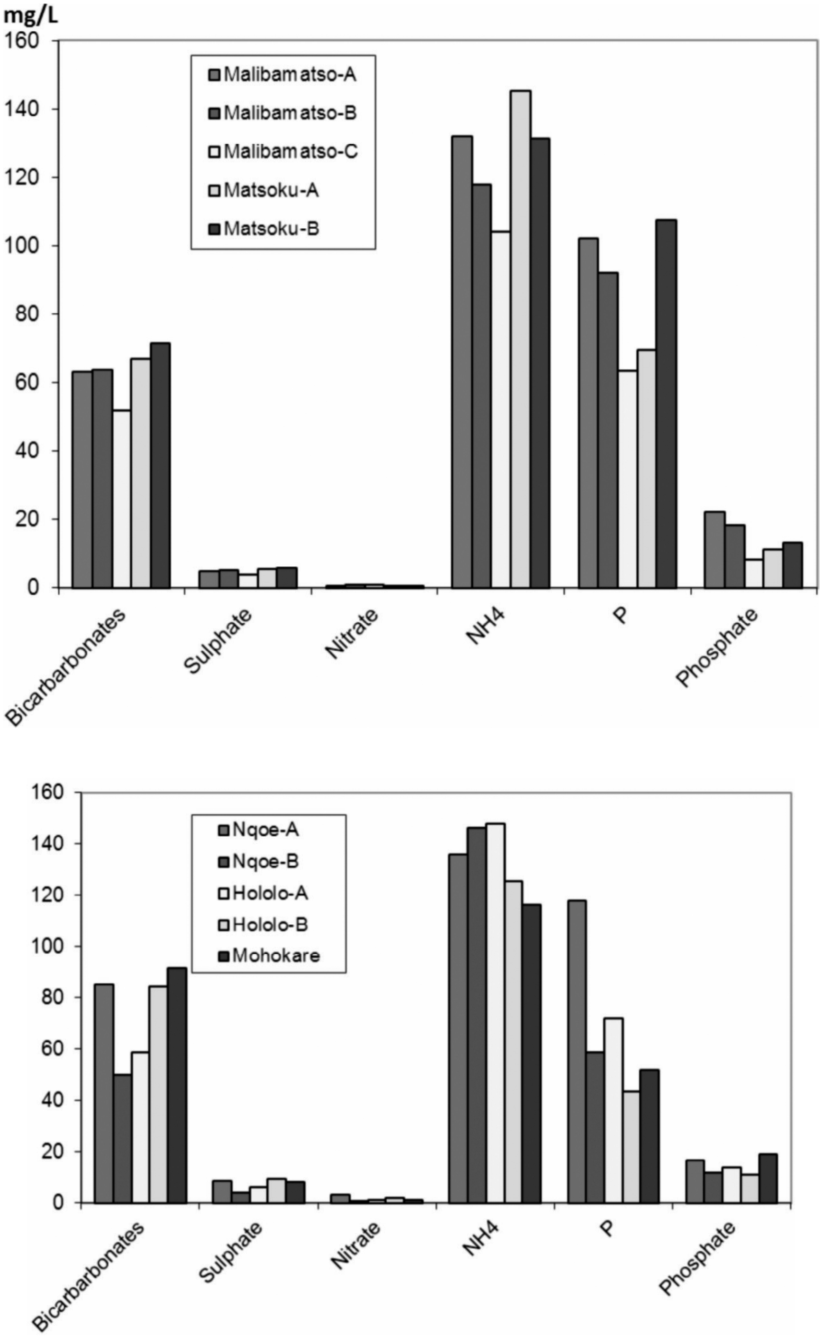

Fig. 6. Carbonates, sulphates, nitrates, ammonium, phosphorus and phosphate in watershed catchments.

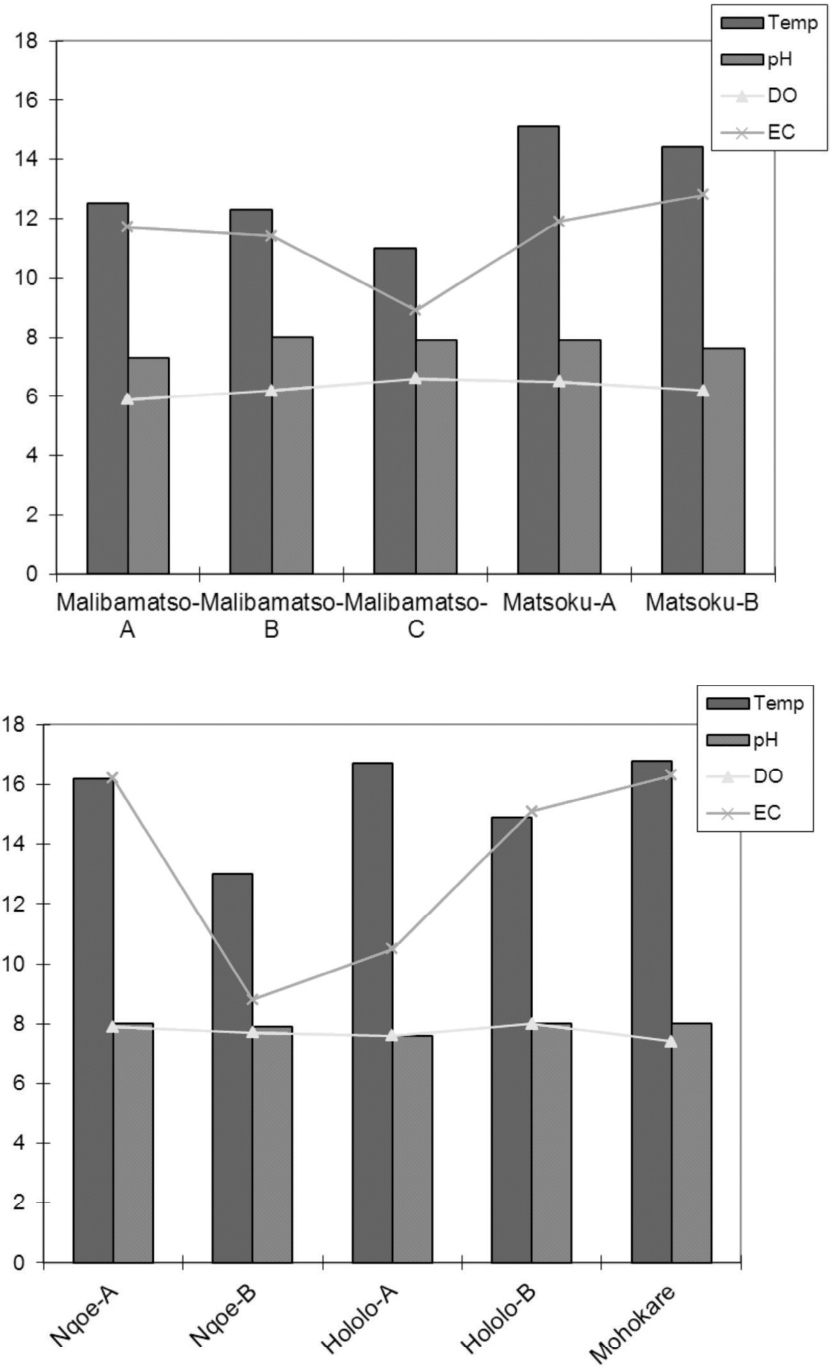

Fig. 7. Water temperature (°C), pH, dissolved oxygen and EC (μs/cm) in watersheds.

4. Conclusions

The Orange-Senqu River basin in Lesotho shows seriously increasing anthropogenic impacts, mainly registered in the lowland AEZ. Mountain wetlands in upper part of that catchment, are very important sources of the river system. However, increasing impact of grazing on stream water quality is evident. The future watershed development projects should take into account the needs, constraints, and practices of local people.

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Part IV

Effects of Forest Practices and Climate Change on Hydrological Phenomena

12

Forest Ecosystems Changes and Hydrological Processes in Western Carpathians

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1. Introduction

The total mountain land of Poland (over 500 m a.s.l.) occupies only 3% (about 10,000 km^2) of the total territory of Poland. Despite small area, mountain areas in Poland play an important role in water management: contribute to 30% of the water resources, mainly rivers. Surface water resources (measured as an average river runoff in many years), being 28% of the precipitation sum, are 1660 m^{3}year^{-1} per capita. This is about three times less than the average European surface water resource, which places Poland in the group of ten European countries with the smallest water resources. Polish water resources depend on the precipitation, which is variable in time and space. The average precipitation sum slightly exceeds 600 mm yearly, but in central Poland it is only 500 mm, and in the high mountains up to 1500 mm. The average precipitation sum varies during the year and also in many years' periods and during wet years can be two times higher than in dry years. The precipitation variation in time and space causes different weather phenomena. One of them is the drought causing crop failure, an increase of forests fire risk and the drying up of wells. On the other hand, sudden thaws and downfalls occur causing periodical water excess and dangerous floods almost in the entire country. Floods in the Vistula basin occur on the average once in five years and in the Odra basin once in every 7 to 10 years.

Mountain forests in Poland occupy the northern part of the Carpathians and Sudeten, extending about 700 km along the southern Polish border and are diversified by climate, soil, vegetation and anthropogenic impacts. The maximum elevation timber line is about 1650 m a.s.l. (Tatra Mts).

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The species composition of the mountain forests in Poland significantly differs from the primeval because of past management (monoculture plantations, lack of natural tree regeneration, and the type of cutting system). In the Sudeten the coniferous sites occupy 46% of forest area and the current percentage of spruce stands area is about 70% but fir stands only 0.3%. In the Carpathians the coniferous sites occupy only about 3% and the average percentage of spruce, fir and pine stands reaches about 55% but in some of forest inspectorates more than 90% (Niemtur, 2007). To the main factors that has the influence on the health of mountain forests belongs also an air pollution, weather condition, insects and fungi. Effects of air pollution are heavy in consequences for the Polish forests and for mountain forests in particular.

The most harmful events in Polish Mountains took place in 1980's in Izerskie Mnt (Western Sudeten), between the 70's and the 80's of the last century, a process of forest decline reached the size of an ecological disaster and 160 km^2 was deforested by acid rains as a main reason. Spruce stands decline on area of Izerskie Mnt in seventies was a first so great ecological disaster in Europe. By this time Norway spruce in Silesian and żywiec Beskid (Western Carpathians) was still famous in Europe for the highest quality with volume above 1500 m^3 ha^{-1} ("Istebna" provenance). It was a result of characteristic for Beskids wide fertility scale of forest sites and long history of forest management. Ten years after disaster in Sudeten, similar processes of spruce stands decline begin also in Beskids, located about one hundred kilometres on East. Artificial spruce stands occupy there above 65% of forest areas and were also strongly influenced by air pollutants transported mainly from Upper Silesia and Ostrava industrial regions. After decreasing of air pollutions the climatic changes were intensifying arduous for spruces, especially for older trees. Therefore artificial spruce stands in Beskids are under multifactor stress from many decades (Bytnerowicz et al., 1999; Staszewski et al., 1999; Niemtur, 2005).

The species composition, not adequate with forest sites, together with abiotic factors like air pollutions and climatic changes, leads to urgent necessity of stands conversion in Polish part of Western Carpathians. It will be long time process, even at cooperation with nature, and will lead to new hydrological conditions in mountain forest watersheds. Consequences of these changes for quality and quantity of water outflow in mountain watershed are main problems discussed in this paper.

2. Material and Methods

The aim of the investigation was to evaluate the changes in the basic components of a catchment's water balance in the mountain watershed affected by decline of spruce stands. Hydrological investigations were carried out in the period 2000-2008 in the Bystra torrent watershed in Węgierska Górka Forest Inspectorate (Silesian Beskid), where process of spruce stands decline appeared first in Carpathians at the beginning of nineties last century. Watershed of Bystra torrent is located in upper part of the massif of Barania Mts. (1214 m a.s.l.). The torrent is left inflow of the Sola River.

The catchments were equipped with measurement facilities to register selected hydrological parameters of water cycling: limnigraphs for water level measurements, spillways for flow rate measurements and pluviometers for bulk precipitation measurements (Pierzgalski et al., 2009). The general characteristics of the studied catchments are given in Table 1. The measurement of outflow were made in two subcatchments (Fig. 1).

Table 1: Basic characteristics of Bystra watershed in Silesian Beskid

Location	*Forest compartments*	*Watershed area [ha]*	*Length of torrent [m]*	*Altitude m a.s.l.*	*Sites**	*Stand density*
Forest Inspectorate: Węgierska Górka,	176–191 196–199	437	13,200	720–1214	HMCF MCMF MMF	0.0–0.7
Forest: Sikorczance						

HMCF - High mountain coniferous forest
MCMF - Mix coniferous mountain forest
MMF - Mix mountain forest

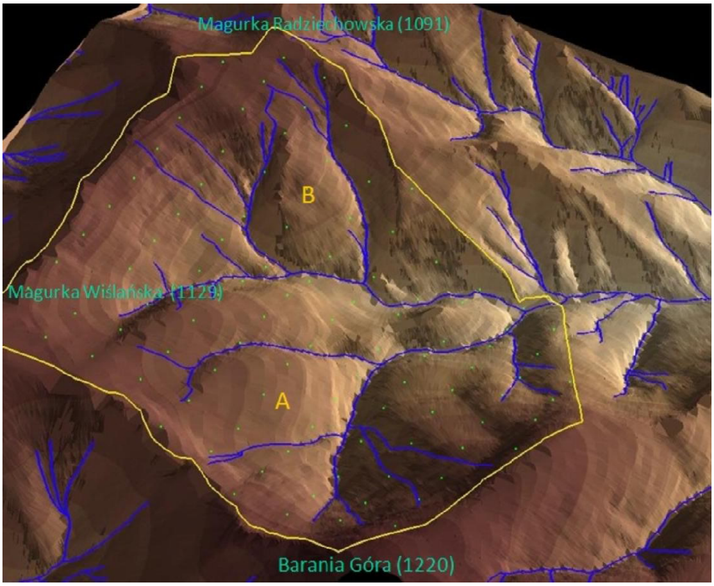

Fig. 1. Digital model of Bystra watershed with two subcatchments A and B.

Analyses of the quality of precipitation and torrent's water were conducted in the period 2000–2008. Samples of rain water were collected each month with collectors installed in an open area at a distance of 150 m from the forest wall. The range of analyses, applied methods and apparatus were following: pH of waters (digital pH meter), Ca, K, Mg, Fe (atomic spectrophotometry), NO_3^-, SO_4^{2-}, NH_4^+ (ion chromatography), and Pb, by atomic absorption in the graphite tray.

Data of quantities of sanitary cutting and change in ecosystem of declining forestry were also collected.

3. Results and Discussion

The volume of sanitary cutting in the period 2003-2010 in six forest inspectorates are shown in Fig. 2 (Silesian and Zywiec Beskid). Dynamics of spruce stands decline in Beskids currently depend on meteorological conditions. Especially important are long periods of the drought which is a negative influence on vitality of the spruce and is favorable to gradations of bark beetles. It was observed that decreasing tendency with volume of dead spruces in 2010 but volume of threatened old spruce stands in Beskids forest inspectorates is still so great that it is only a bomb with delayed ignition (Fig. 2).

The dynamics of spruce stands decline on the area of watershed Bystra by last 10 years is shown in Figs 3 and 4. Recently about 90% of spruce stands were cut because of sanitary needs. Open area was restored after removal of stands by artificial regeneration mostly beech and fir. Natural regeneration with birch, rowan, willows and spruce can be also observed. By next few dozens of years or more these culture will develop transitory biocenosis between

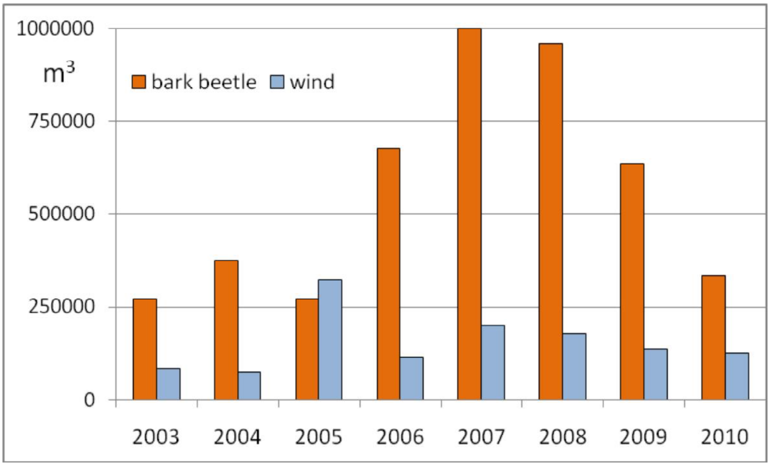

Fig. 2. Sanitary cutting in six forest inspectorates (63,000 ha) in Silesian and Zywiec Beskid during eight years.

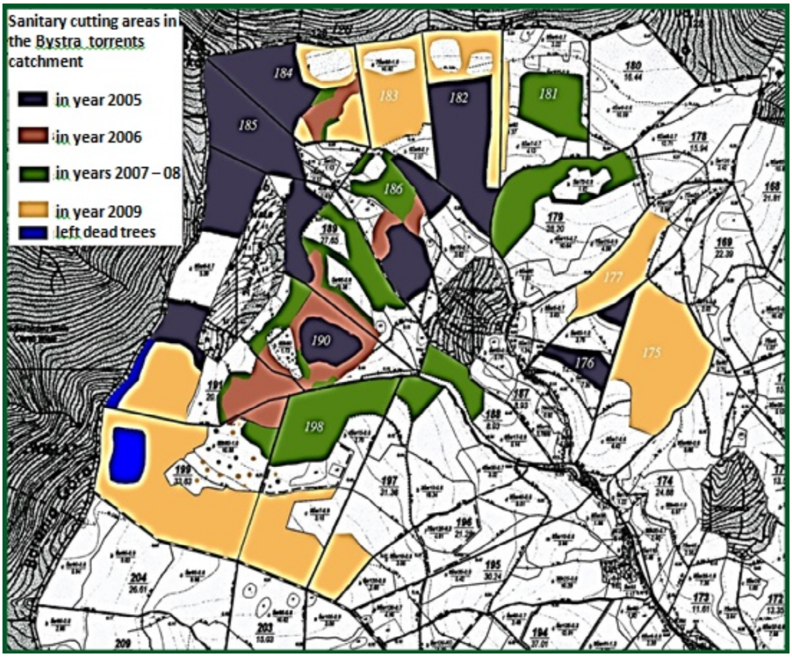

Fig. 3. Decrease of forestage in the Bystra torrents catchment area (Silesian Beskid).

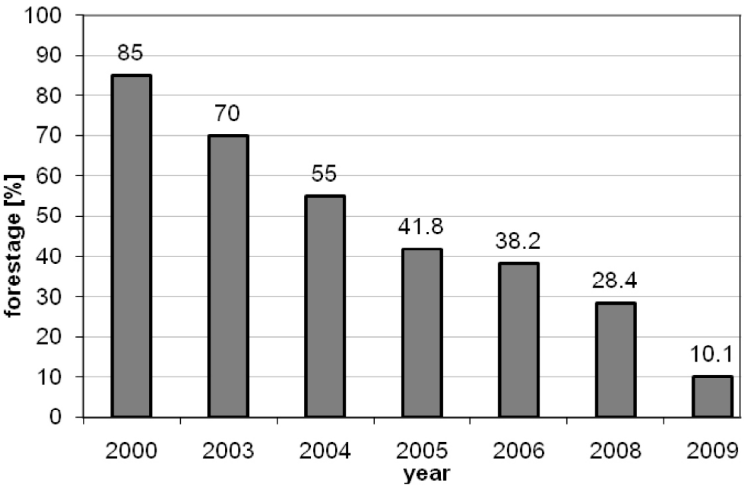

Fig. 4. Decrease in forestage in Bystra torrent watershed.

dying back spruce stands and stands with adequate species and age structure. The current structure and the type of species composition of these regenerations are determined by calamitous decline of stands and by the need to regenerate huge deforested areas in short time.

Hydrological processes will be influencing in the significant way by changes watched in the structure of forest biocenosis in Silesian and żywiec Beskid. It refers to both quantitative and qualitative features of water in outflow from these forest areas. Our investigations confirm these changes like results in numerous publications from other mountain massifs.

Yearly measured values of precipitation and runoff in Bystra torrent watershed are shown in Figs 5 and 6. There was observed, during nine years of progressive dying out of trees, the general trends of decreasing rainfall in months of the summer half year as well as increasing of runoff in months of the winter half year. At the same time an increase in the runoff coefficient was observed (Fig. 7).

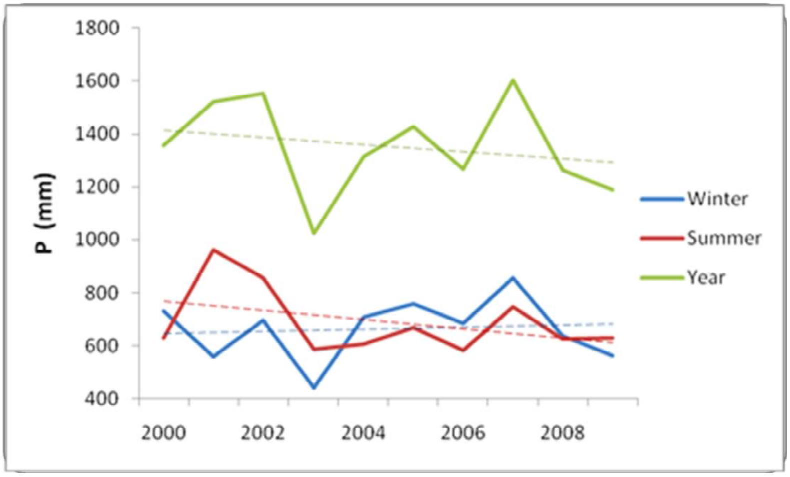

Fig. 5. Annual precipitation value in Bystra torrent watershed.

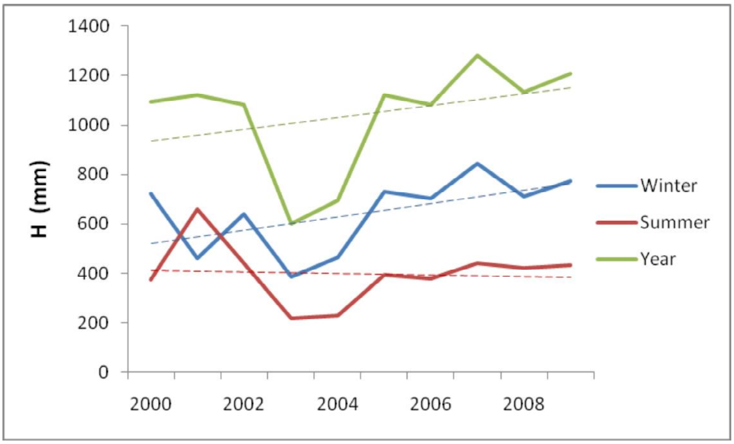

Fig. 6. Annual runoff in Bystra torrent watershed.

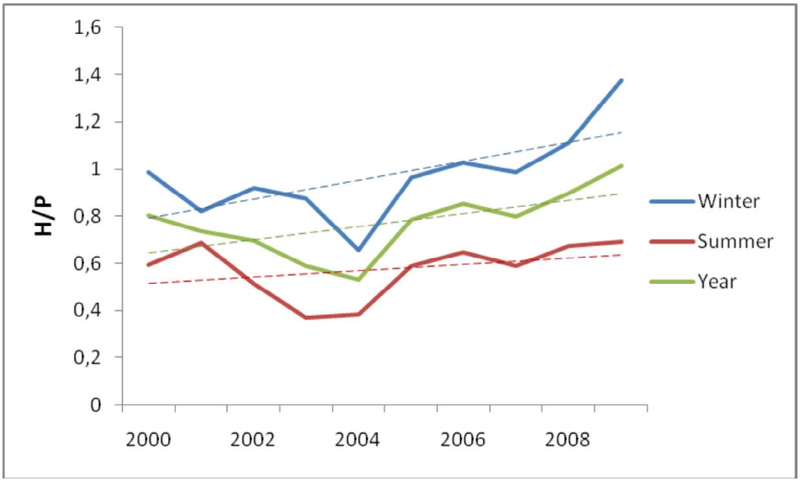

Fig. 7. Change of runoff coefficient in Bystra torrent watershed.

Decline of 90% forest spruce stands on Bystra watershed area caused significant changes within ten years in chemical features of outflow water, presented in Table 2. Substantial changes occurred in outflow of macro components (Ca, K, Mg), over the half smaller concentration of sulphur compounds and the increase in the concentration of nitrates (Fig. 8). Similar dynamics of changes was found in investigations in Slovak Rudawy (Valtyni and Lalkovic, 1995). Authors stated that the outflow of water from a small forested catchment (1 km^2) contained four times less nitrogen in comparison to a non-forested catchment (1.4 km^2). However the concentration of sulphur was higher in the outflow from forested watershed (covered by spruce stands). They also stated in this water over half smaller concentrations of the magnesium (2.14x) and of the calcium (2.23x) compounds.

Other consequences in the changes of stands structure were characterized by Kantor (2004). According to him due to the higher interception and more favourable runoff balance during winter months, spruce stands are more

Table 2: Average concentrations of chosen elements in water during the vegetation period (May to Oct., 2002 and 2009) in Bystra watershed in the Silesian Beskid

Water/year	*pH*	*Ca*	*K*	*Mg*	*S-SO$_4$* [mg/l]	*Cl$^-$*	*N-NO$_3$*	*N-NH$_4$*	*Fe*	*Pb*
Runoff 2009	7.29	9.79	0.978	1.552	2.33	0.98	1.03	0.079	0.017	0.002
Runoff 2002	7.17	7.51	0.717	1.218	5.10	1.47	0.67	0.087	0.012	0.003
Precipitation 2002	4.53	0.45	0.583	0.051	1.15	0.95	0.57	0.539	0.024	0.058
Precipitation 2009	4.78	0.75	0.292	0.091	1.96	0.50	1.76	0.451	0.013	0.008

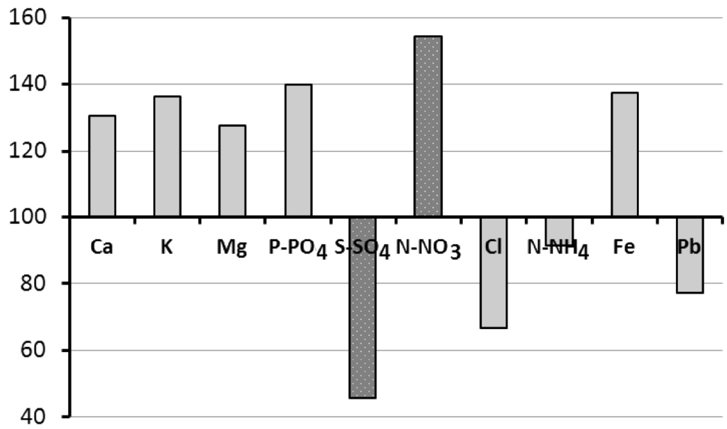

Fig. 8. Changes in concentrations of chosen elements in outflow water from Bystra catchment.

effective than beech stands from qualitative water-management aspects. With respect to the very low interception of beech, the total consumption of water in mature broadleaved stands is as much as 150 mm lower than that of mature spruce stands. From the quantitative water-management point of view, beech stands are markedly more advantageous than spruce stands.

Accelerated changes in the structure of stands are being characterized from many mountainous massifs in numerous papers. Only in Polish part of Carpathians, participation of the spruce lessened in the last forty years over 50% with still growing participation of the beech and the fir. It is possible in accordance with forecasts of climate changes to predict the more increase in participation of deciduous species in future stands in Sudeten and Carpathians.

A study conducted in Austria showed that the length of the growing season in the alpine area increased by 25 days between 1961 and 1990, resulting in an improvement in net primary production of Norway spruce by 5–10%. Global warming is likely to increase the frequency and intensity of extreme events, like drought or heavy rain, (Hasenauer et al., 1998). Mountain ecosystems are strongly interlinked with the hydrological cycle, which was fundamentally altered through global warming over the past several decades. In the southern. Alps, groundwater levels in some regions dropped by 25% over the past 100 years (Harum et al., 2007).

Changes predicted in the structure of mountain stands are resulting from two reasons: naturalization of the artificial stands within conversion in modern forest management and at the same time climatic changes. Conversion of stands is the managed process but results of climate changes are difficult for foreseeing. If we accept, on the basis of IPCC forecasts, the average temperature of air will increase within the nearest decades at least 2° C, it is able in conditions of the Carpathians and the Sudeten mountains, to raise the range of

Table 3: Climatic zones in Tatra Mnt (Hess, 1965) with current forest zones and predicted forest zones after changed temperature according to forecast of IPCC

Climatic zone	*Aver. temp. of air*	*Altitude*		*Current forest zones*	*Predicted forest zones*	*Predict. temp. according IPCC**
		Slopes N	*Slopes S*			
6. Cold	–4-2 ºC	from	from	Alpen Zone		–2-0 ºC
5. Moderate cold	–2-0 ºC	1850-2200	2050-2350	Meadow M.Z.	Pinus mugo	0-2 ºC
4. Very cool	0-2 ºC	1550-1850	1650-2050	Pinus mugo	Upper M.Z.?	2-4 ºC
3. Cool	2-4 ºC	1150-1550	1200-1650	Upper M.Z.	Lower M.Z.	4-6 ºC
2. Moderate cool	4-6 ºC	to 1150 m	to 1200 m	Lower M.Z.	Uphils	6-8 ºC
1. Moderate warm	6-8 ºC	–	–	Uphils		8-10 ºC

The report of IPCC anticipates that in the course of the next 100 years the average yearly air temperature will increase by 2-5 ºC (EEA Report, 2009).

forest zones even one floor, Table 3. It means serious changes in vertical ranges of trees and structure of the existing forest ecosystems, and in consequence the changes of hydrological processes for unprecedented scale.

4. Conclusions

1. Three main factors decided the present condition of forests in the Polish mountains: schematic silviculture in the past, air pollution and climate changes. Recently, the main threats of forest in Polish part of Carpathians are long periods of droughts which are an indirect reason of deterioration of ecosystem's health which cause decline of forests due to the pests and diseases. Climatic anomalies contribute to recently observed serious process of forest decline specially in the Silesian and żywiec Beskid which belongs to the Western Carpathians.
2. The hydrological investigations in Bystra torrent watershed proved that after the large-scale deforestation, the annual runoff from mountain watersheds increase about 20-30%. It has been also observed that the increase of runoff coefficient increase frequency of peak discharges and time change of discharge reaction on precipitation.
3. Dying back of spruce stands caused significant changes within ten years in chemical features of outflow water. Substantial changes occurred in outflow of macro components (Ca, K, Mg), and over the half smaller concentration of sulphur compounds at the increase in the concentration of nitrates.

4. Predicted climate changes in next decades means serious changes in vertical ranges of trees and structure of the existing forest ecosystems, and in consequences the changes of hydrological processes for unprecedented scale.
5. In order to prevent spruce dieback in the Silesian Beskid we have to increase the retention of basic elements like Mg and Ca by stands conversion adequate to site conditions and biodiversity requirement.

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Hydrological Effects of a Large Scale Windfall Degradation in the High Tatra Mountains, Slovakia

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1. Introduction

Influence of deforestation on hydrological cycle has been a subject of numerous studies since the beginning of the 20th century. A temporary increase of discharges after deforestation was typically reported (e.g. Bosch and Hewlett, 1982), but the measured data often show that "… flood and erosion control functions of the forests become to be evident but only in a limited way…" (Bíba et al., 2006). A recent review of the articles dealing with the influence of forests on runoff can be found e.g. in Kostka and Holko (2006). Extraordinary wind induced deforestation which took place on 19 November 2004 in the High Tatra Mountains initiated a multidisciplinary international research. A number of scientists studied the consequences of such an unusual disturbance at different scales and at sites with different follow-up forestry management. The results obtained by more than 70 foresters, biologists, chemists, soil scientists, hydrologists, geomorphologists and other experts were presented at several specialized seminars (Fleischer and Matejka, 2007, 2008; Homolová and Fleischer, 2009).

Hydrological effects of the deforestation were analysed in the small catchments of the upper Poprad river which drains the affected area (Holko et

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al., 2009, 2009a). The analysis of water balance, runoff minima and maxima, number of runoff events and their selected characteristics (e.g., peakflows, concentration times), runoff coefficients, rainfall-runoff relationships, flashiness index and baseflow did not show a dramatic change in the water balance and runoff regime in catchments with areas ranging from 17 to 315 km^2. An example of runoff variability in selected catchments before and after the deforestation is shown in Fig. 1. Separate analyses and measurements of interception, soil characteristics and soil moisture were performed at selected sites in the High Tatra Mountains by Kňava et al. (2008), Novák et al. (2008), Novák and Kňava (2009) and Fleischer and Fleischer (2010). Since the soils generally play the key role in hydrological response of a catchment, it is assumed that better knowledge of soil properties helps to explain the

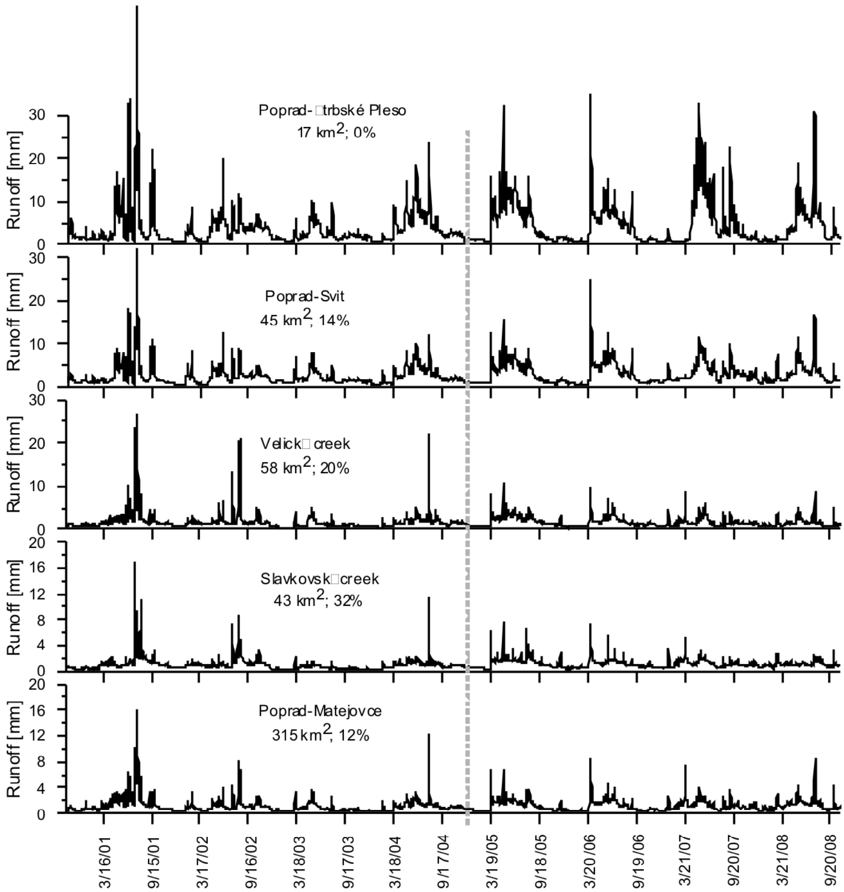

Fig. 1. Daily runoff in selected catchments of the upper Poprad river basin before and after the deforestation (indicated by the grey dashed vertical line); hydrological years 2001-2008; [%] - deforestation caused by the wind; [km^2] - catchment area.

hydrological regime. It can also be expected that the changes in hydrological regime, which are not apparent at the scale of small catchments (tens of square kilometres), might be detectable at the point scales or the scale of headwater areas (several square kilometres).

The objectives of this article are:

- integration of soil science knowledge to better understand the hydrological regime in the High Tatra Mountains after the deforestation;
- comparison of hydrological responses of headwater and small catchments; and
- analysis of hydrological responses of the headwater catchments during the event at the beginning of June 2010 which occurred after an extremely wet May 2010.

2. Material and Methods

Most of the interdisciplinary research of the windfall effects in the High Tatra Mountains took place at four selected research plots (Fig. 2). The area of the plots is approximately 100 hectares. They were established in 2005 to characterize natural and vegetation conditions, degree of disturbance and the follow-up forestry management in the disturbed area. All plots are situated in the forest community *Lariceto-Piccetum*. The site denoted as NEX was left

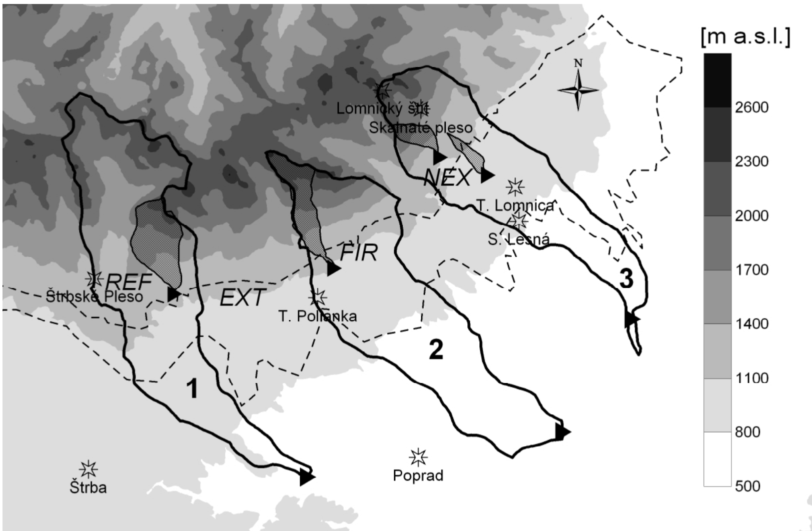

Fig. 2. Nested catchments and research plots REF, EXT, FIR and NEX; 1 – Poprad-Svit and Vel'ký Šum (diagonally crossed) catchments, 2 – Slavkovský creek and Slavkovský creek-fire (diagonally crossed) catchments, 3 – Skalnatý creek and Škaredý and Jazierkový creeks (both diagonally crossed) catchments; stars and names show precipitation stations; the dashed line represents the area deforested by the wind; the triangles show locations of stream gauges.

without any forestry intervention. Traditional forestry management, i.e. removal of the large woods and man-made aforestation was applied at site EXT. Partial removal of the woods took place at site FIR and the site was then affected by the fire on 31 July 2005. Site REF is the reference site which was not affected by the windfall.

This chapter builds on a combination of information from different scales, i.e. point measurements of soil characteristics at a soil pit, spatially distributed soil moisture data at research plots and spatially integrated runoff data from small and headwater catchments.

Physical and hydrophysical characteristics of soils were determined by the data from a soil pit excavated at the site FIR. Proportion of stones in the soil was determined. Undisturbed samples of the soil matrix were collected into metallic cylinders with volume 100 cm^3. The samples were then used to measure saturated hydraulic conductivity, retention curves, bulk density and porosity in a laboratory. Saturated hydraulic conductivity was measured by the falling head method. Soil water retention curves (drainage branch) were determined by the plate method, up to the pressure 0.1 MPa; this range covers majority of retention capacity of the soils from FIR site. Bulk density was evaluated from the weight of dry soil. Vertical distribution of soil porosity was calculated using soil bulk density and specific soil density.

Soil moisture was measured once per hour at all four research plots by means of the Delta-T Theta ML2x sensors located permanently at depths 8, 16 and occasionally also at 32 cm. The measurements were supplemented by repeated manual measurements performed by a modified sensor allowing mobile measurements at depths 8, 16, 32 cm and on the soil surface. Soil moisture content determined by gravimetric method was used to check the measurements given by the electronic sensors. Spatial variability of soil moisture content was measured by the capacitance probe (Aquaterr 300). The probe provides data on saturation of pores by water in the upper 15-20 cm of the soil. Low saturation and small resistance to the insertion of the probe to a soil indicated the presence of pores. Repeated measurements at the same points were performed at six transects at each research plot. The transects have a stellar shape and the distance of individual points is 10 m. Three measurements were made at each point. Manual measurements were carried out every two weeks.

Four gauging stations to measure stream discharges in the headwater catchments were established in 2007. The headwater catchment have areas 0.67-4.59 km^2 (Table 4) and are situated near the above mentioned research plots. They are nested within the small catchments monitored by the standard network of Slovak Hydrometeorological Institute (Fig. 2). Such a setup allowed *comparison of runoff responses and water balances* at two scales. Water levels of the streams flowing from the headwater catchments were measured at the 10-minutes time step interval. Precipitation data needed to calculate catchment precipitation were measured at eight precipitation stations shown in Fig. 2. Altitude gradient was used to calculate the annual precipitation for the water balance comparison. We have compared hydrological years 2008 and 2009. Hydrological responses of the headwater catchments after a heavy rainfall following extremely wet conditions in May 2010 were also compared using the runoff data from the headwater catchments and precipitation from several raingauges (both standard gauges measured daily and the tipping bucket gauges providing instantaneous data distributed at higher altitudes).

3. Results and Discussion

Soil Properties

The soil type at the site FIR was classified as Dystric Cambisol developed on stone centered polygons (Gömöryová et al., 2008). However, at the site of our excavation the parental rock is close to moraine. Consequently, the soil contains a lot of stones. The most abundant fraction of the skeleton was classified according to its diameter (75–254 mm) as gravel (Soil Survey Staff, 1975). Bärwolf (2006) found out that the soil profile is relatively homogeneous along its depth and according to the USDA classification it represents the gravelly sandy loam (Soil Survey Staff, 1975). The soil at the site FIR was found similar to those occurring at other three research plots (REF, EXT, NEX) taking into account the parental rock and texture. Three basic textural classes of the soil matrix were found at the FIR site, i.e. sand, silt and clay. Their proportions slightly varied with the depth (Table 1).

Table 1: Basic texture characteristics of the soil matrix at the site FIR (from data of Bärwolf, 2006)

Depth [cm]	*Soil fraction name*	*Diameter of particles [mm]*	*Proportion of soil fraction; mean (range) [%]*
0-110	Sand	> 0.5	60 (55-65)
	Silt	0.05-0.002	28 (26-29)
	Clay	< 0.002	12 (7-15)

The proportion of stones (particles with the diameter above 1 cm) in the soil was estimated for separate soil layers. The stones were rounded and had the diameter of 1-20 cm. More than 50% of the stones had diameter 3-10 cm. The upper 10 cm of the soil contained only about 10% of stones. However, the amount of stones increased quickly with the soil depth. Stone contents at depths 20 cm, 40 cm and 60 cm were 30%, 40% and almost 50%, respectively. The high proportion of stones does not only influence the water transport through the soil profile, but also decreases the amount of water which can be retained in the soil.

Saturated hydraulic conductivity (*K*) of the soils for soil layers 0-5 cm, 10-15 cm and 40-45 cm was 239-1003 $cm.day^{-1}$, 181-321 $cm.day^{-1}$ and 670-1290 $cm.day^{-1}$, respectively. The results showed generally high *K* (e.g. compared to agricultural soils) and its significant variability even in the same layer. With high values of saturated hydraulic conductivity in soil, there is lower probability of overland flow generation. Modelling experiments showed that the high content of stones in the soil may decrease the effective hydraulic conductivity (by up to 50%) of the soil. However, it is not significant for the infiltration capacity of the soil which remains high (Fig. 3).

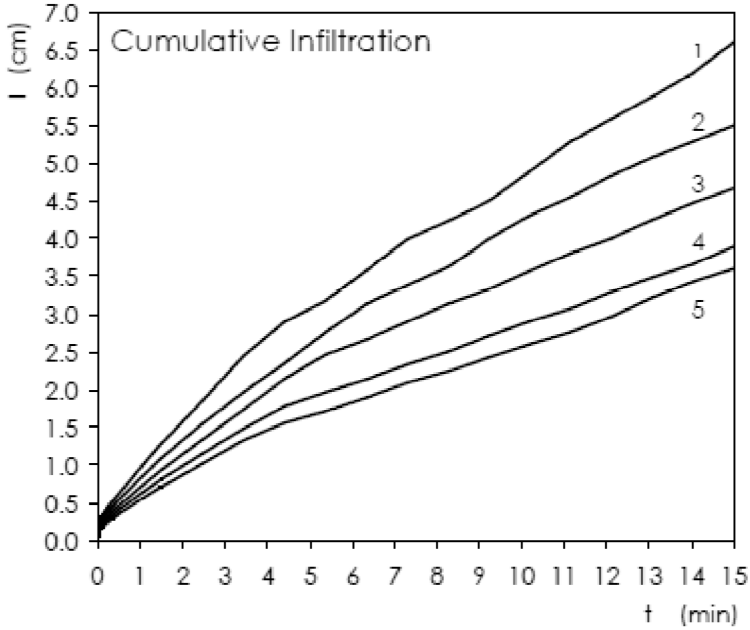

Fig. 3. Simulated cumulative water infiltration into a stony soil with different relative stones contents R_v (proportion of stones in the soil): 1 – R_v = 0; 2 – R_v = 0.1; 3 – R_v = 0.2; 4 – R_v = 0.3; 5 – R_v = 0.4 (Novák and Kňava, 2009)

Bulk density and porosity of the soil matrix at the site FIR are shown in Table 2. Porosity was calculated also from soil densities and specific soil densities for all research plots. The mean values for all four plots varied between 65% and 71%. Porosity increased in the order EXT<FIR<REF<NEX. Upper soil layers had higher porosity at all sites.

Soil water retention curves determined for the FIR site indicated small differences in the soil matrix at different depths. Extremely high water content at soil saturation (up to 68% of soil volume) means the soil has a very high retention capacity. The soil water content at the soil water potential corresponding to "permanent wilting point" is relatively high, too. This is an

Table 2: Vertical distribution of the bulk density of the soil matrix at site FIR

Depth [cm]	*Bulk density [g.cm^{-3}]*	*Porosity [-]*
0-5	0.36	0.86
10-15	0.88	0.66
45-50	0.81	0.69

interesting finding since such values are typical for relatively heavier soils, e.g. silt. The extremely high retention capacities of soil matrix at both saturation and wilting points are caused by low compaction of the soil and the relatively high content of organic material. However, the total retention capacity of the soil profile is decreased by the large amount of stones described above. As a result, the real retention capacity of the soil profile can be characterized as relatively small, particularly at higher depths, where the stone content is high.

Soil Moisture

The results of soil moisture measurements before 2009 can be summarized as follows.

Trend of reduction of the soil organic layer was observed at all sites with disturbance. Significant reduction of organic matter was observed at the EXT site. Lack of humus at the site FIR caused by the fire resulted in significantly reduced water capacity of the soil. Soil moisture at the site therefore increased only after the rainfall and decreased very quickly. Although the highest soil moisture content and its lowest seasonal variability during the vegetations period were measured at the NEX site, statistical analysis indicated that the differences among the sites were not significant. Only in the original forest unaffected by the windfall (REF) the soils were clearly drier compared to other sites.

Measurements in the year of 2009 indicated a changing situation. The highest soil moisture content was generally still measured at the site NEX (Fig. 4). However, compared to previous years the soil moisture at the site EXT did no vary so much during the year. It was probably caused by the intensive succession of the grass vegetation (*Calamagrostis villosa*). It helped to form a thick layer of roots, dead and live plants which prevented higher evaporation from the soil. Site FIR is overgrown with *Chamaenerion angustifolium* which did not form such a layer as *Calamagrostis villosa*. The variability of soil moisture at the site FIR was thus higher than at the site EXT.

Figure 4 also shows the differences in soil moisture at the depths of 8 cm and 16 cm. Soil moisture at the EXT site typically increased with the depth. Soil moisture content in the upper layer of the soil was higher than in the lower one just after heavy rainfalls. Different situation was found at the NEX site where the soil moisture content in the upper soil layer was always higher than in the lower one.

Soil moisture content at the site REF, i.e. in the forest unaffected by the

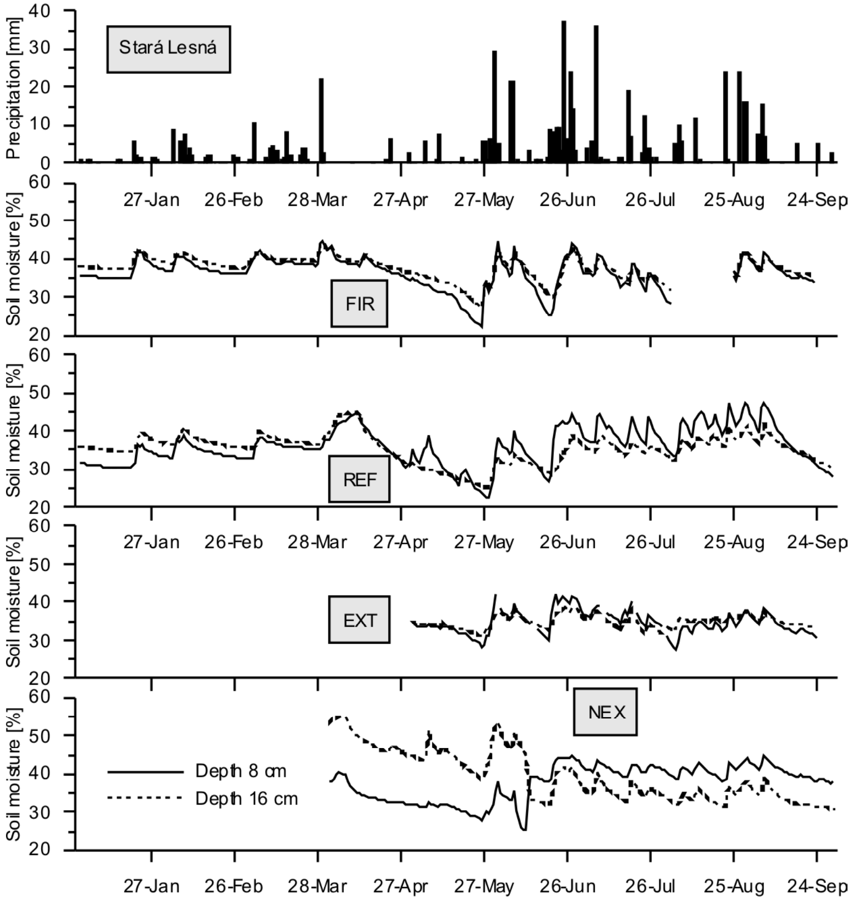

Fig. 4. Daily precipitation at Stará Lesná and soil moisture contents at the research plots with different forest management from 1 January to 30 September 2009.

windfall, was similar at the two measured depths until the beginning of the vegetation season. Then, the soil moisture in the lower soil layer was smaller than in the upper soil layer due to transpiration (Fig. 4).

Mean values of soil saturation measured by the capacitance probe are given in Table 3. Minimum value was measured at the site REF during the dry period. Maximum value was measured at the site EXT after rainfall.

Runoff Regimes in Headwater and Small Catchments

Basic characteristics and the water balance data for the nested catchments in hydrological years 2008 and 2009 are given in Table 4. The data show that in some cases (e.g. the Poprad-Svit catchment in 2008, the Škaredý creek catchment in 2009) the calculated annual catchment precipitation was too small compared to measured catchment runoff. Although the annual precipitation was very well correlated with altitude, the results indicate that

Table 3: Mean saturation of the soil by water (*S*), its standard deviation (*SD*) and coefficient of variation (*Cv*) at the research plots in 2009

Site	*Date*	*S [%]*	*SD [%]*	*Cv [%]*
EXT	19 July	81.7	10.9	13
	28 August	60.5	15.3	25
REF	5 June	63.0	12.0	19
	10 July	67.0	8.9	13
	15 July	73.3	15.0	20
	24 August	65.6	11.1	17
NEX	1 July	70.3	10.9	16
FIR	23 June	73.8	11.7	16
	2 July	60.1	12.2	20
	10 July	70.7	11.7	17
	24 August	67.2	11.8	18

Table 4: Selected characteristics of the headwater and small catchments in hydrological years 2008 and 2009

Catchment	*A [km²]*	*H [m a.s.l.]*	*P [mm] 2008/2009*	*R [mm] 2008/2009*	*R_c [-] 2008/2009*
Vel'ký Šum	4.6	1592	1277/1394	624/580	0.49/0.42
Poprad-Svit	45.6	1396	1134/1235	983/910	0.87/0.74
Slavkovský creek-fire	3.7	1759	1400/1532	563/591	0.40/0.39
Slavkovský creek	43.2	1001	841/907	371/373	0.44/0.41
Škaredý creek	1.1	1564	1256/1371	990/1371	0.79/1.00
Jazierkový creek	0.7	1041	870/940	441/257	0.51/0.27
Skalnatý creek	33.7	1074	894/968	626/519	0.70/0.54

altitude gradient was not suitable to provide correct estimates of catchment precipitation for the highest parts of the catchments where no precipitation stations exist. Runoff coefficients in the catchments affected by deforestation (Slavkovský creek-fire, Jazierkový creek) are not higher than in the unaffected catchments (Ve1'ký Šum, Škaredý creek). The large decrease of runoff from the Jazierkový creek catchment in 2009 compared to 2008 may be related to the reconstruction of skiing slope near the water divide of the catchment.

Figure 5 shows an interesting runoff regime in the Slavkovský creek-fire catchment. While the runoff at the outlet of the whole catchment (Slavkovský creek) responds to precipitation in a common way (increase after precipitation, decrease during the rainless periods), runoff regime in the headwater catchment (Slavkovský creek-fire) shows a very damped response with no reactions to most precipitation events. Such a runoff regime was not observed in the larger catchments in the High Tatra Mountains. The damped regime with gradual

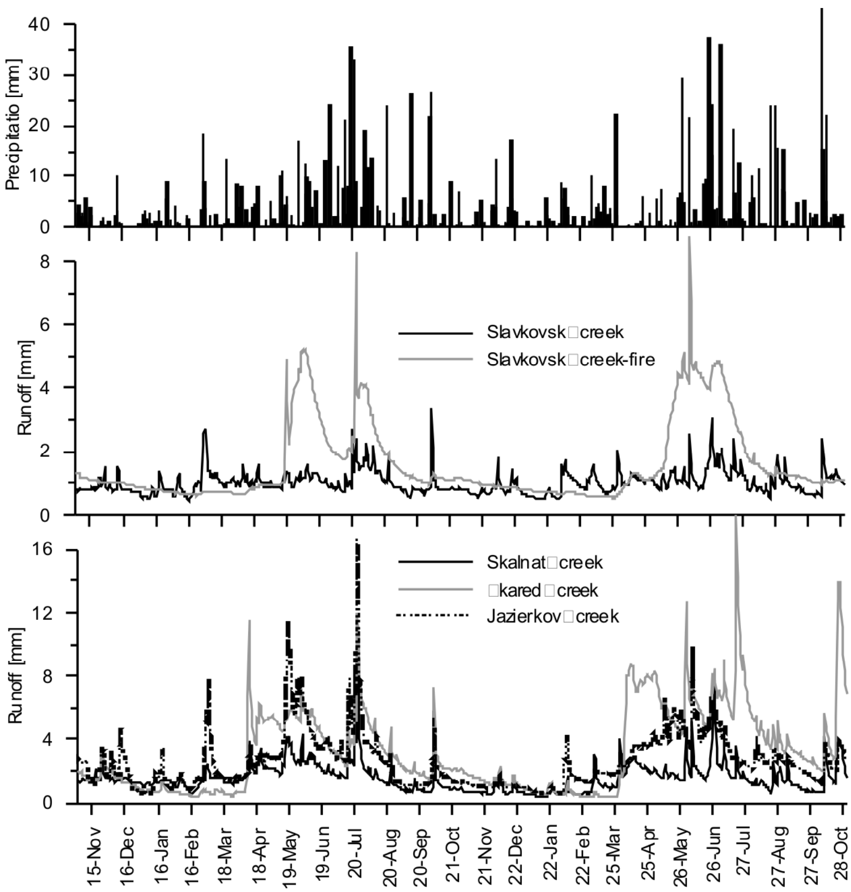

Fig. 5. Daily precipitation at Stará Lesná and runoff from small and headwater catchment in hydrological years 2008 and 2009.

increase and decrease of runoff in a year probably reflects the influence of glaciofluvial sediments (moraines) in the headwater catchments. Runoff in the completely deforested Jazierkový creek catchment was not extremely high compared to the forested Škaredý creek catchment and the whole Skalnatý creek catchment in which both headwater catchments are nested.

May 2010 was extremely wet in Slovakia and also in the High Tatra Mountains region. Precipitation data from stations Stará Lesná (807 m a.s.l., monthly total in May 2010 179 mm) and Skalnaté pleso (1778 m a.s.l., monthly total in May 2010 375.8 mm) show that except two days it was raining every day. The longest available precipitation record in the area exists at station Tatranská Lomnica. It goes back to 1880. The data showed that such a wet May was recorded only once, namely in 1908. Part of precipitation in the second half of May 2010 fell in the highest parts of the High Tatra Mountains as snow. Although there were many floods in Slovakia in May 2010, they did not seriously hit the area of the High Tatra Mountains. However, the heavy rainfall which occurred on 3 June 2010 (daily totals at Stará Lesná and Skalnaté Pleso 44.8 mm and 72.5 mm, respectively) caused an extreme increase of discharges which we wanted to analyse in this article. Our objective was to describe the runoff responses of the headwater catchments during such unusual conditions (a rather intensive rainfall combined with high antecedent soil moisture and snowmelt at high altitudes).

Figure 6 shows that water stages during the peakflow on 4 June 2010 were on an average almost 2-3 times higher than during the extremely wet May 2010. Compared to previous years, the soil moisture contents in May 2010 also reached high values (cf. Figs 6 and 4). Although winter 2010 was snow-poor, the rain-induced runoff event on 4 June was higher than the peak connected with spring snowmelt which occurred in May. The highest increase of the water stage was recorded in the Ve1'ký Šum catchment. The catchment was not affected by the deforestation. However, its large part is situated at high altitudes where some snow from the second half of May was probably still present at the beginning of June.

Water stages during the event at the beginning of June reached extremely high levels which were not covered by current metering during the construction

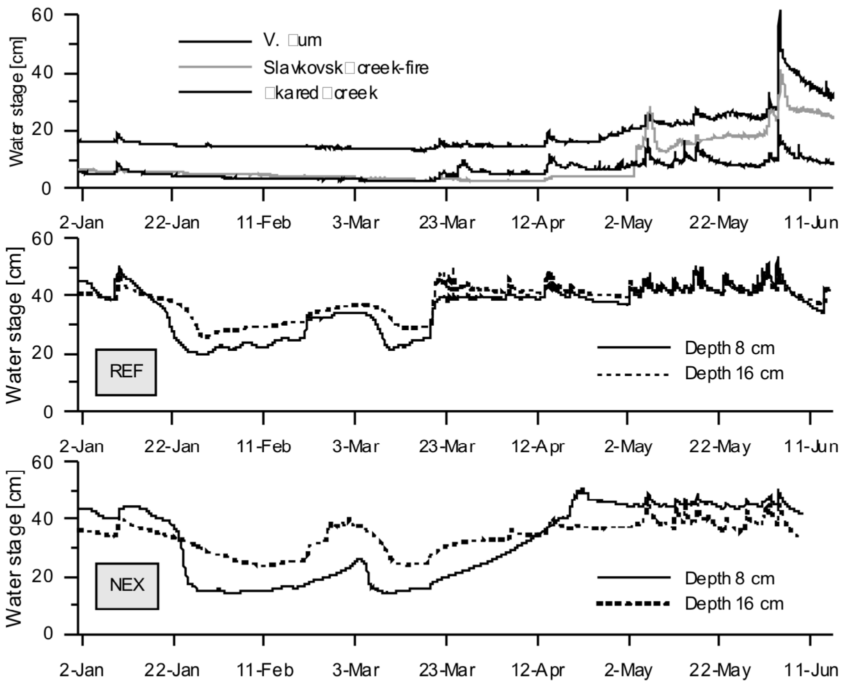

Fig. 6. Water stages in the headwater catchments from 1 January to 15 June 2010 and soil moisture contents at two depths at the nearby reference plots; hourly data.

of the discharge rating curve. The discharge was estimated from the rating curve extrapolated to the high water stages. Water levels indicated that the creeks probably did not flow over the banks of the channels. The extrapolation of the rating curves was therefore based on the relationships between water stage, flow area and mean flow velocity. Runoff in the three headwater catchments and precipitation from two tipping bucket raingauges are shown in Fig. 7. Precipitation data indicate a very high hourly rainfall. Historical data

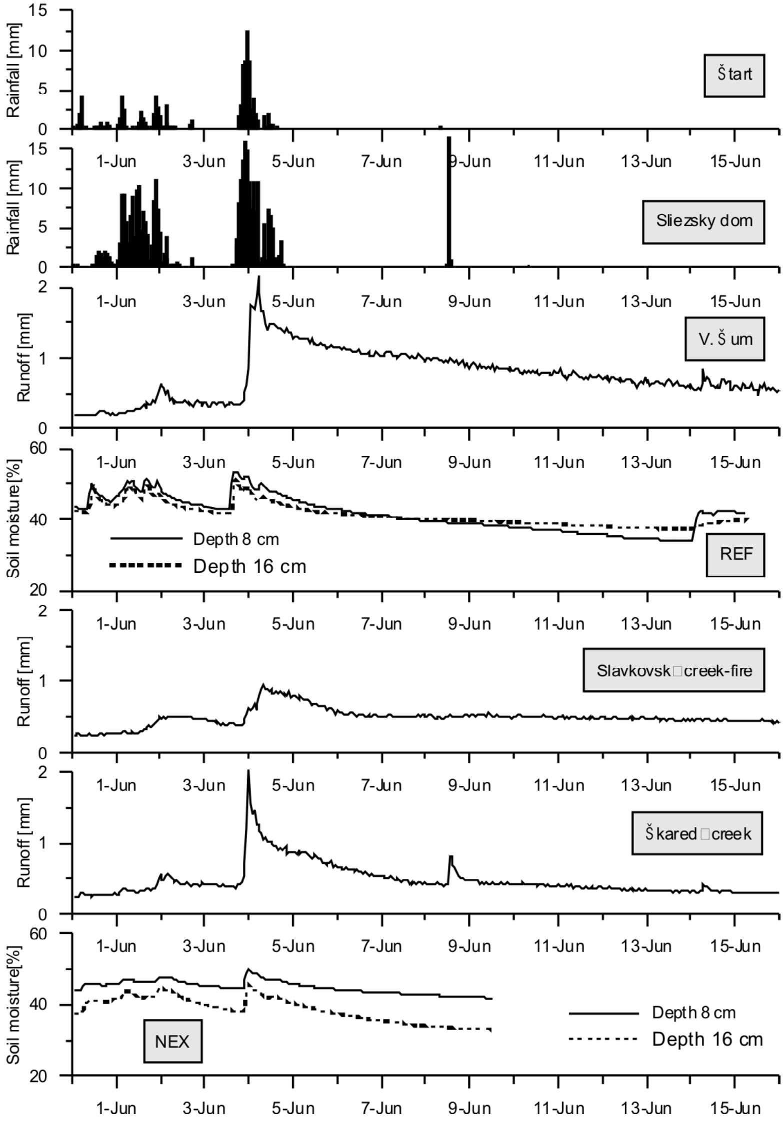

Fig. 7. Hourly rainfall, runoff and soil moisture contents during an extreme event at the beginning of June 2010.

(e.g. Pacl, 1959, 1960) show that much higher rainfall intensities were occasionally observed in the studied area in the past. Yet, rainfall intensities of 10-15 $mm.h^{-1}$ measured in June 2010 do not occur very frequent. It can be concluded that hourly rainfall intensities in June 2010 were not much smaller than those at the end of June 1958 when the largest flood of the 20th century occurred in the studied area (Pacl, 1959). However, daily precipitation totals on 4 June 2010 were much smaller than those on 29 June 1958. This seems to be a decisive factor.

The increase of the water stage on 4 June 2010 (2-3 times compared to the water stage before the event) is comparable with the increase reported for the Belá river in June 1958 (Pacl, 1959).

Runoff data shown in Fig. 7 indicate the differences in runoff generation in the studied headwater catchments. The rainfall event on 2 June caused just a damped response in the Slavkovský creek-fir catchment which is typical for that catchment. A good response reflecting even the change in rainfall intensity (two small runoff peaks) was observed in the Ve1'ký Šum and the Škaredý creek catchments. Soil moisture responded well at both REF and NEX research plots. Rising limbs of hydrographs on 4 June were generally steep in all the catchments and followed the steep increase of soil moisture. Times to peak in the Ve1'ký Šum, the Slavkovský creek-fire and the Škaredý creek catchments were 8, 11 and 3 hours respectively. Time to peak is understood here as the time elapsed between the runoff increase and peakflow. Runoff increase in the Ve1'ký Šum and the Slavkovský creek-fire catchments ceased for short time (3-4 hours) after about 3-4 hours. Then, the second increase was observed and after 2-4 hours the peak runoff occurred. The lag times (the time delay between maximum precipitation and peakflow) for the Ve1'ký Šum catchment, the Slavkovský creek-fir catchment and the Škaredý creek catchment were 7 hours, 10 hours and 1 hour, respectively.

Mean specific discharges during peakflow for the Ve1'ký Šum, the Slavkovský creek-fire and the Škaredý creek headwater catchments were 0.598 $m^3.s^{-1}.km^2$, 0.250 $m^3.s^{-1}.km^2$ and 0.561 $m^3.s^{-1}.km^2$, respectively. For comparison, mean specific peakflow discharges reported by Pacl (1959) for smaller catchments in the High Tatra Mountains during the event in June 1958 (3.3-8.6 km^2) varied from 0.95 $m^3.s^{-1}.km^2$ to 4.1 $m^3.s^{-1}.km^2$ (in most catchments they varied around 3-4 $m^3.s^{-1}.km^2$).

Hydrograph recession in the Ve1'ký Šum catchment was very fast and lasted about 4 hours. Then the delayed subsurface runoff started. It continued for a very long time (more than 10 days). Hydrograph recession resembled to the decrease of soil moisture at the nearby plot REF. Hydrograph recession in the Slavkovský creek-fire catchment had approximately the same intensity for about 38 hours and then the recession practically ceased, although the pre-event runoff value was not reached. Hydrograph recession in the Škaredý creek catchment was similar to that in the Ve1'ký Šum catchment. Fast recession took about five hours. The delayed subsurface flow was shorter than in the

Vel'ký Šum catchment. It would stop approximately after five days if the recession was not interrupted by another event which did not occur in the other two catchments.

It was not meaningful to calculate the runoff coefficients for such a short event using only the raw measured data because an important runoff may have been caused by the rain-on-snow mechanism, i.e. significant amount of water which run off during an event came from snow which was accumulated in the headwater catchments before. Mathematical modelling could be more helpful in explanation of the rainfall-runoff ratios in May and June 2010 than the raw measured data. However, some summary data on runoff and rainfall for the event are given in Table 5.

Table 5: Total runoff from the headwater catchments during the event at the beginning of June 2010 and total precipitation (*P*) at selected stations located near the catchments

Catchment (date of runoff event) (see Fig. 7)	*Runoff [mm]*	*P1 [mm]*	*P2[mm]*	*P3[mm]*	*P4[mm]*
Vel'ký Šum (31 May-15 June)	290.5	92.1	203.1	107.2	341.6
Slavkovský creek-fire (31 May-7 June)	96.6	91.8	172.7	107.0	324.0
Škaredý creek (31 May-8 June)	120.1	91.8	203.1	107.2	341.6

P1 – Stará Lesná (807 m a.s.l.), P2 – Skalnaté pleso (1778 m a.s.l.), P3 – Štart (1200 m a.s.l.), P4-Sliezsky dom (1670 m.a.s.l.).

4. Conclusions

Analysis of measured data in the upper Poprad river catchment and its subcatchments did not indicate significant impacts of deforestation on runoff regime at catchment scales ranging from headwater to small catchments (0.7-315 km^2). There are probably several main reasons for that. Although the deforested area is large (totally about 120 km^2 in the upper Poprad and the neighbouring upper Váh river catchments), it is located in middle sections of the catchments. Headwater areas where the dominant contribution to runoff is formed (and where little forests existed anyway) were not influenced. Deforestation occurred in areas formed by moraines which have high infiltration capacity. Soils developed on the moraines have high saturated hydraulic conductivity and small retention capacity. Therefore, the water can quickly infiltrate into the lower layers formed by mixed sands, gravels and loams. Deforestation affected relatively "small" percentages of catchments' areas as it went across the catchments (in the east-west direction, while the catchments are generally north-south oriented). Thus, not all the forests in the catchment were destroyed. As indicated by the results from year 2009, the low vegetation canopy gradually replaced the role of forest to certain extent (transpiration, interception, prevention of evaporation from the soil surface). These may be the reasons why the deforestation which has disturbed the environment so seriously, was not manifested in the available hydrological data and did not result in severe flooding or erosion.

Combined information obtained at different scales (point measurements, spatially distributed data from research plots and integrated hydrological response of the catchments) improved the understanding of hydrological cycle in the area. Runoff responses of the headwater catchments to intensive precipitation (June 2010) following high antecedent soil moisture conditions pointed out at different runoff formation in individual catchments located in the same study area. Runoff increase in the headwater catchments was comparable with that observed during the largest flood of the 20th century (June 1958). Rainfall intensities in June 2010 reached the values which were not the highest on record, but which do not occur frequently. However, the total amount of rainfall during the event in June 2010 was smaller than the one in June 1958. It indicates that total amount of rainfall is the most important factor in generation of extraordinary floods in the studied area. This agrees with our previous findings in the nearby Western Tatra Mountains (Kostka and Holko, 2003).

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14

Interception Storage in a Small Alpine Catchment

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1. Introduction

Interception is an important process of the hydrological cycle, although it has been often neglected in hydrological considerations (Gerrits et al., 2010). Generally, interception loss is understood as a part of precipitation detained on vegetation canopy or leaf litter. Where vegetation is present, precipitation consists of gross rainfall (observed above the canopy or in a nearby open field), canopy through-fall and stem-flow. In stratified forest communities, where water drips from the canopy and is still intercepted by lower plants, secondary interception occurs. David and Gash (1989) reports the interception loss from forests in the range from 8 to 60% of the gross rainfall (from 25 to 75% of the overall evapotranspiration).

In the Dolomites (North Italy), environmental hazard (mainly high erosion and sediment yield) corresponds with intensive floods, observed mainly in the summer (Lenzi and Marchi, 2000). Therefore, the interception storage might support catchment retention and reduce direct runoff during rainstorms. The aim of this study is to estimate possibilities to regulate interception in small high-gradient catchments of the Dolomites by forestry practices.

2. Material and Methods

Two interception plots (INT-S1 and INT-S2, area of 400 m^2) were instrumented in the Rio Brusa experimental catchment (4.68 km^2, elevation 1343–2540 m,

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South Tyrol, Italy, Fig. 1), and observed in the summer of 2002. Forests cover almost 80% of the basin area with majority (73%) of coniferous stands; dominant tree species are namely Norway spruce (*Picea abies*) and larch (*Larix decidua*). Deciduous stands (7% of the area) are represented mainly by alder (*Alnus glutinosa*), willow (*Salix alba sericea*) and Mountain ash (*Fraxinus cuspidata*). The timber line there is located approximately in the elevation of 2000 m, and the area above the timber line (20% of the basin area) are covered by mountain meadows.

The focused forest stands at two interception plots differ mainly in their altitude (1960 m – INT-S1, and 1420 m – INT-S2), the structure of investigated stands is similar (spruce plantations of 60–80 years, 1500 trees per hectare, height 20 m – INT-S1 and 25 m – INT-S2, and horizontal canopy density of 0.8, Fig. 2). Both plots were instrumented by an open-field gauge (installed in forest openings), sets of ten rain-gauges installed in the ground under the

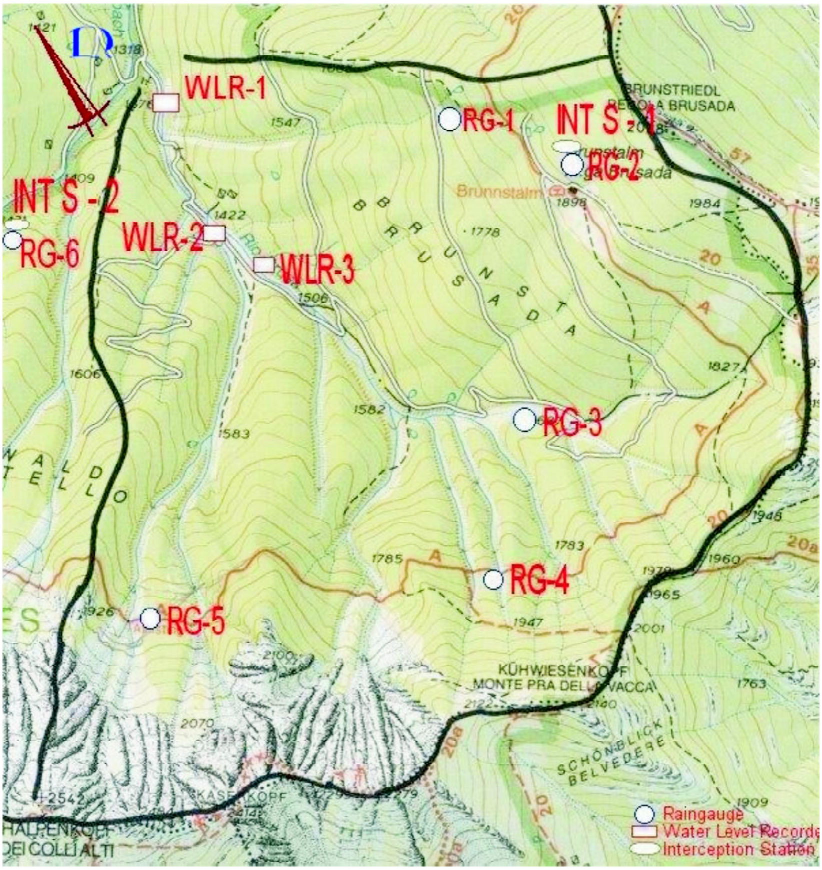


Fig. 1. Topographical map of the Rio Brusa experimental catchment with interception plots (INT-S), open-field rain-gauges (RG), and water level recorders (WLR).

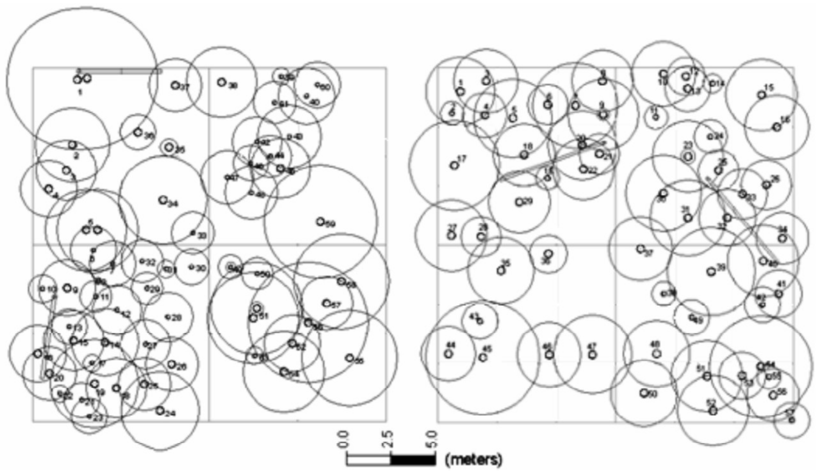


Fig. 2. Horizontal canopy projection at both investigated plots (INT-S1, INT-S2).

canopy, and two interception gutters. The Hellman type rain-gauges (200 cm^2) with typing-bucket devices were used for automatic registration of gross rainfall and through-fall under the canopy. Simultaneously, two interception gutters (area of 1.5 m^2, 5 × 0.3 m) were installed under the canopy, and connected to collectors registered automatically by the typing-bucket sensor. Stem-flow was collected by rubber collars installed at two tree-trunks at each plot and registered manually after every rainfall event.

For each single rainfall, amounts of gross rainfall (P_g), through-fall (T) and stem-flow (F) were measured, and values of interception (I) calculated as their difference (1):

$$I = P_g - T - F \tag{1}$$

To extend the results, two models were applied to simulate the interception loss: the analytical GASH model (Gash et al., 1979), and the conceptual Rutter model (Rutter et al., 1971).

2.1 Gash Model

The Gash model classifies storms according to the amount of gross rainfall, and requires the set of parameters reflecting canopy structure, climate and rainfall interception. Estimates of those parameters are based on field observations, and then optimized by model calibration. The model is based on three main assumptions: (1) Rainfall distribution patterns can be represented by a succession of discrete rain-storms, separated by sufficiently long periods to allow the canopy and trunks to dry out, (2) Rainfall and evaporation rates are constant during each individual rain-storm, and also considered seasonally constant (summer versus winter), and (3) Evaporation from saturated trunks during a rain-storm is supposed negligible.

The model is driven by three basic parameters of the canopy structure:

Free through-fall coefficient p (fraction of rain that passes through the canopy during a rain-storm without touching it), estimated as the slope of the regression line T (through-fall) versus P_g (gross rainfall) for small rain-storms (P_g less than 1.5 mm),

Canopy storage capacity S (mm, total amount of water, the canopy can hold), estimated as the amount of gross rainfall at the moment, when through-fall just starts, and

Intercepted coefficient 1-p (represents the fraction of rain that is held up in the canopy during a small storm); and

parameters reflecting the local meteorological conditions:

Mean rainfall rate R (average intensity of rainfall for all storms registered during the period of observation), and

Mean evaporation rate E (average rate of evaporation for all registered rain-storms). This parameter is estimated as the rainfall rate times the intercepted fraction for all storms on average (I/P_g). I/P_g may be estimated by taking the average I/P_g from field data or by a mass balance approach as ($1-T/P_g$), where T/P_g is the slope of the regression lines of the through-fall versus gross rainfall.

In the case of negligible stem-flow, only the parameter P_g' (*amount of rainfall to fill the canopy storage*) is respected, given by equation (2):

$$P_g' = -\ln\left\{1-\left[\frac{E}{R(1-p)}\right]\right\} S\frac{R}{E} \tag{2}$$

When a rainfall event (P_g) is not enough to saturate the canopy storage ($P_g < P_g'$), canopy interception (I_c) is calculated by the formula (3):

$$I_c = P_g\,(1-p) \tag{3}$$

Contrarily, when the interception capacity has exceeded the canopy storage ($P_g > P_g'$), canopy interception is calculated by the equation (4):

$$I_w = \lfloor (1-p)P_g \rfloor - S \tag{4}$$

Consecutive components of interception, evaporation from the saturated canopy (I_s) and evaporation from the wet canopy after rain ceases (I_a) are given by formulas (5) and (6):

$$I_s = \frac{E}{R}\left(P_g - P_g'\right) \tag{5}$$

$$I_a = S \tag{6}$$

The total amount of intercepted rainfalls (I) in a certain period is then given by the equation (7):

$$I = I_c + I_w + I_s + I_a \tag{7}$$

2.2 Rutter Model

In comparison with the Gash model, this approach needs lower number of parameters given in tables (Rutter et al., 1971); therefore, the direct field observation is not necessary to apply this model.

The schematic diagram for two idealised rainfall events and their response in the canopy is shown in the Fig. 3, storage of water in the canopy (W) and evaporation (E) components reflect rain-storm durations (t_r) and inter-storm breaks (t_b). The component W_c means saturation value for the canopy storage (W), and E_{I0} is the potential evaporation from intercepted water (E_{Ic}). This approach assumes that all rainfall events start at the dry canopy, and the storage of water in the canopy undergoes three phases: wetting, saturation and drying.

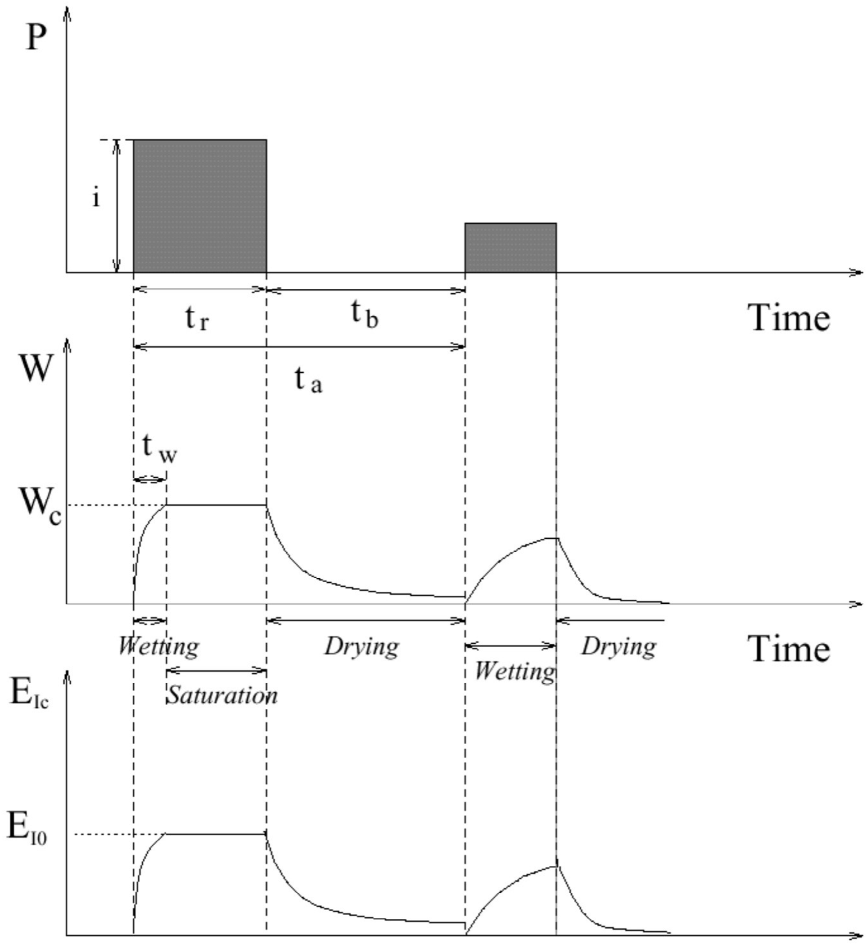


Fig. 3. The scheme of the Rutter model.

The model is based on the water budget of the canopy storage, given by equation (8):

$$\frac{dW}{dt} = P - E_{Ic} - D_r \tag{8}$$

where P is precipitation, E_{Ic} – canopy interception loss and D_r is canopy drainage. Then, the canopy interception loss is expressed by the formula (9):

$$E_k = \frac{W}{W_c} E_{I0} \tag{9}$$

where E_{I0} is potential evaporation calculated by the Penman-Monteith equation, by setting the canopy resistance to zero (E_{I0} is supposed constant during each individual model period). The time τ_o to evaporate water from a saturated canopy (by the potential rate E_{I0}) is given by the equation (10):

$$\tau_0 = \frac{W_c}{E_{I0}} \tag{10}$$

The drainage of the canopy (D_r) is expressed by (11):

$$\begin{aligned} D_r &= \infty \Leftrightarrow W > W_c \\ &= 0 \Leftrightarrow W \le W_c \end{aligned} \tag{11}$$

It means, in this concept, the excess of water (over the saturation capacity W_c) is drained instantaneously. On the contrary, zero drainage is considered from an unsaturated canopy.

3. Results and Discussion

At both interception plots (INT-S1, INT-S2), 22 rain-storms were observed in the summer of 2002. For each separated rain-event, rainfall characteristics (duration, amount and intensity) estimated. The measured amount of rain (P_g), through-fall (T) and interception (I) of registered rainfalls are given in Fig. 4. The observed values of stem-flow (F) were found negligible (below 0.5% of the interception I). It corresponds to the structure of coniferous trees, where the arc shape of trees and rough bark leads to the drainage of stem-flow into branches dripping, mentioned by Balek and Krecek (1986).

In the upper elevation (INT-S1, 1960 m), the measured total gross rainfall P_g = 115 mm, through-fall T = 40 mm, and interception I = 75 mm (65% of rainfall amount); at INT-S2 (1420 m), total gross rainfall P_g = 84 mm, through-fall T = 47 mm, and interception I = 37 mm (44% of rainfall amount). Therefore, in the investigated Rio Brusa catchment, the interception storage (I) is raised by ca 4% per 100 m elevation-increment; reaching 44% of precipitation in the lower part and 65% in the upper part of the basin.

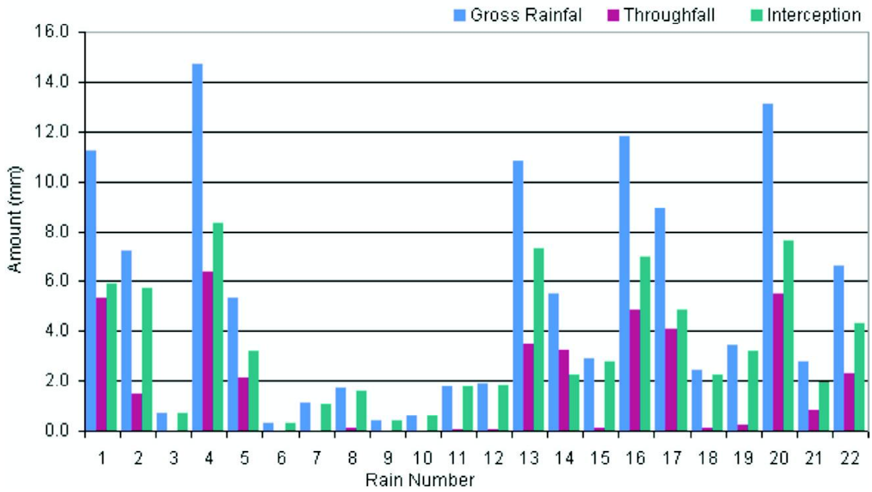


Fig. 4. Registered rainfall events in 2002 at the INT-S1 plot.

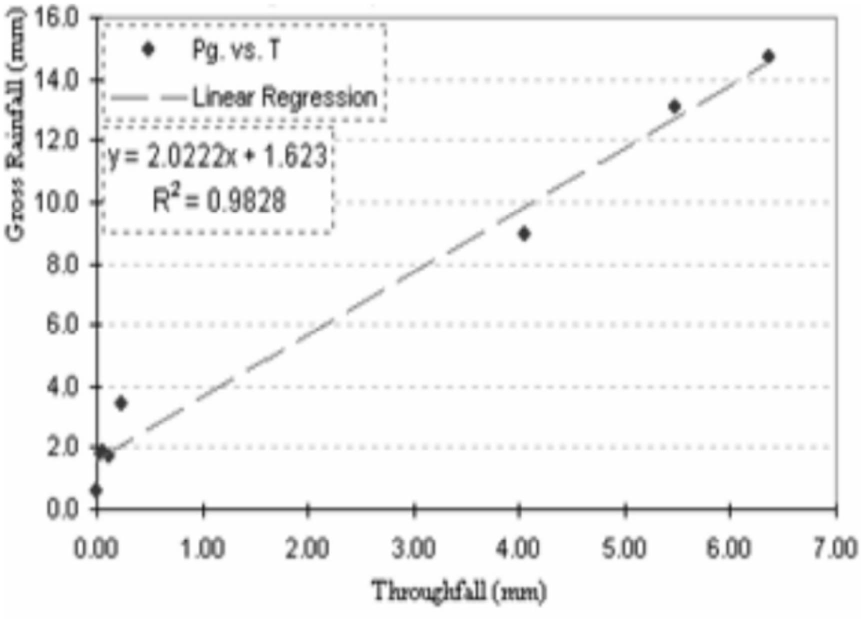
The regression between measured gross rainfall (P_g) and through-fall (T) at both interception plots are shown in Fig. 5, and estimated interception parameters are given in Table 1. The results of simulation show a good correlation between the observed and simulated interception (Table 2) for both models applied. However, the Gash model provides us with a very good agreement between simulated and measured data for rain-storms regardless their amount or intensity; while outputs of the Rutter model decline with increasing amount of rain.

Table 1. Values of interception parameters, estimated at both investigate plots (INT-S1, INT-S2)

Parameter	*Symbol*	*Unit*	*INT-S1*	*INT-S2*
Free through-fall coefficient	p	-	0.22	0.20
Canopy storage capacity	S	mm	1.50	1.33
Rain to fill canopy storage	P'_g	mm	3.51	2.14

Table 2. Correlation coefficient for observed and simulated interception at both plots (INT-S1, INT-S2)

Applied model	*INT-S1*	*INT-S2*
Gash	0.9773	0.9777
Rutter	0.8760	0.8599



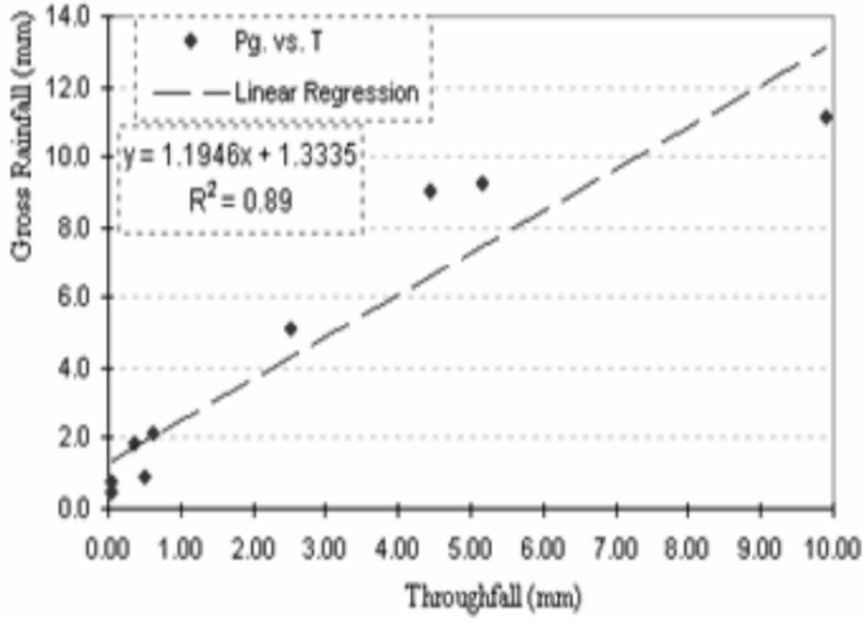


Fig. 5. Estimation of the canopy storage capacity from regression between measured gross rainfall (P_g) and through-fall (T) (left – INT-S1, right – INT-S2).

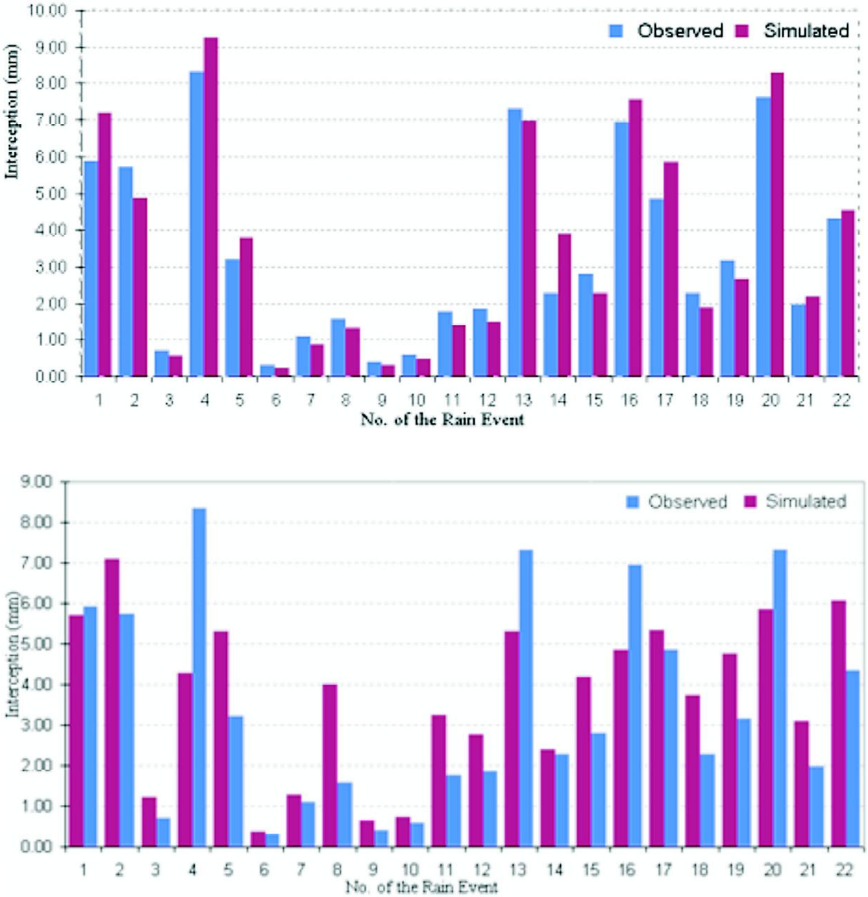


Fig. 6. Simulated interception at both forest stands (upper – INT-S1, lower – INT-S2).

Also results of the residue analysis (observed versus simulated data, Fig. 7) confirm the preference of the Gash model for further considerations. In the case of the Rutter model, simulating the interception of greater rainfalls, the model might provide us with underestimated interception loss.

Similarly with the report of Zeng et al. (2000), the role of the canopy interception controlling summer floods in the Rio Brusa catchment seems to be limited. The canopy of forests can fix instantaneously only the amount of rain close to the canopy capacity (1.5–2.0 mm), and the interception loss is increasing with the duration of rain by evaporation from the canopy during rainfall. For five highest rainfalls (P_g > 10 mm), observed in the Rio Brusa catchment, the interception loss at investigated spruce stands varies from 40 to 60% of the rainfall amount. However, for some extreme summer rain-storm events (P_g > 100 mm, R > 10 mm/hour) occurred in the Dolomites in the past,

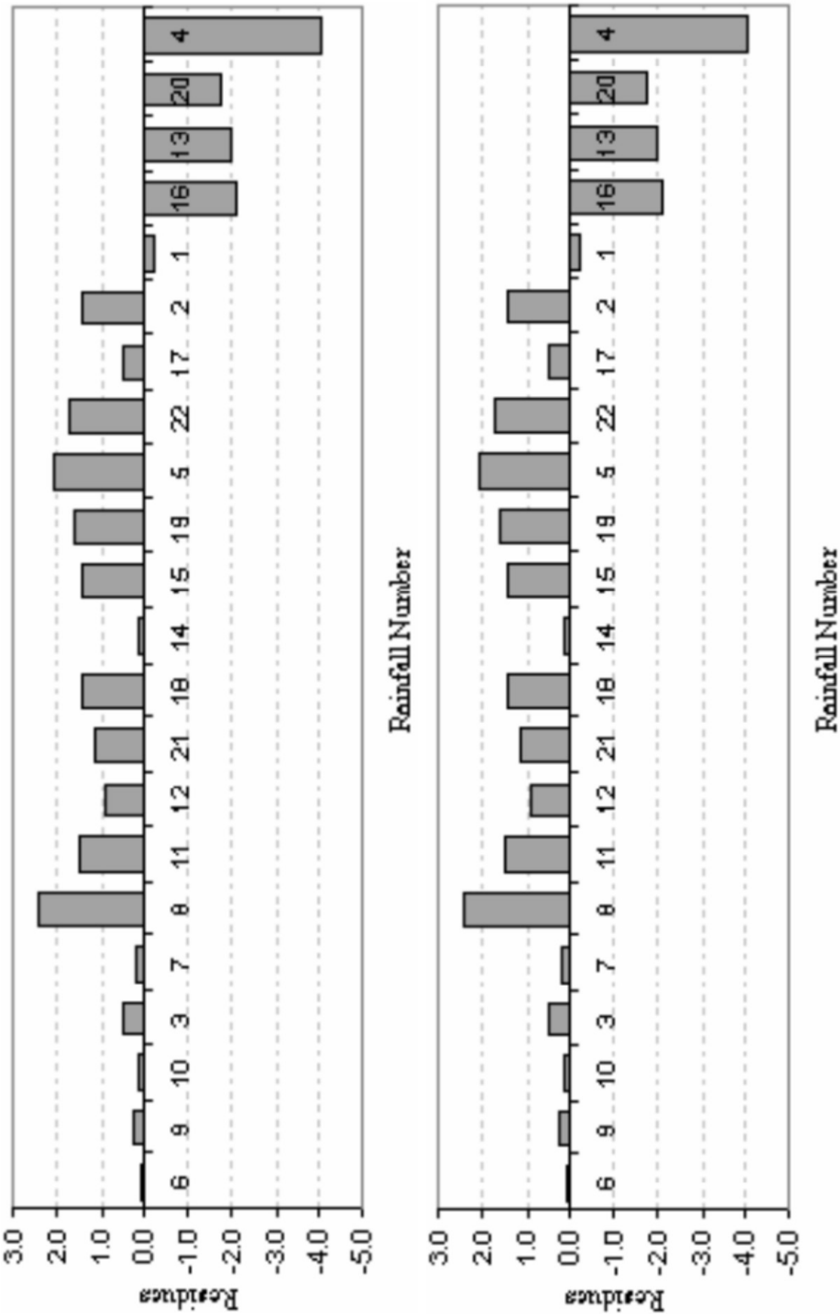


Fig. 7. Residue analysis between the model simulation and observed interception (upper - Gash model, lower - Rutter model).

the interception storage simulated by the Gash model varies from 10 to 15 mm (e.g. maximum 10–15% of the rainfall amount).

Coniferous forests are reported with highest values of the rain interception (Helvey, 1971). Balek and Krecek (1986) stressed rising importance of the interception loss in the Czech Republic with elevation (more frequent precipitation). While in the elevation of 400 m, interception of mature spruce plantations represented 30% of the total evaporation, in 900 m it was almost 60%. Gerrits et al. (2010) highlighted the importance of forest floor, which might still reach approximately 10% of the canopy through-fall. For an alternative grass cover in the Rio Brusa catchment, the interception storage can drop to one half of the values observed at spruce stands.

4. Conclusions

Results of this study confirm that the role of rainfall interception in mountain catchments cannot be neglected. Therefore, both observation and modelling of the interception storage are important tools in catchment hydrology. In the Rio Brusa catchment, interception values grow with elevation; in lower parts, the observed interception storage was 44%, and in upper parts 65% of the rainfall total. The observed values of stem-flow at both investigated plots were found negligible (below 0.5% of the estimated interception storage).

The interception simulated by both models (Gash and Rutter) shows a good correlation with observed values (R varies from 0.86 to 0.98; by R_{crit} = 0.34 and p = 0.05). The Gash model is simpler in structure and demands, and provided better outputs in comparison with the more complicated Rutter model (Table 2).

Spruce plantations in the Rio Brusa catchment have highest interception storage potential in comparison to alternative deciduous stands or grass. However, for some extreme summer rain-storm events (P_g > 100 mm, R > 10 mm/hour) the interception storage simulated by the Gash model varies from 10 to 15 mm (e.g. maximum 10–15% of the rainfall amount).

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15

Long-Term Effects of Silvicultural Practices on Groundwater Quality in Boreal Forest Environment

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1. Introduction

Logging disturbances in boreal forest watersheds alter strongly a forest ecosystem resulting in different light, moisture and temperature conditions (Kubin and Kemppainen, 1991, 1994) and new distribution of forest biomass (Kubin, 1977). The effects on watercourses depend on the regeneration method used. Clear-cutting and site preparation cause the greatest changes in site conditions and to the environment. The oldest research carried out within the boreal coniferous forest zone on the leaching of nutrients into watercourses was conducted in Sweden in the early 1970s (Tamm et al., 1974; Wiklander, 1974). In Finland, the effect of clear-cutting and site preparation on the quality of surface runoff has been monitored since 1974 (Kubin, 1995) and on the leaching of nutrients from entire catchment areas since 1983 (Ahtiainen, 1988). The leaching of nutrients into the groundwater after clear cutting and waste wood harvesting has been monitored since 1986 (Kubin, 1998).

In several studies, nutrient leaching after logging into surface waters has been found to be a few years in duration when nitrogen mineralization and nitrification increase nitrogen availability and exports to receiving waters. Long-term monitoring has revealed that after regeneration cutting, nitrate nitrogen is leached into the groundwater up to 20 years (Kubin and Krecek, 2008). Also, the timing of maximum leaching of nutrients into the groundwater following cutting takes place a few years later compared with leaching into surface water (Kubin, 1998).

The main principle is for forestry practitioners to try to ensure that potential harm caused by forestry to watercourses and the aquatic organisms be minimized. This can be achieved in two basically different ways: by using

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sufficiently wide uncut buffer zones or slightly thinned buffer zones, or by stopping leached nutrients and solid matter by means of overland-flow fields (Kubin et al., 2000) before they actually enter water systems. Compared with surface runoff, the leaching of nutrients into the groundwater is more difficult to prevent. Within the clearcut area itself it seems to last for a long time (Kubin, 1998), which is why it is important to study the effects of different regeneration methods on groundwater quality.

The aim of this study is to update the earlier results (Kubin, 2006; Kubin and Krecek, 2008) on the effects of natural regeneration of Scots pine (*Pinus silvestris*) and Norway spruce (*Picea abies*) on the leaching of nitrogen into the groundwater during the first ten years after cutting. In addition results from clear cutting and waste wood harvesting are updated consisting now 26 years long period. The results can be utilized when developing ecologically sustainable forest management methods as well as to protect drinking water stored in large aquifers.

2. Material and Methods

The experimental site, Pahalouhi, located at 64°28′N, 27°33′E, is representative of the prevailing conditions in the middle-boreal coniferous forest zone. The site type is dryish upland. The total amount of logs and pulpwood harvested was 141 m^3/ha, of which Scots pine (*Pinus silvestris*) made up 51%, Norway spruce (*Picea abies*) 46% and birch (*Betula pendula, Betula pubescens*) 3%. The cutting was carried out in 1986 using a harvester. Logging residues were harvested manually. Monitoring the quality of the ground water was commenced in the year before cutting in 1985. The plots were planted with Scots pine (*Pinus sylvestris*) making use of manually made scalps in the spring of 1987 (Fig. 1). A part of the fields were ploughed but not included in this report. The soil ranged from sand to sandy till.

A total of 24 groundwater wells were set up within the Pahalouhi experimental area. They consisted of plastic piping varying from 4-6 m in length with perforations in the lowermost 1.5 m and a plug seal the bottom. Four treatment areas were established initially: clear-cutting with cutting waste not collected, clear-cutting with cutting waste collected, ploughed treatment, and an uncut control. The corresponding layout was done in Hautala site with 20 groundwater wells, where the site type was not so dry. The total amount of logs and pulpwood harvested was 127 m^3/ha, of which Scots pine (*Pinus silvestris*) made up 11 %, Norway spruce (*Picea abies*) 88% and birch (*Betula pendula, Betula pubescens*) 1%.

In 2001, the Pahalouhi experiment was extended to include natural regeneration by using shelterwood cutting of spruce in part of the old control area and seed-tree cutting in the area adjacent to the old clear-cutting in 1986 (Fig. 1). These areas had 11 new wells set up in the autumn of 2001. The amount of shelter-wood was 300 stems per ha while seed-trees numbered 50

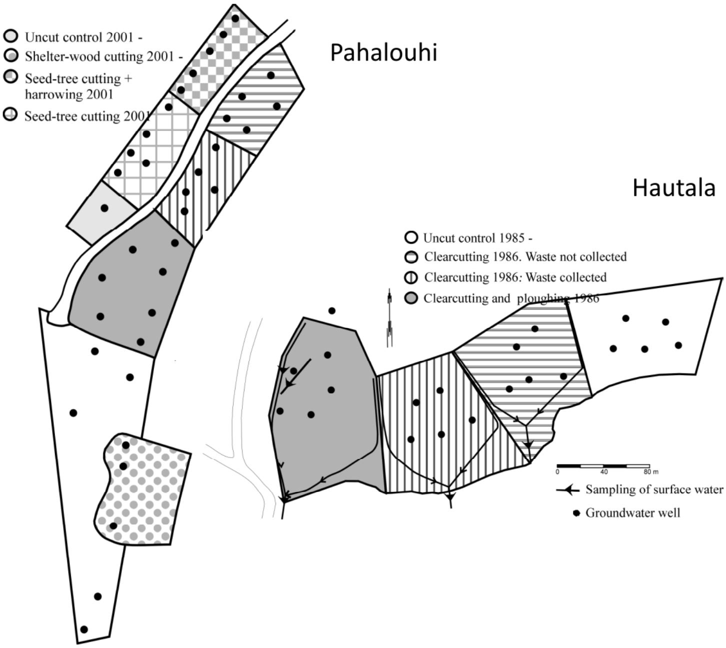

Fig. 1. The experimental sites: Pahalouhi and Hautala.

stems per ha (Fig. 1). The shelterwood area was not treated with site preparation to assist the emergence of seedlings while the seed-tree area was harrowed; these methods are in current use in Finnish forestry. The new groundwater wells were set up within these areas in 2001.

Water samples were taken annually from each well once a month from May to October. A low-pressure pump was used to sample the ground water. Chemical analyses were carried out at the Muhos Research Station following standard methods. This paper presents the results for nitrate nitrogen concentration measurements in the clear-cutting and control areas in the Hautala site over the period 1985-2011 and correspondingly in the natural regeneration areas over the period 2002-2011.

3. Results

3.1 Clear-cutting and Waste Wood Harvesting

At the Pahalouhi site nitrate nitrogen concentrations were initially 30-50 µg/l and they continued to rise for 4-5 years following clear-cutting, reaching their peak of over 500 µg/l in 1990. The concentrations were still above the initial level for 17 years after cutting, after which the values decreased and the monitoring was finished in 2006, 20 years after cutting (Kubin and Krecek, 2008). When logging waste was harvested the concentrations at Pahalouhi site were higher compared with control plot for about 13 years and the situation was about the same when logging waste were left (Kubin and Krecek, 2008). Contrary to nitrate nitrogen behaviour, the results for ammonium nitrogen do not indicate a corresponding increase.

In the Hautala site monitoring was continued 25 years after cutting. In 2011 the concentrations were below the values measured from the control plots when the waste wood was harvested, but stay about the same level when the waste was left (Fig. 2).

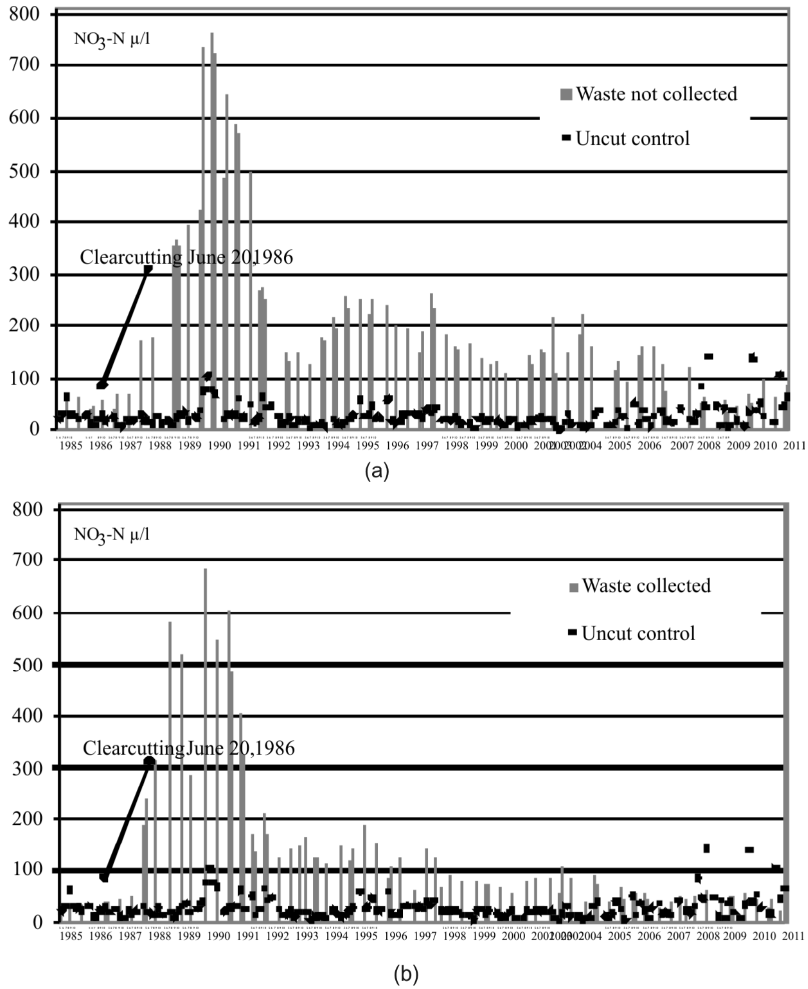

Fig. 2. The effect of clear cutting with (a) and without (b) waste wood harvesting on the leaching of nitrate nitrogen into the ground water in 1986-2011. Each year the samples were collected once a month from May to October.

3.2 Natural Regeneration of Spruce

Shelter-wood cutting was done in the late autumn of 2001. The results indicate that leaching increased during the five years (Fig. 3), but not as much as after

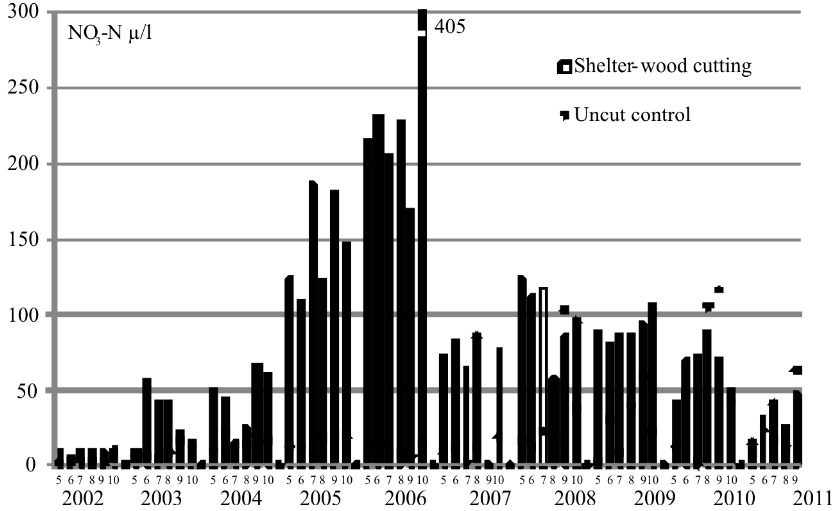

Fig. 3. Nitrate nitrogen concentrations in the ground water after shelterwood cutting of Norway spruce.

clear-cutting during the corresponding time (Fig. 2). After five years nitrogen concentrations were at the lower level, but higher compared with just after seed-tree cutting. There was also unaccountable variation in the control values.

3.3 Natural Regeneration of Scots Pine

The natural regeneration of Scots pine also increased nitrate leaching into the ground water (Fig. 4), but the values were far lower than after clear-cutting within the corresponding period of time. In the clear-cutting area, the maximum concentrations were nearly 800 µg/l (Fig. 2) while in the area involving natural regeneration of pine they all were just above 100 µg/l (Fig. 4).

4. Discussion

The Muhos Research Unit of the Finnish Forest Research Institute has established several experimental fields at Kivesvaara, northern Finland, dedicated to forest regeneration and its environmental effects (Kubin, 1995, 1998; Kubin and Kemppainen, 1991, 1994). The research data collected in this study comprises some of Finland's oldest and most intensive monitoring data on the leaching of nutrients into the ground water after clear cutting and waste wood harvesting, compared with natural regeneration of Scots pine and Norway spruce.

The effects of clear-cutting on nitrate nitrogen leaching and concentrations in surface water have been shown to last only a few years (Tamm et al., 1974; Krecek, 1987; Kubin, 1995; Ahtiainen, 1988; Piirainen et al., 2008), but the long-term property of increasing groundwater concentrations, which have

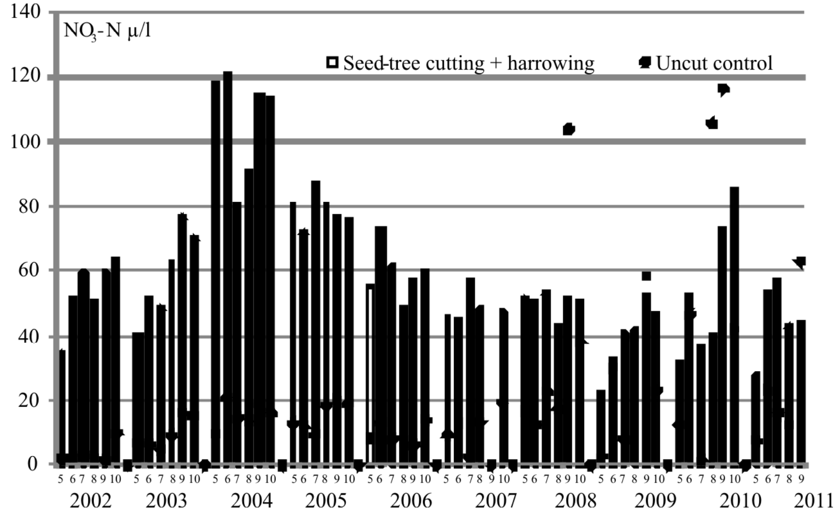

Fig. 4. Nitrate nitrogen concentrations in the ground water after seed-tree cutting of Scots pine.

persisted 25 years after clear cutting and 10 years after natural regeneration, have not been reported in earlier studies (Wiklander, 1974; Rusanen et al., 2004). Clear-cutting increases the input of precipitation, but in northern areas this cannot be the main reason for the higher values. The greater part of the increased concentrations is due to the decomposition of cutting waste and humus (Kreutzweiser et al., 2008), but the reasons for long-lasting leaching need further investigation. There was no increase in ammonium concentrations, as was also observed in boreal areas by Rusanen et al., 2004.

Nitrate nitrogen seems to be the foremost nutrient leached into the ground water as a consequence of forestry operations. The impacts of forest regeneration on aquatic ecosystems can be prevented quite effectively as regards surface waters (Kubin et al., 2000), but preventing the impacts on ground water is far more difficult. An essential aspect would appear to be that the biological cycling of nutrients on regeneration sites should continue to function so as to minimize leaching of nutrients (Borman and Likens, 1979).

The fresh results provided by this study indicate that natural regeneration causes less nitrogen leaching than clear-cutting. However, in order that we might take good care of the forest environment and apply ecologically sustainable forestry, it is worth recommending that natural regeneration be used whenever it is economically feasible. This complies also with the environmental guidelines set for forestry. As an aspect of environmentally sound silviculture, special attention has been given to the effects on watercourses and the protection of water ecosystems. The central objective of watercourse protection guidelines is to preserve the waters in good condition and protect the biodiversity of aquatic and adjacent ecosystems. New challenge of rising demand on the forest base energy now leads to extended forestry practices. The variety of silvicultural practices is increasing but their environmental impacts are not fully understood. Particularly, a special attention still needs the recovery of logging residues and stumps by forestry practices (Kubin et al., 2011).

Acknowledgements

All material was collected by the staff of Muhos Research Unit. The help provided by the landowner, UPM Kymmene Ltd., was of prime importance in the carrying out of practical work in establishing the experimental fields. The chemical analyses were mainly carried out by Timo Mikkonen, Anna-Liisa Mertaniemi and Pekka Honkanen and field works were carried out by Reijo Seppänen and Jorma Pasanen. Help with the drawing of the figures and data processing was given by Tuula Aspegren and Jouni Karhu. The English language was checked by Erkki Pekkinen. The author takes this opportunity to thank everyone concerned in the collating and compiling of the relevant information.

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16

Modelling 100 Years of C and N Fluxes at Fertilized Swedish Mountainous Spruce Forests

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1. Introduction

Carbon sequestration by increased N application has been suggested as an efficient method to reduce green house gas emissions. The boreal forest is one of the largest biomes of the earth where a lot of the world's soil carbon is stored. Obviously a high potential for carbon sequestration (Cannel, 2003) exists but high uncertainties are related to methods of accurate quantifications.

The Swedish Government commissioned 2008 (Jo 2008/1885) SLU (Swedish University of Agricultural Sciences) to investigate possibilities for intensive forestry including risk factors on abandoned agricultural land and on forested land of low value for nature conservation. The term intensive forestry was used for silvicultural models that result in significantly increased yields but which today have restricted practical applications due to legalities or as a result of governmental agencies′ recommendations and policies. This include nutrient optimization systems, vegetatively-propagated spruce (spruce clones), Lodge pole pine and hybrid poplar. The final report covered a broad spectrum and included seven background reports, viz. definitions, available areas and calculation of consequences; silviculture for increased forest growth; a socio-economic assessment; consequences for cultural heritage, outdoor life, landscape scenery and biological diversity; legal aspects; humanistic and social-scientific perspectives; and effects on soil, water and green house gases. The last background report (Nordin et al., 2009) included a large modelling effort to analyze possible effects of intensive fertilization on soil, water and green house gases over Sweden in a long time perspective.

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The objective of the present work is to give an example of how such silvicultural methods can be studied by using a process-based modelling approach. Impacts on soil, water, biomass production and green house gas emission are demonstrated from the forested mountainous north western Sweden.

2. Material and Methods

We used the CoupModel (2009), which is a coupled ecosystem simulation model treating simultaneously daily fluxes and storages of water, heat, carbon and nitrogen. The model was originally developed to treat soil water and heat transfer (Jansson and Halldin, 1979). In the present Windows-based version of the model (Jansson and Karlberg, 2001) also photosynthesis and plant growth are included and all parts are coupled and mathematically treated simultaneously. The plant leaf area (LAI) determines the fraction of available radiation used for photosynthesis resulting in growth of leaves, stem and roots. Soil carbon, formed from leaf, wood and root litter and from root exudates, is mineralized by the microbial community resulting in carbon dioxide emission. Photosynthesis efficiency is determined by the leaf carbon to nitrogen ratio. Nitrogen is taken up by plant roots and is incorporated into plant tissues and again added to the soil nitrogen pool when litter is transferred to the soil pool. Soil organic nitrogen is mineralized by the microbial community and may be nitrified and leached from the soil profile and/or denitrified and lost from the soil by nitrogen gases emission. The plants can take up nitrogen as ammonium, nitrate or as organic nitrogen. Selection of model parameter values was primarily based on data from the long-time fertilization experiment conducted in Flakaliden, northern Sweden (Bergh et al., 1999), but also information from applications to other areas was used (Norman et al., 2008; Svensson et al., 2008a, b).

Driving variables for the CoupModel, as it was run in the present context, were daily values of air temperature and humidity, wind speed, global radiation, precipitation and nitrogen deposition. The data set was formed by about 34 years of daily climate data from seven of the Swedish Meteorological and Hydrological Institute (SMHI) official mountainous network stations, each added three times to form seven separate 100-year records. The nitrogen deposition was gridded data calculated by SMHI (2009) with the MATCH-Sweden model (Persson et al., 2004).

The experiments conducted with the CoupModel spanned three moisture levels (mean groundwater level at –1.8, –1.0 or –0.2 m below soil surface), two initial soil nitrogen storages (2100 and 5000 kg N ha^{-1}, which is comparable to sites in northern and southern Sweden, respectively), three different initial C/N ratios in soil humus (18, 24, and 30, mimicking sites with high to low degree of soil humus decomposition) and a low and a high mineralization rates of the soil humus, respectively. That meant that a total of 36 different site conditions were investigated at each of the seven locations (climate station) daily for 100 years.

The forest management systems used in this modelling experiment included two rotation periods, two times 50 and one time 100 years, respectively. During a ten-year period from planting to clearing no fertilizer was added. Then the forest was fertilized every second or every eighth year and thinned when the leaf area index reached LAI = 8. Finally, neither fertilization nor thinning was applied during the last ten years of the 100- or 50-year rotation period. Besides the no fertilization reference treatment, the total fertilizer application rate was 1400 and 2800 kg N ha^{-1}, respectively. In total ten forest management regimes were modelled.

3. Results

In forested north-western Sweden the annual minimum mineral nitrogen leakage was between 0.2 and 0.4 kg N ha^{-1} yr^{-1} despite fertilizer treatment. The mineral nitrogen leakage from non-fertilized sites was less than 5.7 kg N ha^{-1} yr^{-1} with an average of 1.1 kg N ha^{-1} yr^{-1} (Fig. 1). Fertilization every second year resulted in less leakage than fertilization every eight years using the same total fertilization amount for a rotation period. The mineral nitrogen leakage increased with total amount of nitrogen added (Fig. 1). When 1400 kg N ha^{-1} was added during a period of 100 years the average mineral N leakage was 3.2 kg N ha^{-1} yr^{-1}, while the maximum leakage was 10.2 kg N ha^{-1} yr^{-1}. The highest fertilization amount also resulted in the highest leakage. After adding 2800 kg N ha^{-1} the mean leakage was 8.0 kg N ha^{-1} yr^{-1} and the highest leakage was 22.1 kg N ha^{-1} yr^{-1} (Fig. 1).

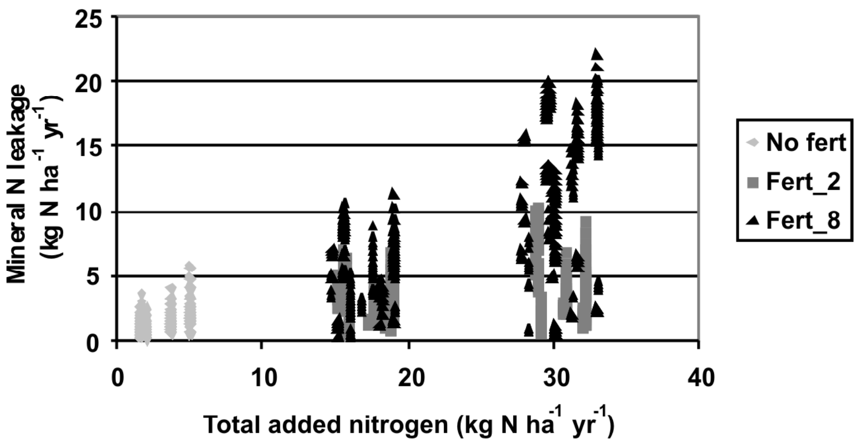

Fig. 1. Average mineral nitrogen leakage (kg N ha^{-1} yr^{-1}) from Norway spruce stands under different fertilization regimes during a 100-year period (2 and 8 years between applications). The added nitrogen includes atmospheric deposition.

While the mineral nitrogen leakage from forest fertilization is coupled to water pollution and eutrophication downstream, fertilization is also coupled to increased net green house gas uptake. After fertilization we found always an increased carbon dioxide uptake, but also an increased emission of the potent green house gas nitrous oxide. The net effect of fertilization on green house gases was, however, an increased uptake calculated in carbon dioxide equivalents (Table 1).

Table 1: Net uptake of green house gases (Mg CO_2 ha^{-1} yr^{-1}) during 100 years in Swedish mountain spruce stands under different fertilization regimes

	F0	*F1400_8*	*F1400_2*	*F2800_8*	*F2800_2*
Min	1.4	2.9	3.4	4.2	5.1
Mean	3.9	6.9	7.8	8.3	10.0
Max	9.0	11.5	12.2	12.2	14.5

The total amount of N added were 0, 1400 and 2800 kg N ha^{-1} and the application intensities were every second or every eight years.

The fertilization effect on nitrogen leakage and net green house gas uptake are compared in Fig. 2. A large variation of both effects was found within each treatment, which can be traced back to the large variation in site conditions in the modelling experiment.

The net ecosystem productivity (NEP) increases with amount of N fertilizer applied and frequent fertilizer application results in higher productivity than less frequent (Fig. 3a). The NEP increased from about 1.1 without fertilization to about 2.6 Mg C ha^{-1} yr^{-1} with a total N application of 2800 kg distributed

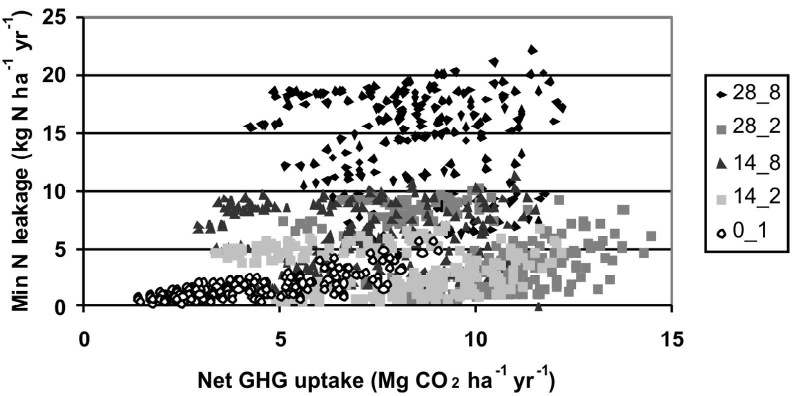

Fig. 2. Average mineral nitrogen leakage (kg N ha^{-1} yr^{-1}) as a function of net green house gases (GHG) uptake in Norway spruce stands under different fertilization regimes during a 100-year period and excluding wet sites. The total amount of nitrogen added during a 100-year period was 0, 2800 and 1400 kg N ha^{-1}, with the time between applications equal to 1, 2 and 8 years, respectively.

in portion every second year. The large standard deviation in Fig. 3 represents the variation in site conditions in the modelling experiment. The possible stem harvest increased in the same order as the NEP and amounted from about 0.9 without fertilization to about 2.1 Mg C ha^{-1} yr^{-1} with the heaviest N fertilization. Also the soil carbon storage increased in the same order as NEP and stem harvest and amounted to about 5–15% of NEP, the lower value for non-fertilized sites and the higher value for the largest fertilization and frequent application (Fig. 3a).

The change in soil N storage also increased with fertilizer application rate and frequency, at the highest level with 11.3 kg N ha^{-1} yr^{-1}, but in the case of no fertilization the soil N storage decreased with about 2.4 kg N ha^{-1} yr^{-1} (Fig. 3b). The situation with inorganic nitrogen leakage differed from the other

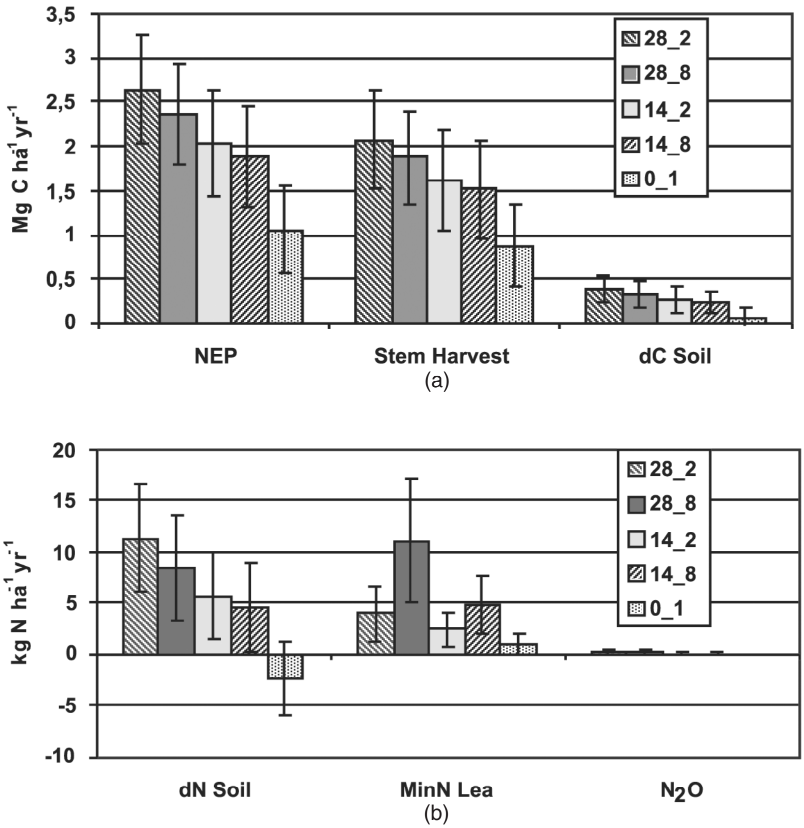

Fig. 3. (a) Average carbon flux and change in carbon storage (Mg C ha^{-1} yr^{-1}) for net primary production (NPP), stem harvest and soil carbon storage during a 100-year period. (b) Average nitrogen flux and change in nitrogen storage (kg N ha^{-1} yr^{-1}) for change in soil nitrogen storage, mineral nitrogen leakage and dinitrogen oxide gas emission during a 100-year period. The total amount of nitrogen added was 0, 2800 and 1400 kg N ha^{-1}, with the time between applications equal to 1, 2 and 8 years, respectively.

fluxes in that fertilizer applied at low frequency but in larger doses led to the highest leakages. For the total dose of 2800 kg N ha^{-1} applied in portions every eighth year leakage losses amounted to 11.2 kg N ha^{-1} yr^{-1}, while the same total dose applied in portions every second year would have led to leakage losses of about 4.0 kg N ha^{-1} yr^{-1} (Fig. 3b). The emission of nitrous oxide gas was small and increased with the frequency of application. In contrast the N leaching decreased with the frequency of application and increase with the amount applied.

4. Conclusion

The response of natural variation in site conditions, climate and possible management on green house gas emissions is complex and cannot easily be studied by field investigations. Model experiments on the other hand can be rapidly executed and a number of variations can easily be studied by using models that are constrained by other independent data. In the present study it was found that from a green house gas point of view nitrogen fertilization is always positive. However, nitrogen fertilizer should be given in small doses and with high frequency to minimize inorganic nitrogen leakage. Nitrogen fertilization also increases biomass production and soil N and C storages. The current uncertainty is not easy to estimate from the simulated results but will be possible to further investigate by adding new experimental data.

Acknowledgements

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Part V

Soil Conservation and Control of Floods and Landslides

17

The Forests of Lake Balaton Catchment and Their Role in Soil Conservation

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1. Introduction

Among the land use categories the forests have a special and very important role in nature and environmental protection. The forest decreases the atmospheric concentration of carbon dioxide, filters polluted air, isolates noise, mitigates temperature changes, diminishes soil temperature by 2-4 degrees ensuring even temperature conditions, lowers wind velocity, increases air humidity and has many more favourable effects on nature and society. The forests play an important role in the water regime of a given area. The large canopy surface slows down the velocity of the rain, most of the rain water remains in the forest and surface water will be converted to subsurface water. Forests protect the soil from drying out, they provide a special microclimate and have a positive climatic influence on the climate of the nearby areas. The above mentioned favourable effects of the forest are only a few out of a long series hereafter we will concentrate on the soil protecting effects.

On hills and mountains, soil erosion is a major environmental problem. As it is well known, forests give a very strong protection against erosion by slowing down or even stopping surface runoff and the transport of soil particles. There is, however, soil erosion even in the forest, in most cases gullies can develop there. Deforestation of a forested area doesn't always mean clearing the whole forest. In many cases a piece of forest remains below the deforested and cultivated arable field. Gully initiation begins on the cropland in the form of ephemeral gullies and these gullies incise also in the forest, especially on unconsolidated sediments (Jakab et al., 2005, 2006). The solution is to collect the water before it enters the forest and lead it away. An even better solution

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is soil erosion control on the arable field. Gullies destroy the soil, the trees and the forest as a whole and the water flowing out from the forest is a considerable loss for the forest itself. Gullies can develop without a contact with arable fields, too. Wood transportation lines, roads, pathways, clearings offer ideal conditions for gully initiation.

New forest plantations targetted at the protection of the soil against erosion usually follow the contour lines. In most cases, terraces are formed along the contour lines to provide better conditions for the samplings.

2. Environmental Management of Forested Areas

Forestry policy in Hungary is directed towards nature conservation and environmental protection with special emphasis on the aspects of ecology and biodiversity. In 2004, the National Forest Programme was launched. The main objective of the National Forest Programme is to ensure long-term sustainability and to satisfy the demands of consumption, environmental protection, recreation taking socio-economic and cultural aspects into account. The protection and support of natural processes as well as the conservation and rehabilitation of quasi natural forests including the protection of protected and rare species are within the scope of forestry and forest ecology. The aspects of landscape protection and the concept of the maintenance of forested area, however, contribute to the protection of the environment as a whole. In this context, forestry policy supports the interests of soil conservation, too. Figure 1 shows the forested areas of the country.

Fig. 1. Forested areas of Hungary (2006).

3. Land Use Changes in Hungary

Table 1 shows the changes in percentages of land use categories between 1895 and 2001. Between the two world wars there were no significant changes. The percentage of agricultural land as well as the percentage of forest area remained roughly the same. The important changes started after 1950. Agricultural land became less and less due to various reasons among which the general European trend of diminishing agricultural areas is the most important. The forest area has been growing continuously (see Fig. 2) and today it is over 20% and 20% of it is protected.

4. Land Use Changes in Balaton Catchment

Land use changes in the catchment follow general national and European trends. The percentage of arable land was 40-45% between 1895-1950 and then it has been decreasing (40% in 1984 and 35% in 2001). In contrast to the national data the percentage of forests was much higher, approximatively 25% during 1895-1950), than the country value and it reached only 25.6% in 1984 (Szilassi et al., 2006) with a growing tendency reaching almost 30% in the early 2000s. Settlements occupy 8.5% of the area (Máté–Sisák, 2006). The percentage of non-cultivated areas altogether is very high (it was already 36% in 1984).

The biggest lake in Central Europe (595 km^2) collects water from an extensive catchment (5200 km^2), which can be subdivided into three subcatchments (Fig. 3).

1. By far the largest subcatchment (2622 km^2) belongs to the Zala river and became part of the Balaton catchment through a river capture. The river flows through a series of settlements with industrial plants which used to be point sources of severe pollution. The drainage of the swamp areas at the mouth of the Zala river (Little Balaton) eliminated an important filter which protected the lake from further pollution.

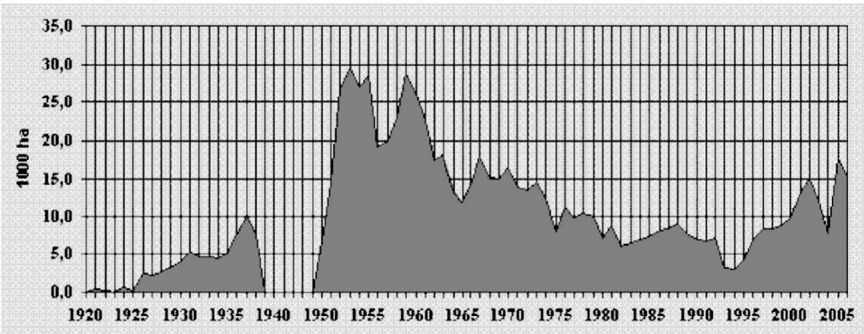

Fig. 2. Afforestation between 1920 and 2005.

Table 1: Land use changes in Hungary, 1895-2001 (%)

Year	*Arable land*	*Gardens orchards*	*Vineyards*	*Meadows*	*Pastures*	*Agricult. land**	*Forests*	*Reed*	*Cult. area*	*Non-cult. area*
1895	55.4	1.0	1.9	8.6	13.7	80.6	13.1	0.5	94.2	5.8
1930	60.0	1.1	2.3	7.2	10.8	81.4	11.8	0.3	93.5	6.5
1945	59.8	1.2	2.3	6.9	10.3	80.5	12.1	0.3	92.9	7.1
1950	59.3	1.6	2.5	6.5	9.3	79.2	12.6	0.3	92.1	7.9
1965	54.6	3.4	2.7	4.5	9.5	74.7	15.3	0.3	90.3	9.7
1970	54.2	3.4	2.5	4.4	9.4	73.9	15.8	0.3	90.0	10.0
2001	48.5	2.1	1.0	11.4		63.0	19.1	0.6	82.7	17.3

*Agricultural land is arable land, gardens, orchards, vineyards, meadows and pastures altogether.

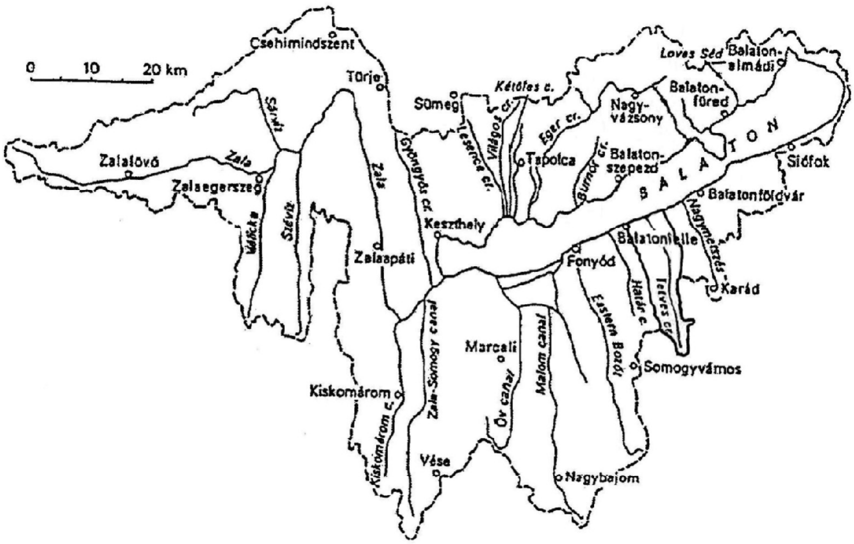

Fig. 3. Lake Balaton catchment.

The catchment area is of rather low agricultural potential, where land use is closely adjusted to topographic conditions. The peak of arable land extension was reached before World War II (63% in 1935) and no attempt was made to increase this area further in the sixties. The recent decline conforms with the national trend. The cooler and wetter climate does not favour the plantation of fruit-trees and grapevines, but vegetable gardening has almost trebled its areal extension over this hundred-year period. The valley floors are either built-up, or remain to be used as meadows. The decline in stock-breeding, however, also manifests itself here.

Before World War II, three-quarters of the Zala Hills were cultivated. A remarkable growth is observed for forest areas, particularly of spruce and pine which occupy a larger proportion of land here than elsewhere in the Lake Balaton catchment. The reed-beds of the one-time Little Balaton swamp (drained in the 1950s) are now being restored. Their role in the filtering of the Zala river water (a major source of pollutants) before entering the lake is crucial.

2. The catchments of the southern shore (1403 km^2) comprise flat, loess-covered hills and broad valleys. With the rapid post-war expansion of tourism, the long reed-beds sections along the shore were interrupted by resorts and beaches in more and more locations. Agricultural land declined to below 60 per cent already 20 years ago, but arable fields still extend over two-thirds of this area. The peak was reached in the late sixties (72%), when production in agricultural cooperatives was profitable and large investments were made to expand production both extensively and intensively. Since the 1970s, however, this trend has been reversed: thousands of hectares are being converted into

gardens, orchards and vine. With the drainage of broad valley floors, the area of meadows was reduced.

The expansion of forests (slightly above the national average) should be regarded a positive development. The area of reed-beds along the southern shore, where once extensive swamps existed, reached a critical minimum value of 0.2 per cent in 1962. Later, however, it was realised that efforts to create more farmland through land drainage are too cost-intensive and hardly profitable. Due to a revised environmental policy implemented since the 1970s, the relative area of reed-beds reached that of the northern lakeshore.

3. The northern subcatchments (1175 km^2) the Balaton Uplands is a series of small basins of diverse geology, soils and land use. The lake shore is also almost contiguously built up. From over 562 km^2 surface, runoff finds direct access to the lake.

The physical environment is the least favourable for farming in the northern catchment. Here it was only in the first half of this century that the percentage of agricultural land exceeded 50 per cent of the total area. At that time small-scale farming was typical. After World War II, when small-plot farming was replaced by large-scale, mechanised farming cultivation, fields of tens or even hundreds of hectares were created. During this process centuries-old tree rows, hedges and field terraces were obliterated.

The expansion of plantations i.e. orchards and vineyards was motivated by the rapid growth of lakeshore resorts from the 1960s. Parallel with this process arable land shrank substantially in the post-war period. Meadows and pastures only show minor changes over the decades since they were restricted to tracts of land hardly suitable for any other purpose. This also applies to forests and reed-beds. Some of the barren limestone and dolomite ridges were planted with pine (*Pinus nigra* and *P. silvestris*) in the 1950s. The conifers, however, do not find optimal conditions on calcareous rocks and they are alien to the landscape. In the following decades stream channelisation and wetland drainage reduced the areal extension of wet meadows. Their heavy soils, however, were of little use for farming.

In the last decades of the 20th century the state of the lake and its environment, particularly in the western basins of the lake, the nitrogen and phosphorus loads are very high (Jolánkai, 1994). While nitrogen oxides primarily reach the lake through atmospheric deposition, in the case of phosphates the amount directly washed down from agricultural land (35 tonnes in 1993) is comparable to that transported by water-courses (38.5 tonnes per year) and to the influx from urban areas (32.5 tonnes per year).

By the 1980s, eutrophication has reached a level when algal blooms reduce the transparency of water, change its colour and thus make it unattractive for bathers (Heródek et al., 1988). Such problems are also caused by decomposition of organic matter in the deeper water layers in the absence of oxygen.

Based on the results of multidisciplinary scientific research, measures were taken to improve the environmental condition of the lake and its catchment. Large-scale investments in sewage treatment, garbage collection, solid waste disposal and drinking-water supply have attempted to alleviate the environmental problems.

The water quality of the lake improved according to the forecasted rate and since roughly 15 years it is impeccable. The long warm and dry period of the 1980s and the decline of manure and fertilizer use also contributed to the improvement process. However, further decrease of the load is needed to stabilize the present good conditions. To achieve this aim, diffuse pollution on agricultural areas of the catchment should be decreased. The role of soil erosion and surface runoff are extremely important in this context. The government order 1033/2004 (IV.19.) declares among others that it is for crucial importance to reduce the nutrient load of the lake.

5. The Forests of the Catchment

Although the landscape around Lake Balaton lost its natural character long ago and some densely built-up lakeshore sections cannot even be called semi-natural any more, the survey of the pre-existing natural vegetation is necessary for an explanation of the present-day land use. A thousand years ago the region was still overwhelmingly forested (Zólyomi, 1989).

In the *northern catchment* the higher-lying surfaces of the limestone-dolomite ranges, which divide small subbasins, were most certainly covered by closed karst forests. This is a collective name in Hungarian plant geography for various zonal associations, the most widespread of which were the following.

- Calciphile karst forests (*Orno-Quercetum*) once formed a contiguous zone across the limestone horsts; the two main tree species were ash and downy oak with well-developed undergrowth rich in bushes. This vegetation community was predominant on summits and N, NW and NE slopes.
- Oak forests (*Quercetum-petraeae-cerris*) grew on deeper lessivée brown forest soils. The main tree species were sessile oak and Turkey oak with abundant herbaceous plants in the undergrowth. These forests occurred in a lower elevation, than those referred to above and occupied N and E slopes.
- Mixed karst forests (*Fago-Ornetum*) occupied the highest dolomite surfaces; the main trees were beech, ash, lime and rowan. This zone provides contact with the forests of the southern Bakony Mountains.
- Hornbeam forests (*Carpino-Quercetum*) occurred in smaller areas on summits and steep slopes with the exception of cliffs, where stony soils prevented the formation of a closed forest, karst scrub forests with heliophile plants evolved. A typical association in the Balaton Upland is called *Cotinetum balatonicum* after its most abundant bush, the Hungarian fustic (*Cotinus coggyra*).

In the drainage basin of the Zala river two plant geographical areas can be identified, primarily on the basis of the carbonate contents of soils. Along the lower sections of the river the slopes were covered by Illyrian oak-hornbeam forests (mainly *Helleboro-Carpinetum*), replaced in the summit position by Illyrian beech forests (*Helleboro-odoro-Fagetum* and *Vicio-oroboido-Fagetum*).

On the more intensively leached, more acidic soils of the headwater area oak forests with Scotch pine (*Genisto-Pinetum quercetosum*) alternate with almost pure Scotch pine stands (*Genistae-Pinetum*).

South of the lake, the loess ridges with brown forest soils are mostly overgrown by sessile oak-Turkey oak forests (*Quercetum petraeae-cerris*) and only occasionally reach into the altitudinal zone of submontane oak-hornbeam forests (*Querco petraeae-Carpinetum*). The lower-most surfaces (one-time lake floor sections) and the valleys had a natural vegetation of swamp meadows and forests.

6. Conclusions

Lake Balaton is exposed to various kinds of environmental impacts. Agricultural activities carried out in the catchment contribute a great deal to the pollution and eutrophication of the lake. According to previous investigations (Kertész et al., 1995), most of the subcatchments belonging to the northern and southern catchments have a very small contribution to the water and sediment influx into the lake. Only a few percent, i.e. in case of Örvényesi-Séd catchment only 2% of the eroded sediments will be transported into the lake. Investigations in the Tetves catchment (Madarász et al., 2003; Jakab et al., 2005; Jakab et al., 2006; Jakab, 2008) point to the importance of gully erosion. Gully erosion transports the sediments of sheet erosion and gully erosion during high intensity rainfalls.

The reasons why the northern and the southern subcatchments deliver rather small amounts of sediment into the lake are as follows. Most of the catchments north of the lake are real basins so that most of the eroded sediment remains in them. South of the lake the surface is rather flat, it is a hilly country with low elevation and the lower parts of the basins, near the lake, are real lowlands; so only very high intensity rainfalls have a chance to move sediments into the lake.

Forests are very important in both cases. In case of the basin-like catchments in the northern part as well as in the elongated catchments with low gradient they slow down the movement of water and sediment. Their role is, of course, much more important on hillslopes with high gradients. Afforestation plans in the future will have to serve the interests of soil conservation, of the protection against soil erosion. Topographic conditions and land use pattern have to be taken into account. Forest stripes should prevent material flux from arable fields and soil erosion from slopes.

The catchment of the Zala river is the most dangerous for the lake ecosystem. Here the swamp areas at the mouth of the Zala river (Little Balaton) filter the polluted water of the Zala river and protect the lake from pollution. In case of this catchment the role of forests is inevitably very significant, but the swamp area is the most important from the aspect of environmental protection.

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18

Landslide Disasters: Seeking Causes – A Case Study from Uttarakhand, India

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1. Introduction

This study is about the fundamental causes and character of landslides in the Himalaya and similar mountain belts. In part, it is intended as a protest against the repetitive and misleading reports that so often follow each successive extreme rainfall event and consequent landslide swarm. The problem is that many of these 'kneejerk' reactions to a disaster do little more than support folklore or a particular political stance. In the words of the philosopher Alfred North Whitehead, it is 'not ignorance, but ignorance of ignorance, that is the death of knowledge'. His rule for every environmental scientist was 'seek simplicity and distrust it' (Whitehead, 1920). Laszlo (1972) continues this theme: *"Ours is a complex world... 'Nature does not come as clean as you can think it,' warned Alfred North Whitehead"*.

In the case of landslide disasters, scientists often feel they 'know' what is happening because that is what their training and textbooks tell them should be happening. In many others, local people feel that they 'know' what is the cause of the problem because they have the evidence of their own eyes. However, while the views of local communities and people with deep personal understanding of their land are very commonly correct and, equally, while the textbooks of environmental science contain much that is, in general, correct and common sense, it is equally true that, when explored in detail, the observations of local communities can be misguided by *a priori* beliefs and the same is true of those who raise their eyes too briefly from their library

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shelves. Of course, any pronouncement made on the basis of presumption, rather than careful study, is vulnerable to error.

Nevertheless, problems arise when the results of detailed study and analysis contradict both the ‘common sense of the educated person’ and the received wisdom of the environmental scientist and engineer. It is the misfortune of many working on environmental matters that their research discovers realities that are unpalatable in political terms. It is also very common for the researcher to be placed in the position of reporting troublesome knowledge, results that do not fit with current theory. The situation, in this case, is more difficult since the findings contain a message that even the environment movement does not much want to hear. However, this study, which deconstructs the messy and often counter-intuitive reality that underpins the causation of one Himalayan landslide swarm, contains a message that is of considerable wider significance. ‘Nature does not come as clean as you can think it’, so its processes need to be explored with due care.

2. Case Study

It seemed to the authors that the best way of illustrating this important point was to systematically and objectively analyse a typical landslide swarm using the best methods available. The results thus obtained are far from being novel or unusual but they contradict much professional opinion. This chapter, then, contains a case study – but the case study is not the reason for this chapter. It exists to illustrate a larger issue and to show why, ultimately and sadly, the world is doomed to a future of the same litany of repetitive academic presumption and the same media hysteria that accompanied the case study event.

However, this study has ambitions that go beyond demonstrating a methodology for the diagnosis of landslide problems. It also aims to demonstrate a way of classifying and interpreting landslide causes that is calculated to resonate both with the affected communities and with the results themselves. Hazard management is a very public subject that affects communities and policy makers as well as applied science. Its diagnoses, practices and recommendations become most effective when they are understood by the community. Community support is more effectively engaged when that community comprehends the meaning, significance and implications of the diagnostic work done by scientific and technological teams and how their advice should impact on land-use decision-making, as well as on expensive investments in land and water management technology. Good communication is more easily achieved when technical advice is couched in terms that are culturally resonant and accessible for their intended audience.

This chapter explores an Indian perspective on the character of landslide disasters. It provides an illustration of the way that such ideas may interact productively with hazard management and disaster mitigation. Its case study is the Almora Landslide and Flood Disaster of September 2010, which caused more than US$ 125 millions of damage and disrupted thousands of kilometres of infrastructure in India's Himalayan State of Uttarakhand, a place that styles itself 'Dev-bhoomi' or 'God's Country'.

3. Three Sources of Problems: A Traditional Classification

"God's energy manifests the varieties of creation along with varieties of consciousness for perceiving them. The manifest result of material transformation is understood in three aspects: adhyatmic, adhidaivic and adhibhautic". Srimad Bhagavatam 11.22.30-31.[1]

Indian tradition holds that troubles come in three varieties and the same applies to landslides. They all share three causal factors. They may be: *adhyatmic*, problems that emerge from the self; *adhibhautic*, those that emerge from the environment and *adhidaivic*, those that reflect the influence of God or fate. These three types co-exist in an interdependent relationship (Parthasarathy, 2001). Collectively, these processes provide the causal dimensions and frame for what Anu Kapur calls the 'disaster scape' of India, as perceived by its people (Kapur, 2010).

Adhyatmic problems are created by the self, by individual human choice; literally, they are problems of the spirit. Translated into the terms of hazard and disaster management, these include cases where humans consciously or unconsciously put themselves in the way of harm, such as by constructing a building on an unstable site or within a flood plain or by actions that reduce their local environmental security, such as by overloading or undermining a hill slope. The distinguishing feature of all of these factors is that none of them had to be that way – all are the result of human decisions.

Adhibhautic problems are those problems that emerge from the environment; literally, from the Earth. Frequently, this is taken to include the impacts of the decisions of other living beings, such as the collective human actions that drive climate change. However, the concept may properly be extended to include all of those factors that may be inherent to a local environment: its geology, vegetation, waters, climate and topography.

Finally, there are *adhidaivic* problems, those causes that insurance companies would like to consider 'acts of God'. These include the unexpected, such as rare extremes of climate, and such random processes as may be counted 'bad luck' or fate, such as being struck by lightning.

The question to be asked in this chapter is which aspects of these three processes are most at work in the case of a landslide swarm disaster?

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[1] *Srimad Bhagavatam* 11.22.30-31; also Vyasa, K-D. *Uddhava Gita - featuring Saratha Darsini commentary by Srila Vishvanatha Cakravarti Thakura* (translated by Bhumipati dasa) Kolkata, Touchstone Media, 2007, p 563.

Environmentalists, engineers and lawyers, naturally, emphasise *adhyatmic* issues, albeit for different reasons. Environmental scientists tend to emphasise *adhibautic* factors, commonly the role of their preferred aspect of the environment, geology, geomorphology or hydrology, while physicists and religionists lean more towards *adhidaivic* explanations and the role of fate or chance. So, who among these are the more correct?

4. Disaster of September 18-19, 2010

Almora District lies in central Uttarakhand State in India's Kumaun Lesser Himalaya (Fig. 1). Almora town was the former capital of the Kumauni kings and, in British times, a hill station. It straddles a steep, north-east-southwest trending mountain ridge and, as it develops, it is spreading down these slopes, especially on the north-western side.

On 18/19 September, 2010, rainfall, unprecedented in 60 years of record, turned Almora District into a disaster area that became headline news. At intensities that exceeded 33 mm/hr between 09.00 and 13.30 hrs, a late monsoon storm dumped 177 mm of rain during September 18 and a further 100 mm on September 19, 2010. This downpour, which followed heavy rain on both September 16 and 17, fell on saturated soil and soaked into rocks and debris already laden with water.

Inevitably, on these steep Himalayan hillsides, this trigger activated a huge number of landslides and debris flows. As runoff and debris swept into the river network, the River Kosi (Kaushilya Ganga) developed an unprecedented flood surge. Its discharge on 18th September, 2010, which climbed to 618.1 m^3/sec, caused severe bank and toe erosion, dealt a further blow to Kumaun's infrastructure, especially its road network. This was, variously, blocked by landslides, undercut by landslides or washed out by river erosion. Much of the network remained impassable in October 2010 when the initial survey was conducted in the study area.

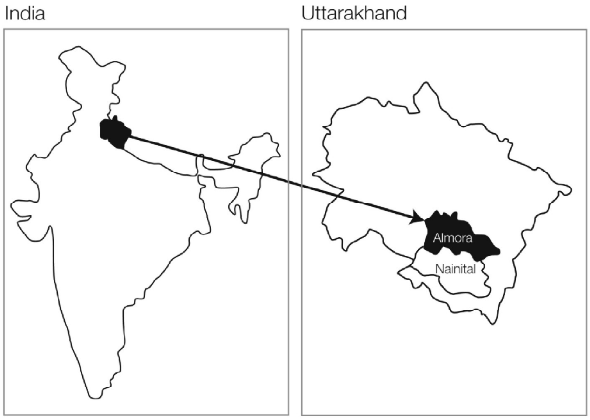

Fig. 1. Almora District, Uttarakhand, India.

Table 1: Disaster damage inventory for Almora District, September 2010 (District Administration, Almora, 2011; Rawat, 2010)

Almora District (Area: 5385 km^2; Forest: 3944 km^2; Agriculture: 1073 km^2).	*Damages*
Population (630,0000) (urban 54%)	80% affected; 5593 resorted to rescue shelters
Lives lost	46
Villages (2244)	1810 (81%) affected
Houses	Destroyed: 422 (partly damaged: 3748)
Schools	Damaged: 219
Agricultural land	2883 ha >50% crop losses (69,000 ha: 0-50% losses)
All roads	4835 km damaged
State Highway	3000 km damaged
Bridges, culverts and causeways	74, 591 and 98 damaged respectively
Estimate cost of damages	Indian Rs. 6,231,056,000 (US$: 125,771,000)

Through the infrastructure of Kumaun University's Natural Resources Data Management System, it was possible to collate and count the human cost of this event quickly (Table 1). Collectively, 80% of Almora District's 836,662 people were affected, 46 lives were lost, and 5600 people were forced to resort to a disaster-relief rescue camp (District Administration, Almora, 2011; Rawat, 2010). Some 80% of Almora District's 2244 villages were affected, 4170 houses were badly damaged as well as 219 school buildings (District Administration, Almora, 2011; Rawat, 2010).Many livelihoods were lost: 69,000 hectares of crop land were damaged and 2883 hectares destroyed. Altogether, 11,109 families lost land to landslides and many small businesses were wrecked (District Administration, Almora, 2011; Rawat, 2010).

In Almora District, 4835 km of roads were damaged, including almost 3000 km of State Highway (Rawat, 2010). In the aftermath of the disaster, many communities found themselves cut off from road communication. In fact, the region's road network suffered such massive damage that some reaches were thought unrecoverable – despite the scores of vehicles trapped or buried upon them. Travel became a matter of finding links among such roads as survived. The modern main roads to both Almora and, her sister hill station, Nainital, were disrupted and for a while the only way to reach either was by the original motor road constructed during the British period. In total, 74 bridges, 591 culverts and 98 causeways were wrecked. Similar figures affect other aspects of infrastructure such as water pipelines and public buildings (Rawat, 2010). First estimates of the cost of the damages are Rs. 6,231,056,000 or U$125 millions (District Administration, Almora, 2011; Rawat, 2010).

4.1 Searching for Causes

Inevitably, in the aftermath, local communities were concerned to know about the causes of the problem and what may be done to make sure that the impacts of future calamities are less? The problem is that the answer is likely to be 'not much'. Scientific commentary, like that from India's *Current Science* journal, consists of little more than a hand wringing overview. Their report by Sati et al. (2011), while nicely written, merely highlights the fact that Indian research into hazards and disasters remains mired in an ancient, reactive and descriptive mode. Ultimately, the report does little more than echo the assertions and assumptions of its many predecessors in the past 40 years (Pande, 2006; Raautella and Paub, 2001). This is unfortunate because, hopefully, landslide hazard research has moved on.

Possibly, the real problem is not a scientific issue but a prejudice and there is little that is more effective in holding back both real investigation and deep understanding. The prejudice, here, takes the form of the common knowledge that these landslides are largely, self-inflicted. They are the result of human development impacts in the Himalayan environment, especially road construction (Sati et al., 2011; Bruijnzeel and Bremmer, 1989) and sometimes deforestation (Tolia et al., 2004). There may be other contributing agents, among which geological and neotectonic factors are overwhelmingly predominant (Pande et al., 2002; Rautelaa and Lakhera, 2000). However, the most usual prescription is that their causes are overwhelmingly human induced (*adhyatmic*) albeit abetted by environmental processes such as geology (*adibhautic*). The only aspect that is counted *adhidaivic* is the rainstorm itself, although even that may be impacted by human-induced climate change. The only problem with such a viewpoint is that, in many respects, it is quite wrong. However, proving this point involves detailed study of landslide activity.

5. Case Study Research Area: Almora Lower Mall

This chapter's case study addresses a reach of rapidly (sub)urbanising mountain highway, which cuts across a steep, north-west facing, mountain ridge on the edge of Almora in Uttarakhand's Kumaun Lesser Himalaya (Fig. 2). It involves a detailed exploration of the causes and character of the 108 landslides that were activated during the September 18-19, 2010 monsoon storms and that consequently deposited debris on a 7.3 km of the Almora's Bypass, Lower Mall Road (Figs 2 and 3). This particular road section has some special significance because, since 1985, it has been the subject of regular scientific study (Haigh et al., 1988; Haigh et al., 1995; Haigh, 2002).

This report focuses on data collected in 2010 and on the diagnosis of landslide causes. It adopts the quantitative and statistical approach to the analysis of landslides frequencies and their correlates that this project, earlier, helped to pioneer (Haigh, 1984). Statistical approaches to landslide hazard

Fig. 2. Almora Lower Mall – south-westerly view.

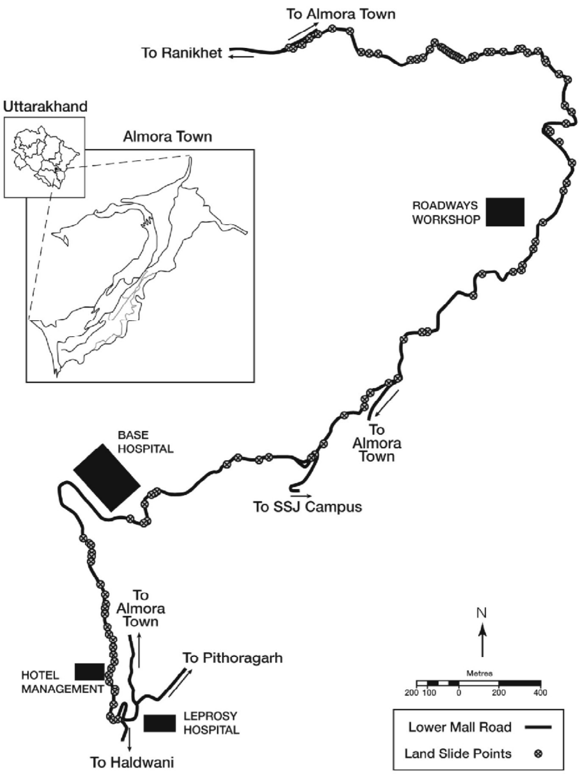

Fig. 3. Landslide locations along the Almora Lower Mall, Uttarakhand, September 2010.

analysis emerged in the 1970s and, because of the advance of GIS technologies, they are now commonplace (Carrara et al., 1982; Magliulo et al., 2009; Guzetti et al., 1999). This example explores the local environments of landslide activity and the volume of the landslide outfall in 2010. The factors examined include landslide type and locationas well as environmental contextual factors, such as slope, lithology, geology, forest cover and the character of recent development. As always, the study accepts the caveat that establishing a statistically significant relationship does not necessarily imply any causal link (Haigh et al., 1988; Magliulo et al., 2009).

6. Site Description

The Lower Mall, Almora, runs along the flank of the Almora ridge from Pandekhola (29º36′42.2″ N, 79º38′56.7″E) to Karbala (29º35′05.1″N, 79º38′23.2″E) at 1440–1560 metres altitude (Haigh et al., 1993). As the map of Fig. 3 confirms, the roadcut's aspect is mainly north-westerly, although its most northerly section faces south.

In 1985 and 1995, aspects of the road environment were sampled by detailed record taking at and between each 200 metre PWD benchmark along the road (Table 2). These records suggest that the average true-bearing of the

Table 2: Site description: Almora Lower Mall (Haigh et al., 1993)

Site Description Variable	*Mean Value (s.d.) – Year of Record*
Hillslope angle above the roadcut (degrees)	22.0 (9.0)
Hillslope angle below the roadcut (degrees)	37.0 (9.0)
Roadcut height (m)	5.7 (3.2)
Roadcut angle (degrees)	64.0 (1.4)
Road width in 1985 (m)	7.4 (1.3)
Retaining wall reinforced roadcut (m per 100 m)	9.4 (12.5) – 1985/ 9.1 (20.06) – 1995
Retaining wall on road's downslope side (m per 100 m)	44.6 (22.6) – 1985
Geological dip (degrees)	18.0 (6.0)
Horizontal discontinuities per metre	145 (80)
Vertical discontinuities per metre	16 (15)
Enlarged joints in rock (%)	30 (24)
Depth of regolith (m)	1.0 (1.7)
Roadbed affected by undermining (m per 100 m)	48 (31) – 1985
Loose scree downslope of roadbed (m per 100 m)	12.0 (20.4) – 1995
Roadbed affected by rockfall debris (m per 100 m)	25.3 (26.4) – 1985/ 31.9 (45.6) – 1995
Roadbed affected by slumping debris (m per 100 m)	17.8 (16.0) – 1985/ 18.0 (20.1) –1995

roadcut face is 300° and the average road width is 7.4 metres. The road is cut into rocks of the Precambrian age within the Saryu Formation of the Almora Crystalline Group in the Almora Nappe (Valdiya, 1980, 1988). The northern part of the road (near Pandekhola) is cut into Sitlakhet schist while the remaining part of the road lies on the Dhamas quartzites, which is interbedded with mica schists (Valdiya, 1980; Kumar et al., 1997).

Structurally, the study area lies on the crystalline zone of the Almora unit that is normally known as the Almora Nappe – a thick folded sheet of Precambrian, medium-grade, metamorphic rocks. The rock's average dip is 18° (s.d. 6) and the true-bearing of the dip 069°. However, while the anti-dip aspect of much of the roadcut restricts the development of translational landslides, in reality, there are sufficient rock discontinuities to allow the geology an apparent but effective dip to the road-bed. In many other places, especially embayments, the road is cut through former landslide debris and alluvial/colluvial valley fill, which is often used for terraced agriculture.

Inevitably, the construction of the new Almora bypass set off a spate of suburban development. This was a focus of attention for the 200-metre unit survey of 1995. In 1985, tree cover upslope had been estimated as 14 (s.d. 16) m-per-100 m (i.e. %) of roadbed and downslope 56 (s.d. 16). In 1995, the figures were 11.8 (s.d. 14.3) and downslope14.5 (s.d.12.7). Nevertheless, the land-use class 'forest' was applied to 21.6 m-per-100 m of roadbed (s.d. 33.2), while 7.4 m (s.d. 15.6) was classed as 'agriculture', 39.7 m (s.d. 37.3) as barren, and 28.1 m (s.d. 33.8) as urban. The team recorded 1.5 (s.d. 2.3) new buildings per 200 m of roadbed and found 5.9 m-per-100 m of roadbed (s.d.10.4) to be affected by new construction. In 1985 around 43 m-per-100 m, and in 1995 around 50, of the roadbed was affected by debris from either slumping or rockfall landslide activity, with the dominant process being the ravelling of weathered rock fragments from roadcut faces.

7. Methodology

Back in 1985, this project was set up to monitor time-dependent changes in the patterns of landslide generation along this 7.3 km reach of, then newly constructed, hill road and the approach to landslide survey remains essentially the same. From the start, the aim was to define, quantify and measure all accessible morphological and contextual components of the landslide system. These include details of the landslide type, landslide scar and, where present, outfall dimensions for volume estimation, and the roadcut (height, angle, orientation, road width and details of any retaining walls constructed), which collectively represent the disturbance caused by the creation of the road. It also includes a suite of contextual variables such as slope angle, geological structure, lithology, water flow-lines, tree and vegetation cover, depth of soil and subsoil regolith, and finally, some variables relating to land-use and development. In the 2010 survey, these included present/absent records of possible influences on individual slides caused by house construction, the presence of another road upslope, the reactivation of an ancient landslide, the collapse of agricultural terraces, which are often undermanaged in suburban areas, and the collapse of a roadcut retaining wall, which is often undermaintained in more rural areas. For analysis, these variables were converted into present = 1, absent = 0 variables. Some other categorical variables were transformed into ordinal scales by the creation of indices. Hence, lithology was converted into a rock-hardness index that ran from 1, loose debris, through 4 schist to 7 quartzite and the plan form variable that describes the water-flow lines to an index that scored convergent flowlines as –1, parallel flowlines as 0, and divergent flowlines as +1. As in previous surveys, the 2010 survey sought to record every possible causal variable that could be recorded in the field at every incident of landslide activity to a minimum size of about one cubic metre (Haigh et al., 1993). The instruments used were simple: tape measure, compass, abney level, clinometer, yardstick, and in the present survey, handheld GPS. This last heralds a new phase in the study, which hopefully, will be continued by the more modern means of GIS.

This said, the 2010 survey was exceptional in three respects. First, it was undertaken within three weeks of the exceptional and catastrophic events of September 18, 2010. This meant that, unlike earlier Almora surveys, landslide scars were fresh and largely unmodified and, more critically, that it was possible to collect a near-complete suite of records for the landslide outfalls. Second, the survey was undertaken by a particularly skilled team of surveyors (Umashankar Negi, Gokhul Singh Rana, Arbind Anand, Pradeep Tiwari and Vikrant, all scholars of Kumaun University), which included some with formal mountain climbing training. Historically, the project was based on field survey that was largely conducted from the roadbed (Haigh et al., 1993), which meant that those variables that could be directly accessed from the roadbed were recorded most accurately and those further away less accurately. However, this team was both determined and, frankly, courageous enough to scale each major landslide, at least as far as the top of its debris cone and typically to the top of its scar (Figs 4 and 7). This means that the 2010 measurements of scar and outfall length as well as scar width were recorded very accurately.

As previously, data analysis involves a battery of statistical methods including correlation, regression, discriminant analysis and T-testing. Non-parametric Spearman's correlation is used because, while it is numerically similar to the more usual Pearson's, it is also more appropriate for diverse data sets. For similar reasons, stepwise discriminant analysis is used to sift out those variables that collectively describe the bulk of the variance. This report, however, emphasises T-tests for the comparison of means and the establishing of differences, arguably causal differences (and the reasons for this are established in the first paragraph of the results section that follows). The focus of these statistical tests is the comparison of landslide records at sites where a particular impact was recorded versus those where it was not. However, in

Fig. 4. Landslide field survey, September, 2010.

the case of scalar variables, T-tests were used to compare the largest third of the data exhibiting with the smallest third. All these tests are based, formally, on a suite of multiple working hypotheses, as detailed previously (Haigh et al., 1993). These working null hypotheses argue that landslide outfall volume at landslide sites that are strongly affected by variable 'X' are not significantly different from those at sites where that variable is not strong.

8. Results

The first finding from the survey is, in many respects, the most surprising. This concerns the number of landslides recorded along the 7.3 km test reach of roadway – 108. This number sounds a great deal but it is by no means unusual. The project's records show that 112 landslides were recorded in 2000, 108 in 1995, 106 in 1990 and 88 in the original survey of 1985 (Fig. 5; Haigh et al., 1993). The result confirms that, whatever other impacts the catastrophic event of September 18 and 19, 2010 may have had on slope failure along the Almora Lower Mall, it did not increase the number of active landslides. It is not yet certain whether or not these 108 events were the same landslides that had operated in previous years, although, in many cases, this seems likely. Of course, it is a popular misconception that landslides are individual one-off events. For the most part they are not. The majority are systems that develop, fade away and sometimes reactivate over extended

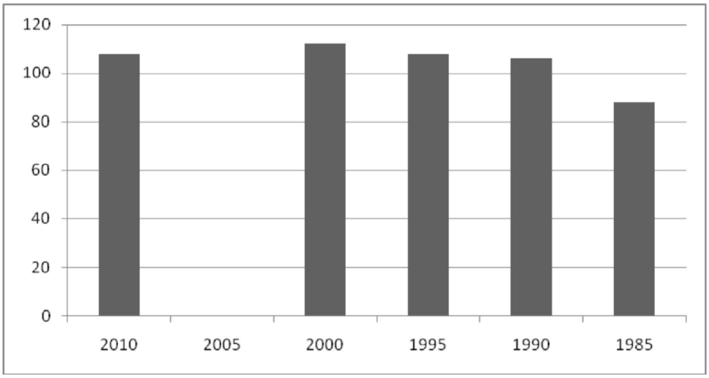

Fig. 5. Number of recorded landslides, Almora Lower Mall, 1985-2010. (Since the numbers are fairly constant, the key issue becomes difference in the sizes of landslides.)

periods of time (Haigh, 2002). However, this specific finding shows that the effects of this storm were not exceptional in terms of the numbers of landslides activated. Their impact mainly concerned the degree of activation of each landslide and the volume of debris each produced. In turn, this implies that the search for causes and correlates of landslide damages should address those factors of the system that are associated – not with landslide creation but – with landslide outfall volume.

Table 4 displays some general results from the survey of individual landslide dimensions and attributes, which was undertaken in October 2010. This includes derived variables such as average landslide outfall volume and scar area. Differences in these two measures is partly due to unpacking and the lower density of outfall deposits but some is also due to the partial obscuration of the landslide scar by the debris plug, especially in the case of active or reactivated rotational slips and slumps. Additionally, Table 4 displays the main environmental contextual (*adhibhautic*) factors and the main possible (*adhyatmic*) human influences, which begin with the dimensions of the roadcut and road and continue with records of the proportion of sites affected by other kinds of human agencies.

9. Discriminating Causes: Who or What is to be Blamed?

The first question asked after a landslide disaster usually concerns who or what is to be blamed and what caused the largest landslides? Stepwise discriminant function analysis is a useful way of screening complex lists of variables to find those that are most important (Klecka, 1975). For this analysis, the data set of 108 landslide outfalls was divided into three equal groups: small, medium and large, based on their ranking by volume. An attempt was

Table 4: Landslide sites on the Almora Lower Mall, Uttarakhand, 2010

Landslide volume	*Mean*	*Std. deviation*
Debris cone volume (m^3)	199	667
Scar volume (m^3)	122	251
Scar area (m^2)	670	1248
Environment of Landslide Sites	*Mean*	*Std. Deviation*
Slope up degrees	31.09	18.341
Tree cover up (%)	27.45	31.376
Ground vegetation cover (%)	73.84	34.033
Soil depth (m)	.219	.1145
Overburden depth (m)	1.69	1.865
Rock strength index	3.0545	1.80639
Apparent rock dip to the road (degrees)	13.66	25.970
Channel incision (frequency)	.06	.245
Reactivated landslide (frequency)	.05	.209
Human Influences at Landslide Sites	*Mean*	*Std. Deviation*
Roadcut height (metres)	5.81	4.78
Roadcut angle (degrees)	78.1	12.8
Agricultural terrace collapse (frequency)	0.30	.460
House construction impact (frequency)	0.19	.395
Impact of road upslope (frequency)	0.15	.363
Retaining wall collapse (frequency)	0.10	.301

then made to reclassify these landslides back into the two extreme categories using only contextual variables. The discriminant function reproduced the initial categories using just three variables: slope angle upslope, roadcut height and landslide type. At either extreme, the classification function was 95% efficient. It incorrectly assigned just one of the largest and two of the smallest into the opposite category. Table 5 compares the mean values for each of these three variables in these two key categories. It shows that the largest landslide outfalls are associated with the steepest upslopes, the highest roadcuts and more slump-like landslides.

Table 5: Largest vs smallest landslides, Almora Bypass, 2010

Landslides in 2010 mean (Standard deviation)	*Slope angle upslope (degrees)*	*Height of the roadcut (m)*	*Landslide type index (Gravitational: 1; Flow: 5)*
36 largest slides in 2010	41.20 (S.D. 12.64)	8.09 (S.D. 6.95)	4.17 (S.D. 1.30)
36 smallest recorded slides in 2010	22.69 (S.D. 16.81)	4.15 (S.D. 2.10)	3.03 (S.D. 1.30)
All 2010 landslides	31.09 (S.D. 18.34)	5.81 (S.D. 4.78)	3.68 (S.D. 1.39)

Bivariate correlation analysis indicates that outfall volume associates most strongly with hill-slope angle upslope (*rho*: 0.417; $p < 0.0005$) and with active channel incision (*rho*: 0.0245, $p = 0.006$). Higher slope angles upslope also correlate positively with stronger rocks (*rho*: 0.374; $p < 0.0005$) but negatively with the depth of loose debris on the slope (*rho*: –0.224; $p = 0.010$) but not directly and significantly with landslide volumes. Channel incision is, of course, closely associated with water concentrating slopes (*rho*: 0.415; $p < 0.0005$), greater depths of overburden (*rho*: 0.210; $p = 0.014$) and weaker rocks (*rho*: –0.253; $p = 0.004$). The pattern confirms the obvious, which is that, following the rainstorm, flow-related processes were a dominant aspect of landslide activity and also the less obvious, which is that the role of geological factors is greatly muted or indirect.

10. Comparing the Large and Small Landslides: T-tests

To explore what further factors determine whether a landslide outfall will be large or small, this study used T-tests to compare the characteristics of the landslides producing the largest third and the smallest third of the ranked outfall data set. The null hypothesis is that there is no significant difference in any of the human impact related (*adhyatmic*) factors or environmental (*adhibhautic*) between the largest and smallest thirds of the landslide outfalls and, with a few exceptions, this is largely confirmed.

The largest landslides differ significantly from the smallest landslides in being more flow-like features ($p = 0.001$), which are generated from steeper slopes (41 vs 23 degrees, $p < 0.0005$), higher roadcuts (8.1 vs 4.2 m: $p = 0.003$), in sites where the water flow lines concentrate ($p = 0.033$) and there is active channel incision ($p = 0.023$). Where they emerge from bedrock, the larger slides are more associated with the more massive quartzitic rocks than schists ($p = 0.043$).

To explore further the factors that determine whether a landslide outfall will be large or small, this study also used T-tests to compare the characteristics of the landslides produced when other commonly cited landslide control variables are examined in a similar way by comparing the largest third and the smallest third of their data sets (or presence/absence for occurrence-based data). The null hypothesis remains that there is no significant difference in the size of the recorded landslide outfalls in 2010 at sites recording the largest and smallest thirds of any of the human impact related (*adhyatmic*) factors or environmental (*adhibhautic*) variables. As the following sections demonstrate, with the few exceptions mentioned above, this is largely confirmed.

10.1 Adhyatmic Factors: The Human Impact

A very common assumption in Almora at the time of the disaster was that human actions, especially recent changes in the urban landscape, were major causes for the landslide. Correlation analysis suggests that roadcut height is the only *adhyatmic* factor that is significantly associated with outfall volume (rho: 0.220; $p = 0.013$) and that this also correlates with the key environmental variable, slope angle (rho: 0.294; $p = 0.001$).

T-test comparison between the largest and smallest third of the roadcuts shows that the highest roadcuts are found on significantly steeper slopes (36.8 vs 26.5 degrees, $p = 0.008$), stronger quartzitic rocks ($p < 0.0005$), with less overburden of loose debris ($p = 0.002$) and more southerly slope aspects, an aspect of geological structural control ($p = 0.003$). Of course, roadcut height is a measure of how much the hill-side upslope was undermined during the construction of the road and the steeper the slope, the greater that undermining has to be to create a sufficient bench for the road itself. In the 1985 survey, this disturbance was relatively recent but now it is long past. However, there remains the possibility that through accelerating rock weathering, through the pressure-release of rock joints, and through making the hillside more vulnerable to other kinds of landslide trigger, it remains a key impact (Sati et al., 2011; Gray and Leiser, 1982). These T-test comparisons between the largest and smallest third of the roadcuts also show that the highest roadcuts have significantly larger landslide scars (156.9 vs 64.3 m^3, $p = 0.032$), larger debris outfalls (216.8 vs 73.7 m^3, $p = 0.027$), and more reactivated landslides ($p = 0.014$). These results support the earlier discriminant and correlation analysis, which identified the height of the roadcut as the key human impact on landslide debris production.

Of course, road engineers are well aware of the problems that are associated with higher roadcuts and they take action to protect those sites that seem most vulnerable. One common action is to provide support to the roadcut in the form of a retaining wall. Of course, this reinforcement is not always a success, especially if the retaining walls are not maintained. In the 2010 survey, collapsed retaining walls were associated with 11/108 landslides. T- testing comparison of these sites with the others shows that landslides associated with retaining wall collapse were found on significantly lower strength rocks, often loose debris ($p = 0.003$), slopes with lower angles (9.6 vs 33.3 degrees, $p < 0.0005$) and with less forest (8.2 vs 29.6% cover, $p = 0.008$) upslope of the road. However, it also shows that the landslides that resulted from retaining wall failures were relatively small compared to the others along the road (debris volume: 13.7 vs 218.5 m^3, scar volume 15.0 vs 133.8 m^3, $p < 0.0005$). The conclusion is that retaining wall collapse is not responsible for 2010's enhanced landslide volumes.

Where roads crisscross hillsides, those at the upper level can have impacts on those lower downslope (Fig. 6). These impacts can be due to traffic vibrations, loading and creep affecting the downslope roadcut's strength. They can also involve accelerated drainage and runoff from the upslope roadbed, its drains and culverts, which may affect the flow in minor channels and hence enhance channel incision. They can also contribute sediments, which may find their way across the roadbed or are shovelled downslope during road

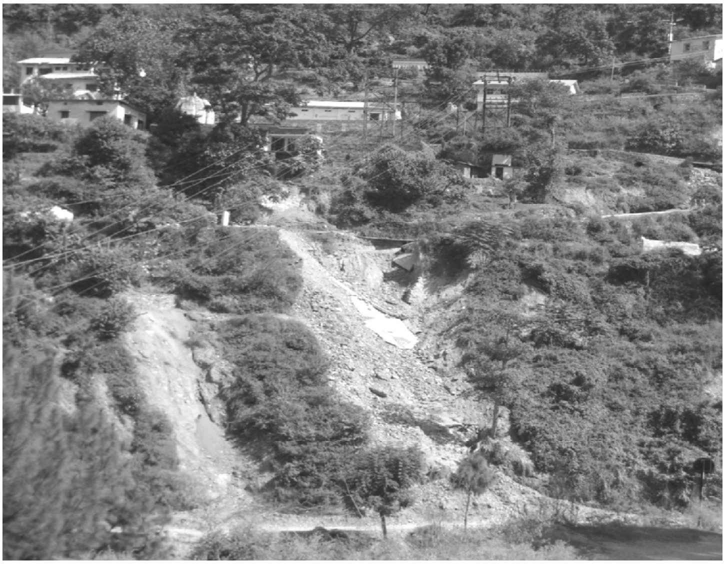

Fig. 6. Impacts of roads upslope on landslides, Almora Lower Mall.

clearance. As previously described, the impacts of instability associated with road construction can be more damaging downslope than upslope of the road (Haigh et al., 1987). In 2010, such problems affected a sixth, 17/108, of the landslides on the Lower Mall Road, Almora. However, T-tests show that, on an average, this impact is associated with smaller landslide outfalls and smaller landslide scars (62.8 vs 225.5 m^3 and 63.8 vs 132.6, $p = 0.040$). So, this also cannot be considered a general factor in the enhancement of landslide activity in 2010.

Of course, more human impacts in the landscape affect the development of landslides on roadways than simply those linked to the engineering of the road itself (Howell, 1999). Among these, three are very commonly mentioned in environmental commentaries. They are: deforestation (Dapples et al., 2002; Gray and Leiser, 1982), building and construction activity (Sah and Pande, 1987) and neglect of the agricultural landscape, especially the collapse of agricultural terraces (Glade, 2003; Gerrard and Gardner, 2002).

The relationship between landslide activity and forest cover along these roads has already been subject to detailed investigation and with results similar to those added here (Haigh et al., 1995). Here, T-test comparison of 2010 data recorded on that third of the sites of landslide activity that had the greatest tree cover upslope and that with the least tree cover show that those with greatest tree cover survive on slopes where the apparent dip of the rocks towards the road is significantly greater (19 vs 6 degrees; $p = 0.042$), where the depth of soil is more (0.28 vs 0.17 m; $p < 0.0005$) but loose debris is less (1.1 vs 2.7 m; $p < 0.0005$), and where there is less house construction ($p < 0.0005$). However, as in previous studies, it was the sites with the most tree cover that supported the larger landslide outfalls, 303 vs 95 m^3, and, even if these differences are not statistically significant ($p = 0.32$), the relationship is counter intuitive. Theory demands that slopes with the most depleted forests should generate the greater landslide outfalls but here the situation is reverse. Only one result suggests that greater tree cover might be associated with reduced slope instability and this is that sites with fewer trees displayed a significantly smaller incidence of retaining wall collapse ($p = 0.014$). In general, as determined previously, trees persist only on those slopes that are too unstable for development, so more trees means more landslide activity (Haigh et al., 1995). In sum, there is little in these data to suggest that deforestation is currently a positive influence on landslide outfall volumes.

New construction was widely blamed for the enhanced landslide activity of 2010 (Sati et al., 2011; Sah and Pandey, 1987). Suburban development has become the most obvious landscape change along this roadway in recent years and new constructions sustained a disproportionate amount of the damage caused by the storm of 2010. Field survey records show that new construction was linked to 21/108 landslides. T-testing, again, allows comparison of those sites where landslides are linked to this cause with those where they are not. Those where house construction was linked to landslide activity had significantly weaker rocks ($p = 0.004$), more gentle slide plane angles (44 vs 53 degrees; $p = 0.003$), lower roadcuts and they had fewer trees (15 vs 30%, $p = 0.019$) with less ground vegetation (53 vs 79% cover; $p = 0.011$) than elsewhere, although this loss of vegetation was probably a consequence of the construction. There was a significantly negative association between house construction and problems from roads upslope ($p < 0.0005$) and agricultural terrace collapse ($p = 0.033$). Most critically, there was no significant difference in the sizes of the landslides or outfalls in places where new construction was identified and those where it was not considered a factor. Hence, there is no evidence that it was a factor in the enhancement of landslide activity in 2010.

Gerrard and Gardner (2002) were among the first to popularise the notion that the agricultural terraces that line these steep Himalayan hillsides (and that are frequently cited as exemplars of best agricultural land management practice), are major sources of landslide sediments. In fact, their observation allows a useful point about sustainable development. Of course, sustainable, from its Latin roots, means to hold up; the term implies maintenance. In the case of agricultural terraces, that maintenance has to be continual. Each year, terrace risers become damaged and degraded and each year, they have to be restored and repaired. When this does not happen, the terraces soon begin to collapse with any water that they collected for agricultural use now abetting their slumping downslope.

Sadly, Kumaun University's SSJ Campus in Almora provides a dramatic illustration of the process at work. During the 1980s, campus expansion determined that the University would purchase some adjacent terraced farmland.

As it did so, maintenance ceased and the terraces, many of which were constructed on old landslide debris, began to slump. In fact, these relatively surficial changes seem to have been party to the activation, probably reactivation, of a much larger and more deep-seated landslide plane. Today, the campus rides on top of the largest landslide complex along the Lower Mall Road. Active slumping continues despite massive remedial works that include drainage and the construction of huge retaining walls, which protect the Lower Mall Road and help support the playing-fields and other structures upslope. As survey work proceeded in 2010, the road leading up from the Lower Mall to the SSJ Campus remained closed due to landslides and another team from the Kumaun University Department of Geology was at work assessing damages to University buildings.

Previously, Rawat (2000), responding to the onset of catastrophic mass movement during severe rain in September 1993, established the environmental controls of an expanding problem. His report does not emphasise any association between this problem and land use change, although it does warn against undermining. This undermining, of course, began, albeit very mildly at this location, with the creation of the roadcut and continued with land forming for the University's buildings and playing fields. It was enhanced by flow within the same subsurface aquifer that made the previously terraced agricultural fields so productive. However, the question remains open as to whether this slide is associated with new construction and drainage arrangements associated with the University, more directly with the creation of the roadway, or whether it is something larger that the roadway accidentally traverses (Haigh, 2002). In 2010, as well as previously, the bulk of the mass movement associated with this feature occurred either at a considerable distance, tens of metres below the roadway or above the roadcut. However, in 2010, while movement of the main slide impacted elsewhere, the Kumaun Campus retaining walls protected the Lower Mall Road and there was little debris on the roadbed.

Elsewhere, the collapse of poorly maintained agricultural terraces was linked to nearly a third, 33/108, of the landslides recorded. These landslides emerged from lower roadcuts (4.6 vs 6.4 m; $p = 0.021$) but they differed, significantly, from the other landslides mainly by being smaller (60 vs 148 m^3; $p = 0.018$). They also produced less, if not significantly less, debris. However, the association of terrace collapse with smaller landslides suggests that this was not an important factor in the enhanced debris production of 2010.

In sum, then, the only human factor that was positively and significantly associated with enhanced landslide activity was roadcut height, which is a measure of the undermining of the hillside upslope. Deforestation, new construction, the collapse of agricultural terraces, the collapse of roadcut retaining walls, and impacts from other roads on the hillside had no significant effect.

Fig. 7. Who should we blame?

10.2 Adhibhautic Factors: The Role of the Local Environment

Geological factors provide the dominant theme in those discourses that aim to explain landslide vulnerability in terms of the external, natural environment. Here, the road cuts through folded and fractured rocks and, for much of its length, traverses areas where the rock discontinuities tip the rocks towards the road bed (Rawat, 2000). Previously, there was great interest in the rock control of geomorphological features including landslides (Suzuki, 2002) and here the road environment is dominated by three contrasting lithologies. These three rock types are hard, massive quartzites, finely foliated and easily weathered mica-schists, and loose debris – much derived from previous mass movement and the balance from colluvial and alluvial processes. In places, more or less deep soils have developed above these geological levels, where they are more or less stabilised by forest and ground vegetation (Valdiya, 1980).

Geomorphology, the shape of the land, is also important. In combination, tectonic uplift and rapid river incision has created a landscape with very steep slopes and the Lower Mall is cut across the upper convexity of such a hillside. However, this hillside is itself complicated by the incision of minor channels, which are not unusually linked to landslides and to fault lines and other lines of seepage and weakness in the underlying rocks. Much of the length of the Lower Mall winds in and out of these minor valley embayments that bend the contours along this mountain ridge. So, these features also complicate the planform of the roadcut into sites where water flowlines merge and flow is concentrated, sites where the water flowlines run parallel and sites where they diverge. In a rainfall disaster, it might be predicted that sites with convergent flowlines and where active channel incision is recorded might prove to be the most engaged with landsliding.

Analysis here begins with the main geological factors starting with degree to which geological discontinuities tip the rock towards the road. This is the apparent, rather than the true geological, dip, the dip measured normal to the road. Analysis compared the means of this factor in the third of the records where this factor is most strongly expressed with the third where it is least strongly expressed and excluded all sites where the rock type is 'debris' and no apparent dip is expressed. Results show significant differences between the two sets with orientation of the roadcut ($p = 0.002$), that is with alignment with the true geological dip, and less strongly to the numbers of discontinuities recorded in the horizontal plane ($p = 0.011$). However, the measure correlates with nothing else. Records for the size of the landslide scar were almost identical and while outfall were larger on sites with lower apparent dip, neither difference was remotely significant. The results indicate that there is some influence of the dipslope but not that this affects the degree of landslide activity.

The influence of rock type was determined by comparing debris-dominated sites with the others. This showed that debris-dominated sites had significantly more convergent water flowlines ($p = 0.034$), deeper overburden ($p < 0.0005$), a greater incidence of channel incision ($p = 0.007$), more flow-type failures ($p < 0.0005$) as well as more house construction ($p = 0.003$) and less upslope ground vegetation ($p = 0.004$). However, there were no significant differences between the mean size of the landslide's scars or outfall volumes. The conclusion is that rock control affects landslide type but not so much mean landslide size. Soils are commonly implicated in shallow surficial slides. However, comparing sites with deeper soils with those with more shallow shows nothing more than deeper soils have significantly more vegetation ($p = 0.003$).

Fracturing and structural weaknesses in the rocks are another factor that is frequently mentioned in connection with the rock control of landslides. In this case, there was a distinction between the massively bedded and jointed quartzite and finely foliated schists of the road cut. T-test comparisons of these two rock types showed that the harder quartzites had significantly higher roadcuts ($p = 0.005$), much less loose overburden ($p < 0.0005$), much less construction ($p = 0.004$) and were more rotation and slump type failures than the schists ($p = 0.008$). However, there were no significant differences between the mean sizes of the landslide scars or outfalls.

The conclusion is that, whatever may be the role of geological factors in landslide initiation, they have relatively little direct influence on landslide size, at least as far as the record from the 2010 disaster is concerned. However, it may be that geomorphological factors, which are often indirect expressions of geological controls, have a greater and more immediate influence. Here these include slope angle, slope planform, which affects water concentration, and the presence or absence of channel incision at a landslide.

The earlier discriminant analysis has already suggested that slope angle upslope is a powerful control of landslide activity and volume. Here, T-testing compares the characteristics of those landslide sites developed on the third most-steep slopes in the data set with those on the least-steep third.

The results show that the steepest slopes that generated the larger outfalls had significantly stronger quartzitic rocks, with fewer beds ($p = 0.018$) but more joints ($p = 0.043$), and less overburden.

In line with the discriminant analysis, the T-tests show that the largest landslide outfalls formed below the steepest hill-slopes (250 vs 20 m^3, $p = 0.002$). They also show that these steeper slopes included significantly larger landslide scars (199 vs 25 m^3, $p = 0.001$) above higher roadcuts (8.6 vs 4.0 m^3, $p = 0.001$) but with less loose debris ($p = 0.008$) above much stronger bedrock ($p < 0.0005$). The landslide sites on these steepest slopes showed significantly fewer incidences of agricultural terrace collapse ($p = 0.046$), retaining wall collapse ($p = 0.003$) and impacts from roads upslope, mainly because these land uses have greatest effect on weaker rocks and because development focuses on the more gentle slopes with deeper soils.

Planform embayments are water concentrating sites, which, naturally enough, are significantly more likely to be flow-type slope failures ($p < 0.0005$) and have landslide sites associated with deeper soils ($p = 0.011$) and channel incision ($p = 0.006$). These embayment sites are also more likely to be affected by new building ($p = 0.038$). However, there is no significant difference between the landslide scars or outfalls within or outside embayments.

Just 6/108 landslide sites were associated with local channel incision and this small sample size may explain why, although these places had much larger landslides than elsewhere, the differences were not significant. Of course, these were very significantly linked to slopes with water concentrating flowlines ($p < 0.0005$), more vegetation ($p = 0.004$), deeper soils ($p = 0.008$), loose debris rather than bedrock ($p < 0.0005$), and the reactivation ($p = 0.025$) of more slump-flow type landslides ($p = 0.0200$) as well as the collapse of associated retaining walls ($p = 0.001$).

A similar number of events were also positively identified as reactivations of older landslides. These were all associated with loose debris ($p < 0.0005$) and were strongly linked to the collapse of either agricultural terraces ($p = 0.005$) or roadcut retaining walls ($p < 0.0005$). On average, these reactivated landslides had much larger landslide scars, although the difference was not significant ($p = 0.138$).

In sum, however, although there is clearly a great deal of geomorphological differentiation of both environmental and landslide processes, the only geomorphological factor clearly associated with larger landslide outfalls is slope steepness.

10.3 Adhidaivic Factors: 'Acts of God'

In general then, the case for arguing that either human impacts or attributes of the local environment, especially geological factors, are the key causes of enhanced landslide outfall does not look as strong in reality as it might either in theory or as suggested by ‘informed’ assertion. When these phenomena are truly studied both in detail and across a whole population of landslides, the lack of strong evidence for a particular cause is very striking.

So, the search for causation must move on to explore the third, and least popular, category, which broadly attributes the problem to an act of God. The rainstorm that triggered the Almora landslide swarm and flood disaster is a prime example. The whole Himalayan region is vulnerable to these events and there is a major landslide and flood disaster every few years across the mountain chain (Joshi and Kumar, 2006). Dahal and Hasegawa (2008) linked 193/677 landslide events in Nepal, to a strong log-linear relationship between rainfall intensity and duration and used this to define an ID (intensity duration) threshold described by the line:

$$I = 73.9D^{0:79}$$

where I is hourly rainfall intensity (mm h^{-1}) and D is duration in hours. Previously, Pant (1990) had applied a similar approach to all of the environmental factors that affect landslide activity undertaking work that might have defined a multidimensional envelope for the threshold of landslide activity. His approach involved regression to zero probability for each landslide variable. Meanwhile, these rainfall intensity-duration values demonstrate that with increased rainfall duration, the minimum average intensity likely to trigger shallow slope failures decreases linearly (cf. Guzetti et al., 2007a). Dahal and Hasegawa’s (2008) equation has a coefficient of determination of 0.993 and a functional range of five hours to 30 days. They conclude that when daily rainfall exceeds 144 mm, there is always a risk of landslides in Himalayan contexts, although (Guzzetti et al., 2007b, 1999) advise that such thresholds allow a small possibility for landslides to occur in less extreme conditions and demonstrate that the nature of this threshold varies geographically. Here, the Almora Swarm’s peak intensities, which exceeded 33 mm hr^{-1} between 09.00 and 13.30 hrs, lie slightly above the Dahal and Hasegawa (2008) threshold, while the daily total of 177 mm for September 18, especially when supplemented by 100 mm on September 19, 2010, place this event clearly above the threshold for landslide activation.

Of course the Almora event also affected hillsides already soaked by heavy rain in the previous days. Glade et al. (2000) propose an *Antecedent Daily Rainfall Model*, which includes two factors: rainfall total on the landslide day and rainfall over a previous period, which, while it remains in the ground, acts as a lubricant for both flow and sliding processes. Glade et al. consider that this effect may persist for more than five days, although it diminishes more quickly in steeper slopes with more shallow soils that drain more quickly. This study from the New Zealand School, introduces a more refined threshold concept by recognising minimum thresholds, where no landsliding may occur, and maximum thresholds, where landslides always occur. However, the study’s caveats include that their team finds no link with landslide magnitudes or type. Additionally, it has nothing to say about why, above their maximum threshold, landslides are not universal but remain sporadic in occurrence. The conclusion is that, certainly, the *adhidaivic* factor of rainfall is a critical control of landslide occurrence, but that it is far from being the whole explanation.

There is, however, one further and truly *adhidaivic* factor, which is chance. As the preceding analysis shows, it may be possible to discuss the landslide 'ecology' of Himalayan hill slopes but landslide generation is also affected by processes that are beyond landslide ecology (Haigh, 1993). The signature of these processes is apparent when the distribution of landslide outfalls is graphed. Their general distribution displays a semi-logarithmic rank size relationship (Fig. 8) of the type commonly found in these kinds of researches (Haigh, 2002). Previously, the existence of this distribution encouraged Haigh (1984) to suggest that the relationship could be used as a tool in post-Monsoon road clearance planning. Once, the slope of the line has been determined, the size of progressively smaller outfalls may be predicted by extrapolation down to the minimum size of interest. This would allow the auditing and costing of post-Monsoon road clearance work to be accomplished with minimal field survey investment (Fig. 9).

The landslide frequency distributions, described here by a rank-size rule, provide a power law relation (Haigh, 2002; Brunetti et al., 2009).

$$\log_n N_L = 0.2 \log_n V + 9.11$$

where N_L is the cumulative number of landslides and $\log_n V$ is the cumulative volume of the debris cones (m^3), with $r^2 = 0.81$ (ANOVA significance: $p < 0.0005$). The graph permits the estimation of landslide outfall volume by projection from data of the larger landslides to that of the smallest size that is of interest, in this case an outfall of 1 m^3.

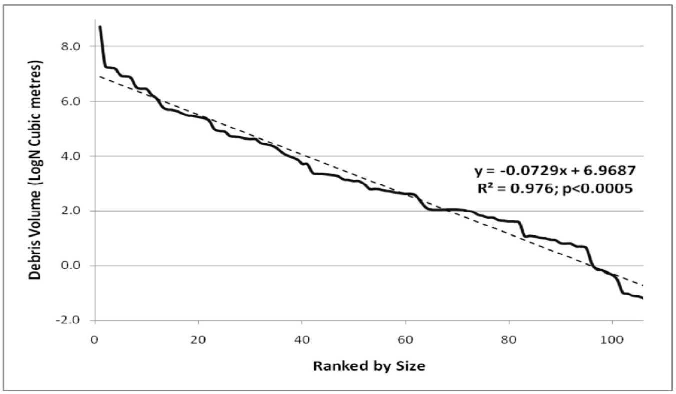

Fig. 8. Landslide rank-size relationship for $\log_n$ Outfall Volume (m^3): Almora Bypass 2010.

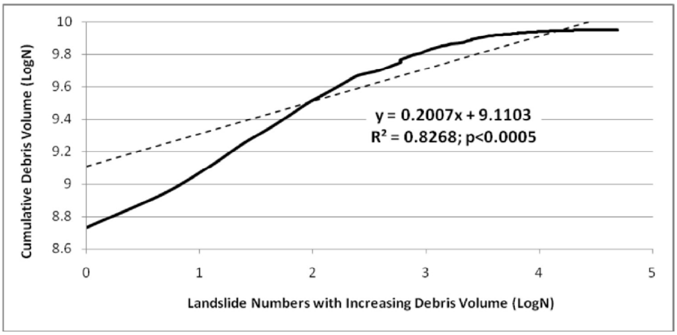

Fig. 9. The increase of total debris volume with increasing numbers of smaller landslides recorded (Natural Logarithm transformed axes) cf. Cumulative Distribution Function.

There are, however, deviations from the trend (Fig. 9), and these may have two sources. First, measurement errors increase (along with the possibility of under-representation) at the lower end of the series. Second, some of the larger landslides at the top end of the spectrum may be larger landscape-scale features rather than creatures of the roadcut itself (Haigh et al., 1992). Similarly, Stark and Hovius (2001) who note that GIS recorded landslide size distributions generally exhibit power-law scaling over range that is set by the unit of measurement or resolution of the map, also caution that the pattern is commonly distorted by under-representation and inaccuracies at the lower end as in this project. However, the authors' earlier work has shown that there may a difference in character between the majority of landslides and those events at the upper end of the graph, which although often obscured by conventional modes of analysis, are recognised as chronic, recurrent or entropy-minimising landslide systems (Haigh et al., 1992).

However, the message from Fig. 9 is that the more you reduce the minimum threshold size for the landslides that you record, the greater the number of smaller landslides and the greater the amount of total debris that will be recorded. Paradoxically, this situation harks back to the pioneering research of Mandelbrot (1967), who sought to answer the question – 'how long is the coastline of the UK'? His answer was that it depends on the size of the measuring rod that used. As the measuring rod is smaller, so the recorded length of the coast becomes larger and larger. It is the same for landslides, which emerge in all sizes from the massive to the molecular. Mandelbrot's achievement was that he found a regular relationship within the relationship between the measuring rod and the measured that he termed the fractal dimension. In fractal analysis, the Cumulative Distribution Function is the probability that an event of smaller than any size will be found in a data set (Brown and Liebovitch, 2010). This can be abstracted from Fig. 8, which includes the observation that the probability of finding records smaller than the smallest outfall measured is 100%.

More important, however, in this context is what the presence of this fractal power law means. In fact, it is a signifier of the presence of mathematical chaos (Wu et al., 2009). Chaos theory is applied widely in the applied environmental sciences and in hazard research, where it remains the only technique available for the prediction of phenomena like earthquakes. The signature of chaos is an event that appears unpredictable in detail but, when explored statistically, contains the regularity implied by the power law. So, while scholars such as van Westen et al. (2006) wonder why landslide risk prediction is so difficult and blame the inaccuracies and shortfall of environmental data, the true answer is much more difficult. It is that, like earthquakes, landslide distributions contain an inherent unpredictability (Pelletier et al., 1997).

In an analogous situation, Lockwood and Lockwood (1997, 2008) explored another 'landslide-like' feature, catastrophic grasshopper infestations in the north-western United States. Ecologists suggest that the nature and extent of these outbreaks is affected by >20,000 factors. However, the size distribution of these outbreaks can be described by a simple power-law, just as in the case of landslides. The reason for the inherent unpredictability of these outbreaks is also similar. The scale of these outbreaks, like those of earthquakes and landslides, depend on a threshold of initiation that is defined by a myriad of small contributing factors (Pant, 1990). Above a certain threshold, the stability of the system be it grasshopper population, fault-line or hill slope, becomes dependent on a complex web of interactions in the process control agents. In fact, they develop such sensitivity to externalities that a small disturbance of any one of a wide range of factors may result in change. Of course, usually, the outcome will be small, more rarely of medium size, but rarely very large – hence the power law relationship. This condition is popularly known as 'the Butterfly Effect' for the reason, in theory, a disturbance as tiny as the flapping of a butterfly's wing could destabilise the whole system – with disastrous consequences.

The existence of this relationship within the larger context of this study has already been identified by the founder of the theory of Self-Organised Criticality (Bak, 1996). Bak worked with computer-generated 'sand-piles' onto which he slowly dropped additional grains. When the grains reached their characteristic cone shape, which has a characteristic slope of approximately 34 degrees, representing the angle of internal friction between the sand grains – the inter-granular frictional strength that prevents the cone collapsing, the form of the cone, of course, remained stable. As more grains were added, the cone grew but it did so by landslides. Each additional grain rolled downslope to add to the next layer of the cone. Sometimes, it carried a few grains with it, sometimes many, and sometimes very many. Collectively, the volume of failures could be described by a rank-size power law similar to that described in Figs 8 and 9.

Of course, even after a massive failure, the continued addition of grains causes the former cone shape, gradually to reinstate itself until, once again, it exists on the edge of collapse. Bak (1996) argued that this was a fundamental process in Nature and applied to all complex systems that developed by slow accretion toward a threshold of failure. Of course, landslide accumulations on Himalayan hillroads are one of the closest imaginable 'Natural' approximations to Bak's sandpiles (Noever, 1993; Bak, 1996). This is why Haigh's landslide records from Uttarakhand's Mussoorie-Tehri road were taken into physics by NASA scientist Noever and echoed by Bak (Noever, 1993; Bak, 1996). However, another very close approximation to the situation on the roads is, of course, that of the Himalaya itself. Here, hillslopes are stressed towards their critical upper limits of stability by, in combination, on-going tectonic uplift and active river incision. This is why Haigh (2002) has argued that the main task for landslide prediction in the Himalaya is first to determine which hillslopes are at criticality, where landslides will be inherently unpredictable and those where they are below criticality, where landslides may be explained by geoecological factors.

Of course, in the case of the roads, proximity to criticality is exacerbated by disturbances emanating from the road and associated development and by the creation of the roadcut, which, by undermining, moves that slope closer to criticality than might otherwise be the case. This might help explain why studies elsewhere, in the Darjeeling Himalaya, the Central Japanese Mountains and the hills of Puerto Rico, confirm that landslide frequency increases 5-8 fold in the immediate vicinity of a road (Ayalew and Yamagishi, 2005; Larsen and Parks, 1997; Sarkar and Kanungo, 2002).

More generally, this also helps explain why Montgomery et al. (2000) found that a random model worked as effectively as process-based model for some landslide prediction. The truth is that, as with earthquakes, while it is possible to model the frequency distribution, it is impossible to predict their actual sizes with any great accuracy because of their sensitive dependence on a complex array of initial conditions (Haigh, 2002).

11. Discussion

This study is about the fundamental causes and character of landslides in the Himalaya and similar mountain belts. It is, of course, more than simply a detailed engineering case study of the problems of land-sliding along a small reach of a Himalayan hill road. It is a protest against the repetitive and under-researched reportage that follows each successive extreme rainfall event and its consequent landslide swarm. It is also an attempt to qualify the narratives of those who put a political or sectarian disciplinary spin on these events, for whatever reason. For the authors, it seemed that the best way of achieving this goal was by means of demonstrating a methodology, by systematically deconstructing a typical landslide swarm and then reporting the results in terms calculated to resonate with the affected communities. Inevitably, the results of this study contain much that is counter-intuitive and that will inevitably prove distasteful to some vested interests.

First, studies of landslide swarms commonly make the presumption that a host of new landslides have been triggered (Parry, 2011; Tamura, 2008). This is questioned by this study, which (although it did not identify many landslides as overtly 'reactivated') shows that the number of landslides (over the 1 m^3 threshold) on the Almora Lower Mall has remained remarkably constant since 1990. Since the extreme event of this 2010 case study did not generate larger numbers of landslides, its effect must have been to make these landslides proportionally larger (and so make the slope of the trend line of Figs 8 and 9 much steeper) than in previous years.

Second, although this study has downplayed the role of geological factors, the authors remain convinced that geological factors are the major contextual controls of landslide initiation. Three lithologies affect landslides – these are hard, massive quartzites, finely foliated and easily weathered mica schists, and loose debris, mainly derived from previous mass movement or alluvial processes. Here, the weakest material, loose debris sponsors the largest outfalls, while those from schist and quartzite are similar, but none of these differences are statistically significant. Of course, the landslides from debris dominated sites more typically flow-related features emerging from lower roadcuts, on more gentle slopes and water concentrating sites. However, in general, the authors' earlier work suggests that the factors that initiate landslide formation are not the same as those that affect the size of the landslide and its outfall (Haigh et al., 1995). Other factors seem to be at work and their character is suggested by the fractal nature of the landslide outfalls and scars. In fact, the reality in the field seems to echo that produced in Bak's computer (Bak, 1996). Landslide size seems to be determined by a complex of interacting factors and, beyond certain general controls, there is such a sensitive dependence on the initial conditions within the landslide site that landslide volume itself remains inherently unpredictable (Huang et al., 2009). This is the reason that it is not possible to predict the size or location of any particular outfall with any degree of certainty.

Third, "Chance" also plays an important role. Landslide activity on these steep Himalayan hill slopes displays such a very sensitive dependence on initial conditions that it is largely impossible to predict their sizes except in the statistical terms of a size vs frequency power law or rank-size rule (Bak, 1996; Haigh, 1994).

Fourth, there is little in this study that supports the widespread notion that human impact factors, other than the height of the initial roadcut (cf. Maharaj, 1993), are major impacts on landslide volume. Of course, studies in the Darjeeling Himalaya, the Central Japanese Mountains and in Puerto Rico, also confirm that landslide frequency increases 5-8 fold in the immediate vicinity of a road (Ayalew and Yamagishi, 2005; Larsen and Parks, 1997; Sarkar and Kanungo, 2002). However, as Panikkar and Subramanyan (1996) found in the Mussoorie-Dehradun Himalaya, while many small landslides are associated with roadcuts, they are not major regional contributors to landslide volumes.

Humans like to live near others and enjoy the benefits of urban areas. In a hilly area, the first people to move in tend to use the best and most stable sites. In Almora, the older houses are built on hard rock and in the least hazardous places. Unfortunately, only steeper hill-slopes and more vulnerable sites remain for later development. It is a matter for observation that most of the houses damaged in Almora during 2010 were new builds, relatively few older buildings were affected, no matter how badly maintained. It must be concluded that new builds were more affected because they were constructed on inherently less stable sites. In Almora's suburbs, the collapse of abandoned terraces also seems an important associate of landsliding. In fact, human impacts such as the collapse of agricultural terraces, house construction, poor road drainage upslope, even the collapsed of those retaining walls built to stabilise potentially unstable slopes, all tend to be associated with smaller rather than large volume landslide events (cf. Gerrard and Gardner, 2002; Larsen and Parks, 1997; Montgomery et al., 2000; Rautelaaa and Paub, 2001; Sah and Pande, 1987).

Fifth, and perhaps surprisingly, although geological controls may set the general pattern of landslide generation and initiation, they are poor predictors of landslide volume (Valdiya, 1980; Korup and Weidinger, 2011) . A key reason for this may be the sheer number of discontinuities within the Himalayan bedrock, which allow many dimensions of possibility for the formation of failure planes, and also the prevalence of loose debris from previous landslides.

Sixth, certainly, deforestation is a major problem in the Himalayan region which has many damaging environmental impacts. It is also a very important associate of landslide activity in forested landscapes, where the removal of trees eliminates the stabilising effects of tree roots and makes deep forest soils vulnerable to slippage (Dapples et al., 2002; Glade, 2003; Haigh et al., 1987). Normally, as in Sardinia, Barbieri and Cambuli (2009) give a high landslide hazard weighting to areas with bare rock and shrubby vegetation but low to areas under forest (and also urban) land use.

However, in the Himalaya, once the main forests have gone, those that remain survive only on the most unstable slopes, so high levels of tree cover commonly correlate with increased landslide activity, as is the case here (Haigh et al., 1995).

Finally, it is concluded that the best predictors of outfall volume in a landslide swarm, other than random chance, are also the most obvious. They are the steepness of the hill slope and the degree of undermining by whatever cause – human as in the roadcut creation of this case, natural channel incision in others (Froehlich et al., 1989). The strongest influence on landslide outfall volume was hill slope angle upslope. The steep slopes that generated these larger outfalls also had significantly stronger rocks, with more joints and less overburden. Of course, slope steepness in this, as in similar, mountain region is the collective consequence of tectonic uplift, rock strength and river undermining (Korup and Weidinger, 2011).

Researchers in Andorra suggest that there is a minimum threshold slope angle for landslides, but this was not apparent in this study (Corominas et al., 2003). In Jamaica, Maharaja (1993) mapped 789 landslides on slopes between 20°–45° but none on slopes less than 10°, although he found a cluster of landslides at sites where the land immediately upslope has a very low angle. Barbieri and Cambuli (2009) give a high weighting to the influence of hill slope angles greater than 40º, while Barnard et al. (2001), working on the landslides consequent upon the Garhwal Earthquake disaster of 1999, found a landslide slope threshold at 20 degrees and more than 63% of all slides on slopes between 30 and 50 degrees. Similarly, in Korea, Lee and Min (2001) report a correlation between landslide frequencies and steeper slopes, which is echoed by this project, and also equally, they found that they were unable to distinguish differences due to land use because of the link between land use and slope. Elsewhere, researchers have linked landslide activity to convergent slopes but here the slope planform did not associate significantly with landslide volume (Glade, 2003).

As diagnosed at the time, the chief *adhidaivic* factor affecting this landslide swarm was the rain storm that triggered the event. Its effects can be seen in the morphology of the scars. The largest slides show more flow and spreading. Elsewhere, there is widespread acceptance that there is a soil moisture threshold for landslide generation exceeding a threshold value, which is related to pore-water pressure, and wetter climatic conditions (Wieczoreck, 1996; Pelletier et al., 1997). The second most important *adhidavic* factor, however, is random chance, as witnessed by that signature power law linking landslide size and frequency (Bak, 1996). Beyond a threshold of criticality, landslides emerge randomly, ‘chaotically’ and unpredictably because of their very sensitive dependence on tiny differences within their environmental contexts. Previously, Haigh (2002) has recommended that landslide hazard planners should aim to distinguish between sites that exist close to the critical thresholds of collapse and sites that are further from criticality and where landslides may be inherently more predictable.

Conclusion

This study has been prepared in an attempt to allay some common misapprehensions about the character of such landslide swarms, including many ideas endlessly parlayed across the popular, environmental, and scientific literature. Many of these misapprehensions, often partial truths, are dangerous because they are embedded in public discourse and inform public policy, public works expenditure, sometimes litigation, but more seriously popular expectation.

The greatest of these is that landslides can be predicted and prevented. In fact, while it may be possible to calculate the probabilities of landslide activity, especially in sites where there is already landslide activity, there are aspects of landsliding in environments like the Himalaya which are inherently unpredictable. The environmental conditions that control landslide activity are so complex and finely tuned, landslide development on hill slopes close to their critical limits of stability is so sensitive to small variations in initial conditions, that the only secure way of predicting landslide occurrence, frequency and location is using the mathematics of deterministic chaos. In other words, landslides in these conditions do not have to be anyone's fault and it may never be possible to prevent them.

There are many more problems within the popular and scientific discourse on landslides, which are illustrated by the case study analysed here. However, the main points are as follows:

1. Extreme events do not necessarily result in more landslides but they may affect the volume of debris produced by landslide activity. This study of landslide activity on the Almora Lower Mall finds that the number of landslides recorded has changed little through 25 years of observation.
2. The controls of landslide volume are not necessarily the same as those for landslide initiation. Hence, the suite of variables that correlate with landslide outfall size are not necessarily the same as those linked with landslide initiation.
3. "Chance" is an important determinant of landslide size. Landslide activity on these steep slopes displays a sensitive dependence on initial conditions. It is possible to predict the spectrum of landslide outfalls because the relationship between size and frequency may be approximated by a power law or rank-size rule. However, it is not possible to predict the size or location of any particular outfall with any degree of certainty because the landslide system contains the signature of mathematical chaos – as problematised by physicists including Bak (1996).
4. Human impact factors, other than the height of the initial roadcut, are poor predictors of landslide volume. In fact, in this case study, human impacts such as house building, poor road drainage upslope, the collapse of agricultural terraces, even the collapse of those retaining walls built to stabilise potentially unstable slopes, tend to be associated with smaller rather than large volume landslide events.
5. Perhaps surprisingly, while geological factors may set the general pattern of landslide initiation, they are poor predictors of landslide volume. A key reason is the large number of discontinuities within the Himalayan bedrock, which allow many dimensions of possibility for the formation of failure planes, and also the prevalence on the slopes of easily mobilised loose debris – much of it deposits from previous landslides.
6. In forested landscapes, the removal of the trees eliminates the stabilising effects of tree roots and makes deep layers of forest soil and weathered bedrock and so makes steep hill slopes vulnerable to slippage. However, in largely deforested landscapes, where forests survive only on the most unstable slopes, high levels of tree cover commonly correlate with increased landslide activity, as is the case here.

7. The chief predictors of outfall volume in an active landslide event are the most obvious. They are the steepness of the hill slope and the degree of undermining. Of course, slope steepness in this and similar mountain regions is the collective consequence of tectonic uplift, rock strength and river undermining.

To once again return to the case study, in September, 2010, Almora's already rain-saturated hillsides were subjected to a two-day downpour of 277 mm at intensities that reached 33 mm/hr, which easily exceeds the usual threshold for landslide swarm activity in the Himalaya (Dahal and Hasigawa, 2008). Landslides got duly activated and this survey explored 108 of them, all larger than a 1 m^3 threshold size, through a resurvey of a 7.3 km reach of the Almora Lower Mall (Haigh et al., 1993). The number of landslides recorded was not exceptional. Similar numbers had been recorded previously in 1990, 1995 and 2000. In 2010, landslides formed from steeper slopes, and because of the intense rain, those activated were mainly slump/flow features, often in the loose debris mantled slopes of former landslides and at places where there was undermining of the hill side upslope either by the recent incision of stream channels or by the initial road cut for the highway.

However, in the final analysis, the explanation for landslide outfalls found on the Almora Lower Mall in 2010, remains fairly straight-forward. A low probability extreme rainfall event triggered landslides, which emerged chaotically on hill slopes already near their critical limits of stability. Their characteristic sensitive dependence on complex initial conditions of these features mean that it is difficult to assign particular strong environmental causation. However, landslide volume was significantly more related to flow than fall processes and emerged from steeper slopes and at sites that had been more undermined by higher roadcuts or by channel incision.

In an attempt to communicate these findings more easily and to contest the on-going discourse about landslide causes, this study has adopted a traditional classification of sources of trouble. This divides problems into those that are self- or human-induced (*Adhyatmic)*, those that emerge from the environment (*Adhibhautic)*, and those that are due to fate (*Adhidaivic*). In popular understanding, as well as the flatlands of science, the blame for landslides is ascribed to human or environmental causes. However, when explored from the perspective of complexity theory, the over-riding causes, both of the triggering rain-storm and the size of the individual landslides, are shown to contain a very large element of unpredictability. Their causes are effectively *adhidaivic*, an explanation that has special resonance in Uttarakhand's Hindu-dominated society. It is hoped that promoting this language may, by association, help shift the discourse on landslide swarms to a more secure scientific footing.

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19

Control of Landslides in Mountain Watersheds, Japan

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1. Introduction

In 2008, Japan has celebrated the 50 years anniversary of the legal establishment of the "Landslide Prevention Law". This law, which supplies a specific legal basis for whole public works for landslide prevention and control, was enacted in 1958. Nowadays various techniques are available for comprehensive control of landslide disasters, including investigation and analysis methods, planning and design of control measures, as well as maintenance and administration of installed structures. In addition to the conventional landslide conrol measures, mainly so-called "hard measures", which focus on the stabilization of active landslides, so-called "soft measures" such as prediction of landslide occurrence, landslide hazard zoning, arrangement of evacuation system to avoid human casualties are possessing continuously more importance. This chapter has been focussed on the landslide occurrence, investigation methods, research results, and landslide control measures applied in Japan over five decades.

2. Geology and Geomorphology of Japanese Archipelago

The Japanese archipelago extends over the area of 378,000 km^2 (Fig. 1). Seventy-five percent of the total land area consists of mountain terrain. These arcs approximately represent plate boundaries. Japan is located in an area under strong crustal movements and belongs to one of the seismically most active regions. There are 86 active volcanoes in Japan. Furthermore, epicentres of deep-seated earthquakes around Japan are distributed along Trenches. Landslides occur frequently in the following physiographic zones. The Inner

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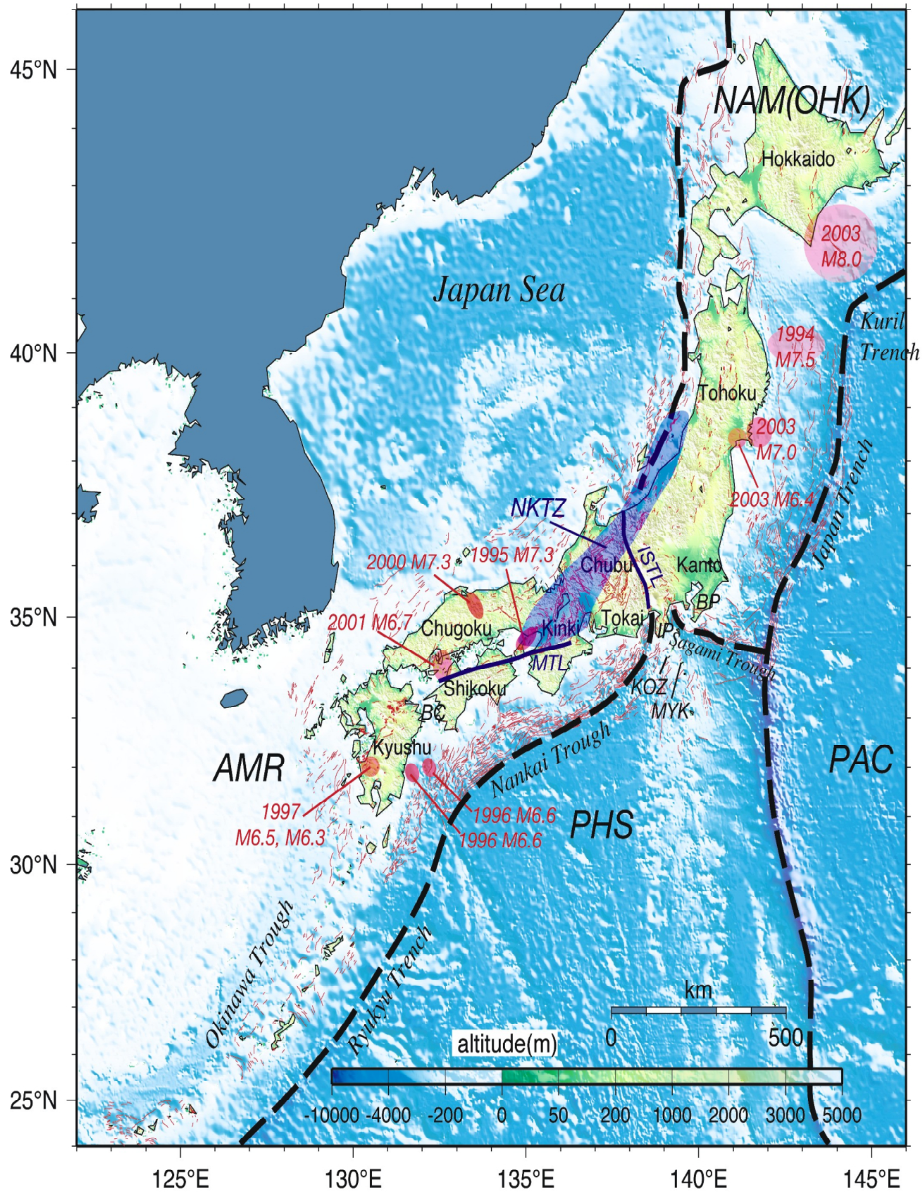

Fig. 1. Trenches and island arcs around Japan.

Northeast Honshu Arc is a representative landslide zone. The Northwest Kyushu Island in the Southwest Honshu Arc is a zone of high density landslide distribution. The Outer Southwest Honshu and the Central Western Honshu are zones represented by very slow landslides and by very large-scale rapid slope failures.

3. Climate of Japan

The Japanese archipelago is situated in the monsoon region of eastern Asia between North Latitude of 20° and 45°. Its winter climate is dominated by wind and air from eastern Siberia. Numerous landslides have been triggered by the large quantity of snowmelt along the slopes facing the Sea of Japan. In early June, the Northern Pacific High Pressure Zones gradually move from the south, and the northern air masses move from the Sea of Okhotsk. Both air masses collide with each other above the Japanese archipelago, forming a stationary seasonal rainy front. This rainy front brings intermittently a large quantity of rainfall. These rainfalls often cause landslide disasters. In autumn, typhoons formed in the low latitude regions of the Northern Pacific Ocean move northward and often attack the Japanese archipelago. These typhoons usually generate very strong wind and intensive rainfalls and cause frequently severe landslide disasters. The mean annual precipitation of Japan is ca. 1800 mm. However, at Owase in Kii Peninsula it records ca. 4000 mm and in Joetsu (at the side of the Sea of Japan) it records ca. 2900 mm (of which one-half is snow). Figure 2 shows regionally different characteristics of monthly mean precipitation and temperature.

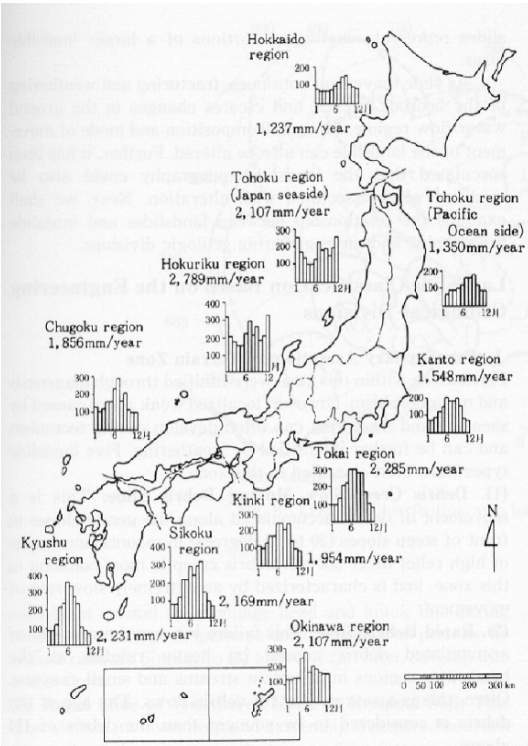

Fig. 2. Monthly mean precipitation and temperature.

4. Distribution of Landslides and Geotectonic Structures

In the 1950s, Japan has experienced a series of severe landslide disasters. Such frequent landslide disasters led to the enactment of the "Landslide Prevention Law" in 1958. Under this legislation, landslide control measures have been intensively developed. The Landslide Threatened Areas administered by the three governmental agencies are summarized in Table 1. The number of the whole Landslide Threatened Areas amounts to 6922 and their total area amounts to 319,011 ha. It means that about 0.8% of the total area of Japanese territory is designated as Landslide Threatened Areas. The total expenditure of landslide mitigation measures implemented by the responsible agencies during the fiscal year of 2000 is shown in Table 2. Figure 3 shows distribution of landslide prone areas and related geotectonic structures. Landslides are highly concentrated along the major tectonic lines such as in the northern Fossa Magna Region and near the Median Tectonic Line in Shikoku Island. Figure 4 shows an example of extremely high concentration of landslide areas in Matsunoyama District in Niigata Prefecture. This area is geologically characterized by Neogene formations which consist of black mudstone or alternation of sandstone and mudstone. Soils along the sliding surface in these formations show extremely low shear strength. Twenty percent of the total landslide areas in whole Japan are concentrated in Niigata Prefecture and especially in neighbourhood of this district. Figure 5 shows distribution of large-scale landslide areas and landslide threatened areas in whole Shikoku Island. Landslide areas are concentrated in fractured zones which are composed of metamorphic rock formations.

Table 1: Summary of designated landslide threatened area

	Ministry of Land, Infrastructure and Transport	*Ministry of Agriculture, Forestry and Fisheries*		*Total*
		Rural Developement Bureau	*Forestry Agency*	
Number of area	3,329	1,868	1,725	6,922
Total area (ha)	114,023	107,061	97,927	319,011

Table 2: Summary of landslide mitigation expenditures in fiscal year 2000

	Ministry of Land, Infrastructure and Transport	*Ministry of Agriculture, Forestry and Fisheries*	
		Rural Developement Bureau	*Forestry Agency*
State subsidy	37.505	14,068	22,273
Direct spending	8,421	5,982	6,471
Total	45,926	19,960	28,744

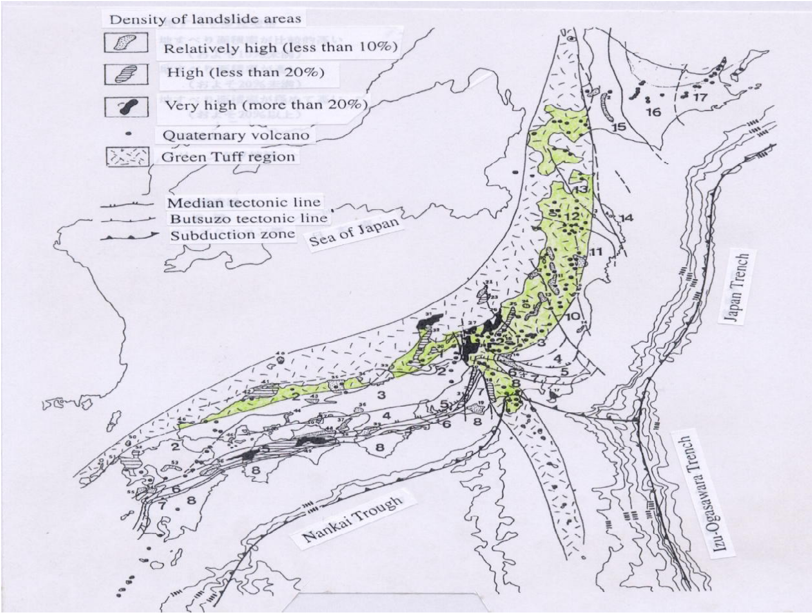

Fig. 3. Distribution of landslide prone areas and geotectonic structures.

Photo 1 Landslides in Neogene formation.

5. Investigation Measures

Various investigation measures are required for formulating an effective and appropriate landslide mitigation plan. The flow chart shown in Fig. 6 illustrates

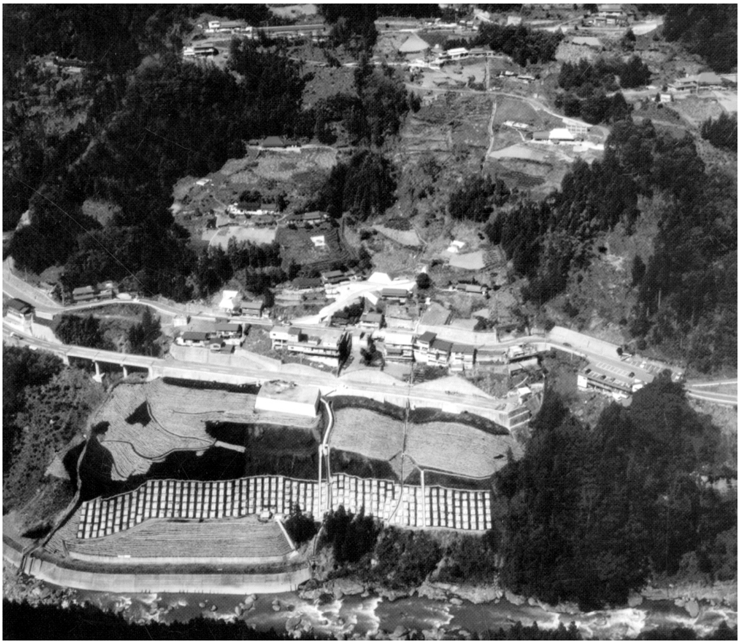

Photo 2 Landslides in metamorphic rock formation.

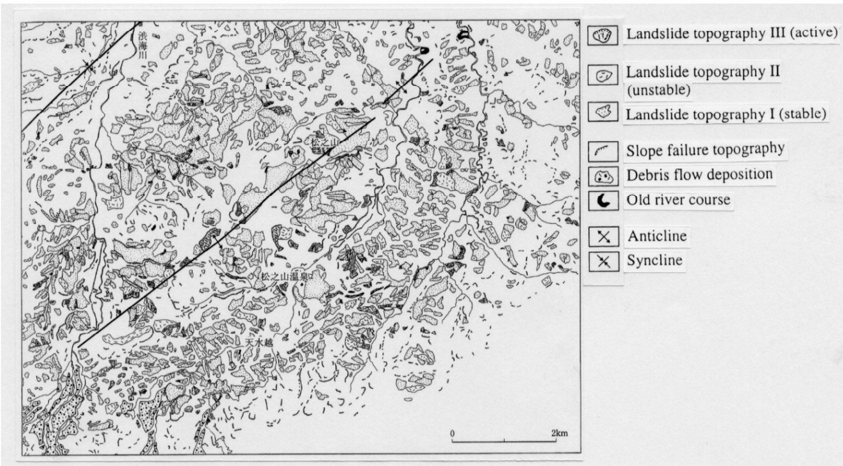

Fig. 4. Distribution of landslide areas in Matsunoyama District in Niigata Prefecture (Suzuki, 2005).

the general investigation procedures in order to understand the mechanism of landslide occurrence and to predict the movement and the resulting deformation of sliding soil mass. Preliminary investigations are carried out prior to detailed investigations and necessary information for drafting full investigation plan.

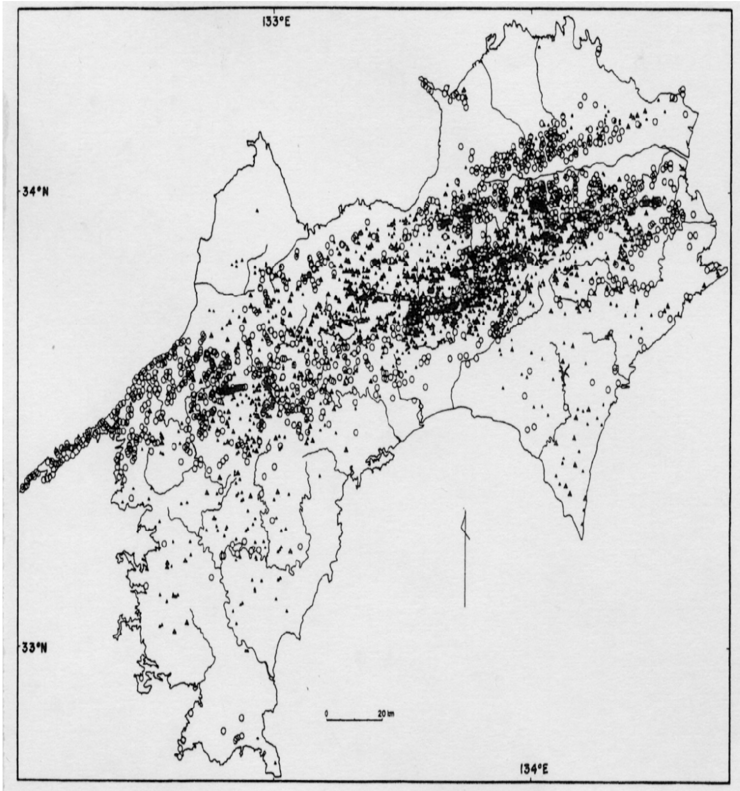

Fig. 5. Distribution of large scale landslides in Shikoku Island (Terado, 1986).
▲ Large scale slope topography (large: more than $10^6 m^3$, small: less than 10^3–10^6 m^3)
○ Designated landslide-threatened areas and landslide prone areas

Preliminary Investigation

As a first step, it is important to utilize existing data in order to grasp geomorphological and geological conditions, meteorological factors and history of the past landslide movements. Interpretation of aerial photographs is an effective tool to identify topographical changes in a target landslide area. Recently, remote sensing methods using satellite images have been highly developed.

As a next step, preliminary filed investigations are carried out in order to determine necessary target areas and essential items for full investigation. A draft plan of detailed investigations should be framed up to include proper examination of the following items: (1) spatial extent of the landslide area, identification of moving blocks, direction of movement, (2) location and configuration of sliding surface, (3) characteristics of sliding soil mass, (4) possibility of subsequent movement, (5) possibility of accelerated sliding, and (6) distribution of ground water.

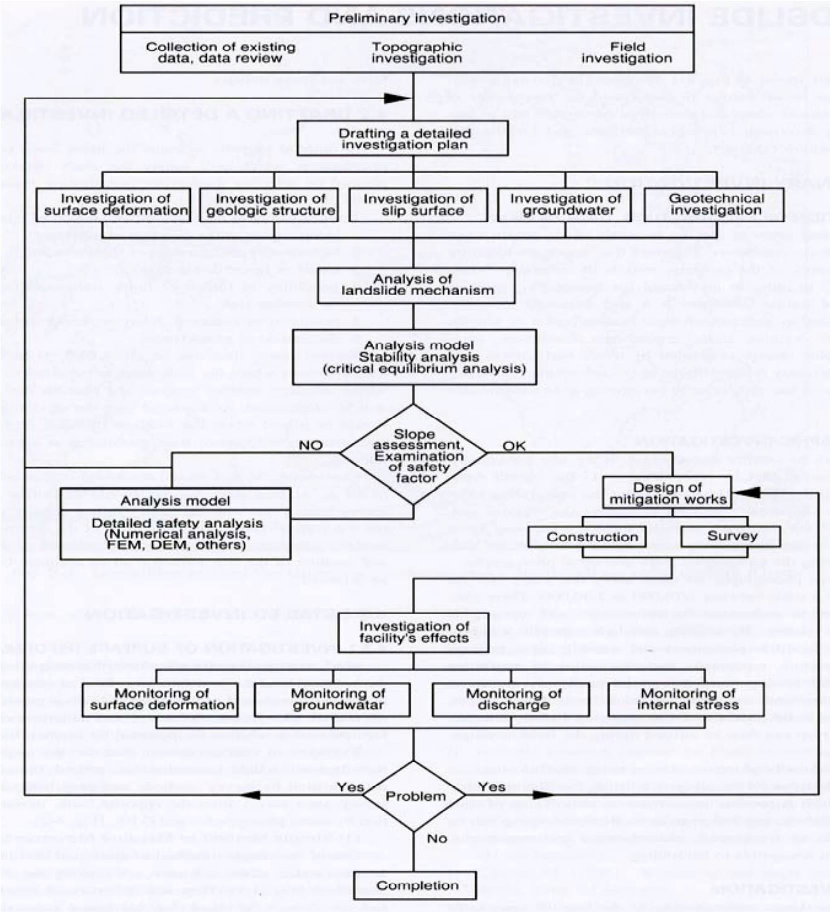

Fig. 6. Flow chart for landslide investigation and analysis (JLS, 1996).

Investigation of Surface Deformation

In order to define the boundaries of landslides, activity level, direction of movement and individual moving blocks, it is necessary to investigate surface deformation. A comprehensive instrumentation used for the investigation of surface deformation include extensometers, ground tilt meters, equipments for surveying movement like transverse surveying, grid surveying, laser surveying from the opposite slope, and GPS. Surface movements are also determined by detailed aerial photographs.

Investigation of Geologic Structure

In most cases, investigation of geologic structure relies on exploratory borings. Geophysical exploration using seismic survey, electrical survey and radioactive survey is combined with the boring data. Geologic assessments based on the boring data obtained from the drilling site should include evaluation regarding the differentiation of moving soil blocks, semi-moving earth blocks and stable ground. Clays along the sliding surface generally have high moisture content and are highly sticky, plastic and often associated with abrasion scars and slickensides. Furthermore, using the boreholes the following investigations and tests are performed: (1) Determination of sliding surface, (2) Observation of groundwater level, (3) Detection of groundwater flowing layer, (4) Tracing of groundwater flowing path, (5) Standard penetration tests, and (6) Sampling of soil specimens for various soil tests.

Determination of Sliding Surface

The sliding surface of active landslides can be determined by measuring displacement of casing pipe according to the movement of the sliding soil mass. Depending on the requirements for surveying accuracy and magnitude of movement, the appropriate instruments should be selected from the following representative instruments: (1) Pipe strain gauge, (2) Inclinometer, and (3) Multi-layer movement meter.

Groundwater Investigation

Investigation of the behaviour of ground water, which is an essential triggering factor of sliding, is very important item, because groundwater control works as landslide mitigation measure can be effectively planned and designed on the basis of this investigation results. This investigation includes determination of groundwater level, measurement of pore water pressure, detection of groundwater flowing layer, tracing of groundwater flowing path, pumping test, water quality analysis, electric survey and geothermal survey.

Geotechnical Investigation

In order to conduct slope stability analyses and to design appropriate control measures for mitigation of landslides, physical properties such as the strength of soils along the sliding surface, location and depth of the sliding surface must be determined. The following tests are generally performed: Standard penetration tests, soil physical test, and soil mechanical tests (unconfined compression tests, tri-axial compression tests, box shear tests, ring shear tests, in-situ shear tests along the slip surface). Furthermore, the intensity and degree of alteration of the slip surface clays are evaluated by X-ray diffraction methods.

Automated Monitoring System

Recently, automatic monitoring systems using data loggers and computers are being used. The instrument set up in the field has been designed for easy installation and is weatherproof, durable, maintenance-friendly and economical. The following points are main objectives to install automated monitoring system: (1) Surveillance of the situation of landslides, (2) Understanding of the situation of landslide deformation, and (3) Evaluation of effectiveness of landslide mitigation measures. Fully automated monitoring systems permit remote control in real time and rapid graphic data processing and display and

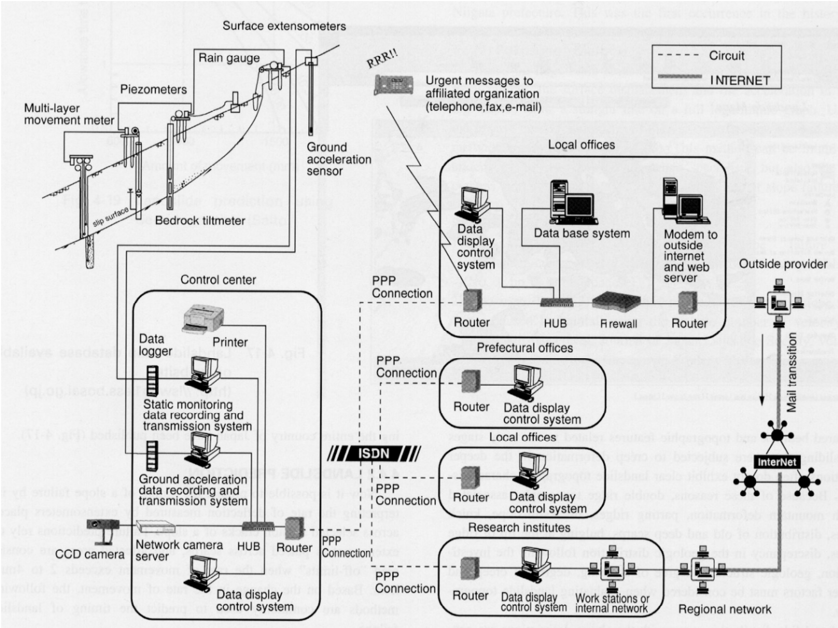

Fig. 7. Automated monitoring system using IT technology (JLS, 2002).

would provide early warning signs of sliding activity. Figure 7 shows a schematic diagram of an automated monitoring system using IT technology.

6. Mitigation Measures

Landslide mitigation measures are conducted in order to prevent or reduce the movement of the sliding soil mass so that the resulting damages can be minimized. For planning of effective and appropriate mitigation measures, a clear understanding of causes and mechanism of the target landslide is the important prerequisite. Landslide mitigation measures can be classified into two major categories, namely “hard measures” and “soft measures”. Hard measures involve construction and implementation of various engineering structures. Soft measures involve land use restrictions and arrangements for warning and evacuation system. The necessity of soft measures for landslide mitigation has been increasing parallel to the intensive urban development expanding into mountain watersheds in recent years. It is important not only to promote instrumentation of the automated landslide monitoring system, but also to impose land use restrictions on inhabitants in highly populated areas. For this purpose a specified law to promote landslide disaster prevention in affected areas was enacted in 2000.

Hard measures are classified into two types, namely “landslide control measures” and “landslide restraint measures”. Landslide control measures involve modifications of the natural conditions of landslide areas such as

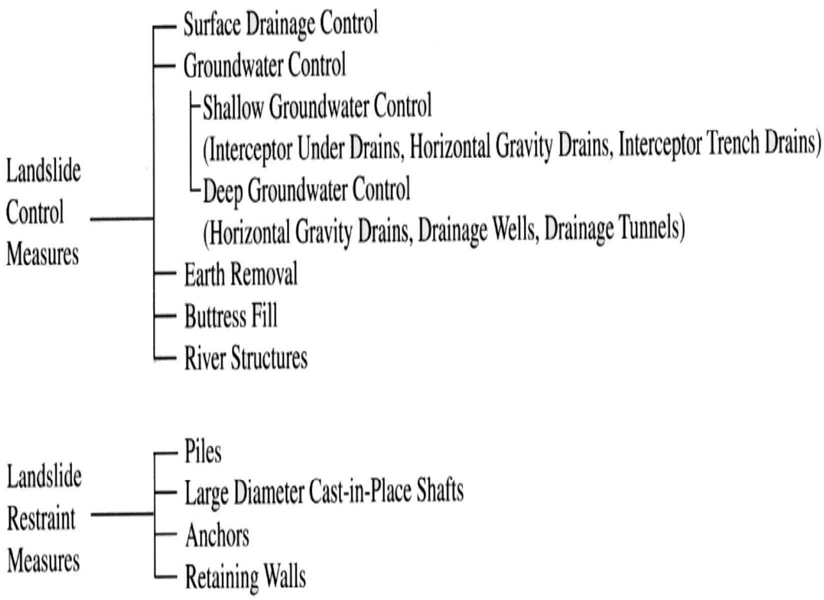

Fig. 8. Various types of landslide mitigation measures.

topography, ground water and other conditions that indirectly control the landslide movement. The restraint measures, on the other hand, rely on preventing the landslide movement by directly adding a resisting force to the sliding movement. Individual measures included in both type of mitigation measures are listed in Fig. 8.

Landslide Control Measures

1. Surface drainage control measures: These measures are implemented to control movement of landslides accompanied by infiltration of rain water and spring flows.
2. Groundwater control measures: The purpose of the groundwater control measures is to remove the ground water in the sliding soil mass and to prevent the inflow of ground water into the sliding soil mass from outside sources. (1) Interceptor Underground Drains and Interceptor Trench Drains: They are most useful to remove shallow groundwater from up to 3 m below the ground surface. (2) Horizontal Gravity Drains: In order to remove ground water, horizontal gravity drains with length of 30 to 50 m are installed. (3) Drainage Wells: Wells with a diameter of 3.5 to 4.0 m are excavated in areas of concentrated groundwater. A series of radially positioned horizontally gravity drains are drilled at various elevations and collect the ground water into the drainage wells. (4) Drainage Tunnels: Tunnels which are constructed below the sliding surface in a stable bedrock formation is installed to remove collected water from the sliding soil mass by interconnecting the drainage wells.

3. Earth Removal: This is one of the methods by which the most reliable results can be expected and generally applied to small to medium sized landslides. Except for special cases, the earth removal is focussed on the head portion of the slide.
4. Buttress Fill: This measure is placed at the lower portion of the landslide areas in order to counterweigh the sliding soil mass. This method is often managed as an emergency measure.
5. River Structures: Degradation and channel bank erosion reduces stability of soil mass and often tends to induce slide activity. In such cases, check dams, ground sils, revetments and other river structures can be constructed to prevent further erosion by the river.

Landslide Restraint Measures

1. Piles: Piles are driven into the pre-drilled shafts in order to tie the moving landslide blocks and the stable ground together. Piles are designed to resist against shearing and bending stress and generally consist of thick walled steel construction.
2. Large Diameter Cast-in-Place Shafts: Large diameter cast-in-place shafts function similar to those of the piles and are also designed to tie the moving landslide block and the stable ground together. Generally, shafts with diameter of 1.5 to 6.5 m are used and then filled with reinforced concrete.
3. Anchors: Anchors utilize the tensile force of anchor bodies embedded through the sliding mass into stable bedrock. Anchors are connected to thrust blocks located at the ground surface.
4. Retaining Walls: Retaining walls are constructed to prevent smaller sized secondary landslides that often occur along the toe portion of the larger landslides. Flexible crib walls are common instead of conventional reinforced concrete retaining walls.

7. Conclusions

Vulnerability for landslide disasters essentially depends on both natural and social conditions. It can be fundamentally improved by preparedness for emergency case and continuous mitigation efforts of extreme landslide events. Landslide-prone areas are extensively distributed in the entire Japanese archipelago. Since hundreds years people have been living also in landslide-prone areas. Especially in the last several decades, much more people have settled in such areas with high vulnerability for landslide disasters because of high population density corresponding to the fast economic growth. Therefore, mitigation of landslide became a very important task of public welfare policy. Intensive landslide mitigation measures have been carried out as public works on the basis of the Landslide Prevention Law. Nowadays, a comprehensive system of various landslide mitigation measures is available and proved to be practically effective so far as for conventional type of landslides which are triggered by intensive rainfall and/or snow melt.

In recent couple of decades, the territory of Japan has faced heavy earthquake-induced landslides. For example, a huge number of landslides were induced by the Chi-Chi earthquake in Taiwan (1999), by the Mid-Niigata Prefecture earthquake in Japan (2004) and the Northern Pakistan earthquake (2005). The Wenchuan earthquake occurred with magnitude 8.0 in central part of China on May 12, 2008. This gigantic earthquake also caused a tremendous number of landslides. A large number of landslides were also triggered by the Iwate-Miyagi Inland earthquake on June 14, 2008. Intensive field researches and analyses have been carried out to clarify the mechanism of eathquake-induced landslides as well as to propose appropriate landslide contorol measures. We are expecting that emergency measures and risk management operations experienced in Japan can also serve mitigation of future landslide disasters induced by earthquakes somewhere in Asian Orogenic Zone.

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