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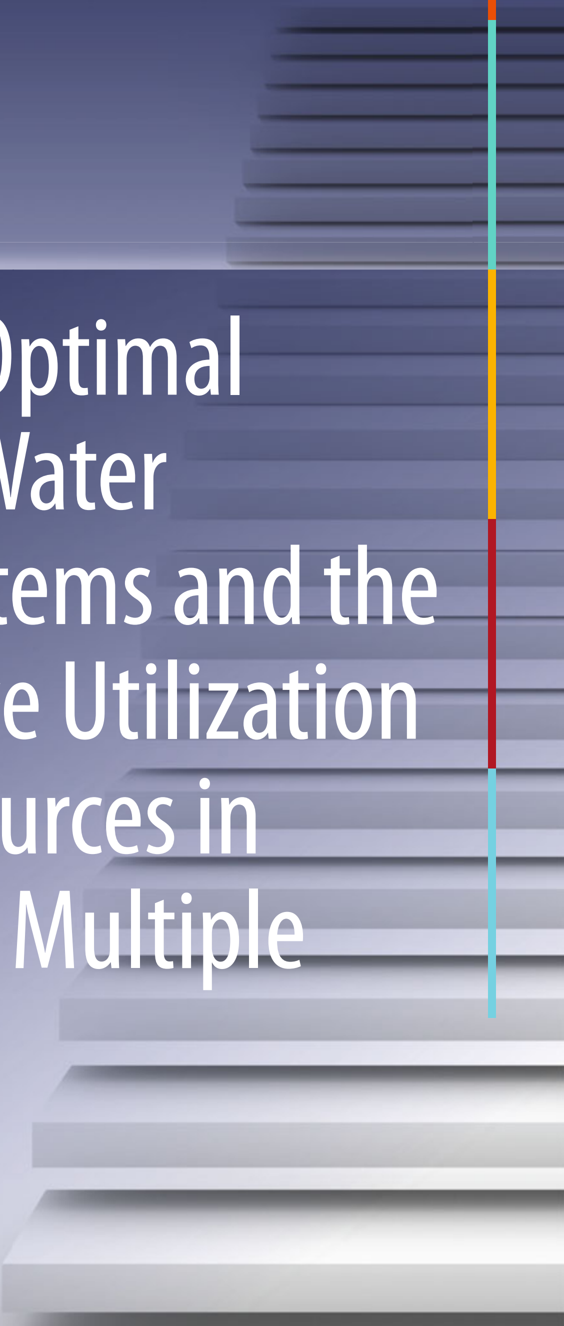
Study on the Optimal Allocation of Water Resources Systems and the Comprehensive Utilization of Water Resources in Arid-Semiarid Multiple Mining Areas



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Study on the Optimal Allocation of Water Resources Systems and the Comprehensive Utilization of Water Resources in Arid-Semiarid Multiple Mining Areas

Doctoral Thesis accepted by
the Chang'an University, Xi'an, China

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Supervisor's Foreword

Arid-semiarid regions have suffered from sharp conflicts among water resource utilization, mining, and the environmental protection. Sustainable development in these regions requires a rational water resources allocation to meet the needs for economy, society, and the environment. Based on systematic hydrogeological investigations, laboratory and in situ tests, and application of innovative methodologies including theoretical analysis modeling and prediction to study water resource distribution (including surface water, groundwater, mine water, and coal mine domestic water) in mining areas, this dissertation provides detailed analysis of the current situation and trend of water uses in domestic supply, agriculture, and industry. This dissertation was supported by the project "*Basic Research on the Occurrence Regularities of Deep Coal Resources, Mining Ground Pressure Conditions and Fine Detection (2006CB202200)*"—a project of "973" Program of the state's key basic research development, and the key scientific and technological research project of The Ministry of Education—*Transformation Mechanism of Precipitation (Evaporation)—Water in Aeration Zone—Groundwater and Its Ecological Effect in Maowusu Sandy Land (308021).*

This thesis evaluates the status development and utilization, evolution trend, exploitation and utilization potential of water resources in Shen-Dong Coal Mine area. The study area is one of China's extra-large coal bases and situated at the Loess Plateau (Northern Shaanxi Province) and northeast Ordos Desert fringe. Incorporated with the long- and intermediate-term development strategies of this area, the dissertation lays out a scientific allocation scheme of water resources in different hydrological years and proposes a planning mode of water resources development and utilization and a technical scheme for comprehensive water resources utilization to provide technical supports for the optimal allocation, rational exploitation, comprehensive utilization, and scientific management of water resources. Shuning Dong's research demonstrates that optimal allocation of the complex water resources can be achieved by multiobjective programming models. His research results, as presented in this thesis, have provided the state-of-the art methodologies that balance mineral mining and water resource conservation in arid-semiarid regions.

I congratulate Shuning to this excellent work. His dissertation is one of the best in Chang'an University because of the volume of reliable data, defensible scientific analysis, and world significance of the research results.

Xi'an, China
February 2016

Dr. Wenke Wang

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This dissertation is accomplished under the guidance of my supervisor, Prof. Wang Wenke. His profound professional knowledge, rigorous scholarship, noble morality, and unpretentious personality are my learning model. In the past 4 years, Prof. Wang has not only provided me with a good environment and concentrated guidance in my study, but also given me advice in my daily life. All my achievements are attributed to my supervisor. At the point of accomplishment of the dissertation, I would like to express my sincere thanks and respect to Prof. Wang for his advice and instruction.

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Chapter 1
Introduction

1.1 Objective, Task, and Significance

China is a country with water resources shortage; its per capita water resources are only a quarter of the world per capita water resources. In many areas, particularly in northern arid and semiarid areas, the water shortage is more serious. A quarter of groundwater has been extracted or destroyed and cannot be recovered. The contradiction between water shortage and social economic development becomes more prominent [1]. Water crisis has become the important constraint factor for China's sustainable development. It is a basic/overall strategically important problem for realizing social economic development objective in the new epoch [2].

Shenfu Dongsheng mining area (hereafter shortened as Shendong mining area) is located in the zone bordering Shaanxi northern Loess plateau and the southeast margin of Maowusu Desert. It is characterized by good quality of coal, big reserves, shallow burial depth, and relatively simple mining conditions. It is the world's largest coal production base in construction in China.

With the development of coal resources in Shendong mining area, collapse occurs continuously in the overburden layers of seams, forming caving zone and water-conducting fracture zone, inducing fractured and collapsed area on the surface. Therefore, the structure of aquifers, runoff, and discharge conditions of groundwater has changed. Phreatic water in the Quaternary loose layer is converted from horizontal runoff and discharge into vertical seepage. Groundwater level has changed significantly. In the collapsed zone and areas with induced fractures and water-enriched loose layers, groundwater level has lowered continuously, resulting in drying aquifer. In another aspect, boreholes for dewatering and water discharge in the mine have accelerated the lowering of groundwater level. In recent years, precipitation tends to decrease from year to year. As a result, the water recharge is relatively reduced, which has further lowered the groundwater level each year. The discharge of local springs has decreased and even dried up. The situation of water

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shortage has been aggravating continuously, influencing seriously the sustainable and healthy economic development in the area.

In recent years, the scope of coal resources development has been broadened progressively, mine water discharge, water consumption in production, households and industries has increased each year, contradiction occurs in the development of coal mining industry and other energy and chemical industries, regional water resources development and utilization, coal mining and ecological environmental protection in mining area. Therefore, it is an important subject to assess the current situation, the dynamic characteristics, variation trend, development and utilization potential as well as its feasibility of water resources in Shendong area, so as to put forward operational strategic decision and technical path for rational development, comprehensive utilization, and scientific management of water resources in the area. It is the big problem to resolve for the sustainable development in the mining area.

1.2 Current Status of Research and Technology in Related Fields

1.2.1 Current Status of Research on the Technology of Comprehensive Utilization of Water Resources

1.2.1.1 Current Status of Research Abroad

From 1894 when the concept of water resources was put forward to 1995 when the theory and methods for optimized adjustment and control of water resources were preliminarily formed, reviewing the development history of research on water resources for approximately 100 years, we can find that deep change has occurred in the thinking of coordination and resolution of the relationship between human being and water and the discipline of water has significantly developed correspondingly [3, 4].

The concept of water resources value has developed from the simple economic standard measuring the effect of water resources development and utilization to integral consideration of economic, environmental, and social benefits [5].

The research methodology of water resources has developed from decision-making of single engineering to systematic decision-making, from single utilization objective to multiple utilization objectives, and from the mode of single decision maker to the mode of multiple decision makers [6].

The research scope has progressed from the research of water resources themselves to the research that combines water resources with economy, environments and society [7–9].

The focus on water–human relationship has developed from simply relying on engineering measures to emphasize on both engineering and non-engineering measures, from simply relying augmentation of water amount to emphasize on both broadening resources and saving resources and the management of water resources demand, and from simply considering water quantity to emphasize on both utilization and protection and the control of total contaminant of water environments.

Since the United Nations summit meeting of environments and development in 1972, the concept of sustainable development has been accepted generally, and this provides new value and new methodology for coordination of human being–water relationship [10]. Inspired by the concept of sustainable development, from the development mode, different countries recognize the mutual relation between the development and utilization of water resources and economic development, the mutual relation between the utilization and protection of water resources, and the relation between the economic development and protection of ecological environments. The world's largest international cooperative research project in the field of water resources "*Macro Economic Water Resources Management in North China*" accomplished in 1992 conducted firstly the overall research on the theory and methods for optimized adjustment and control of water resources, and the formal report was submitted in 1996, which marked that the discipline of water resources has moved into preliminary mature stage [11].

In 1994, as the chief research unit, the France's National Center for Scientific Research organized sixty research teams of different objects. Four hundred researchers, on the basis of the theory of material cycle and the principle of four water conversion, from the angle of four dimensions, fully studied the characteristics of water change in biosphere and a series of problems induced by the influence of human activities, implemented unified normalized management, and set up unified database, so as to enhance and encourage the cooperation of different subjects and to ensure the realization the research results of hydrological system [12]. This research method has broken the conventional fixed research method mode of a single object, with the urgent research problems, the up-to-date theory, the most advanced technical approach, the research content of the most numerous levels, the widest concerned fields, the biggest organizational structure, and macro- and micro-organic combination, and the research reached the world's top level in wideness and depth, embodying the trend of the modern science development.

1.2.1.2 Current Status of Research in China

The research of hydrology and water resources has been carried out for several decades in China, and significant results have been obtained [13], particularly in recent years with the advanced technical approaches such as remote sensing and telemetry, weather satellites, radar, GPS and geographic information system, and renovation of testing equipment, and the research of single object has reached some progress. However, most researches are repeated and lack systematics and comprehensiveness, and the combined research of multiple subjects needs to be improved. This backward situation does not adapt to the need of China's present social economic development and the change of natural environments [14]. Therefore, it is necessary to set up the concept of large hydrological system and the idea of sustainable development, to pay attention to the systematics and comprehensiveness of ecological, environmental, and social economic relation, to focus on the combination of multiple objects and fields, and to emphasize the advancement of the research on hydrology and water resources, thereby guiding the rational development and utilization of different economic activities and consciously protecting and improving the natural environments in which the people live on.

1.2.2 Current Status of the Theory and Technology of Water Resources Assessment

In order to adapt to the need of economic development, during 1985–1987, we conducted the research on the development and utilization of water resources in North China, including the research on rational allocation of water resources in the region, compilation of the plan for medium and long-term national water supply and demand, research planning of groundwater development and utilization, planning of water source sites in cities with water shortage and other regional and monographic assessment of water resources [15]. While the state's key research projects No. 38 and No. 57 in North China during the Sixth Five-Year Plan and Seventh Five-Year Plan were conducted, the assessment of water resources and the analysis of water supply and demand were carried out. The development of all these researches has made the assessment of water resources in China more matured. During the 1980s of last century, Wang and Zhao [16], and others of Hohai University set up joint assessment model of surface water and groundwater in karst areas, and they used the model based on the hydrological model and the groundwater dynamic model of Xin'anjiang basin to conduct joint assessment of surface water and groundwater and conducted transplanted mutual verification of the evaporation coefficient of phreatic water in the model. But they selected only one average parameter, so the calculation accuracy of the model was limited to some degree.

In 1990, the International Forum "Hydrological Basis of Water Resources Management" was held in Beijing. In the forum, six topics were discussed: interaction of surface water and groundwater under conditions of development and utilization of water resources, water quality assessment and management, collection and arrangement of hydrological data and setup of information system and database, expert's system for decision-making of water resources management and specific plan, environmental change and water resources and hydrology, planning, development, and management of water resources.

In 1991, the International Conference "Groundwater Flow and Simulation of Pollution" was held in Nanjing. Experts and scholars attending the conference reached the common opinion that with the long-term development of electronic computer technology, "simulation" has become internationally the most important approach for groundwater research. In 1992, the International Forum "Groundwater and Environments" was held in Beijing, and topics such as groundwater and environmental geology, groundwater pollution and environments, soil salinization, and local mechanism are covered. In 1994, Hebei Branch of North China Water Resources Center used the transformation model of four water in plain to assess the water resources in Hebei plain and obtained good results [17]. Because the situation of China's water has changed greatly in past 20 years, the second assessment of water resources began in 2000, and the task was to assess the amount of groundwater resources, allocation and storage capacity, and environmental and ecological function, to put forward the plan for rational development and utilization of groundwater and to set up a space information system of national groundwater resources and a platform for dynamic assessment.

The results of the first assessment of water resources in China have played an important role in guiding the development and utilization of water resources in the country at that time. But with the development and utilization of water resources in recent years, many new problems have occurred. For most China's rivers, the amount of water resources in them has changed because the consumed water amount outside the river has constantly increased, the mode of land utilization has changed continuously, different water conservation measures have been implemented, and human activities have significantly influenced the process of runoff and confluence and water yield in water basin. Particularly excessive development and utilization, as well as pollution of water resources and excessive extraction of groundwater, have caused lowering of groundwater level, aggravated drought, destruction of buildings, and big loss. The pollution of surface water environments has continuously caused big difficulty for utilization of surface water resources, and at the same time, the infiltration of sewage has polluted shallow groundwater in some areas, inducing difficulty to people and domestic animals to get drinking water [18]. The continuous increase of such problems has greatly influenced China's sustainable economic development. Nowadays, when there is increasing shortage of water resources, it is necessary to assess again water resources.

There are many methods for assessing the water resources in China. In practice, we must select suitable assessment method according to the objective of water resources assessment, hydrogeological conditions, water demand, extraction plan, and degree of research.

1.2.2.1 Assessment Methods of Water Resources

From the basic characteristics of hydrological phenomena, it can be seen that the time–space variation regularity of hydrological phenomena is intricate. In order to find out its variation and to conduct quantitative calculation and qualitative description, we must firstly carry out long-term observation and collect sufficient hydrological data, and then according to different objectives of research and conditions of data, we have to employ various efficient analysis and research methods.

At present, the major assessment methods of water resources include balance method, analytical method, simulation method, correlative analysis method, method of allowable extraction and available amount [19], random simulation method, analysis method of groundwater, hydrological cut method, and hydrogeological analog method [20].

Balance method of water volume

The balance method of water volume focus on how to precisely and reasonably determine different recharge and drainage information. With the identified human activities, the research on dynamic transformation of various information becomes especially important and is the core content of assessment, planning and management of regional water resources. The method is suitable to the area with simple groundwater recharge and drainage conditions, under which the water balance factors are easy to determine and do not change after groundwater extraction.

Analytical method

Analytical method requires strictly idealized hydrogeological conditions. Its application is limited to homogeneous aquifer with simple hydrogeological conditions in small area.

Simulation method

After 1950s of last century, some scholars began to use simulation method to study the regularity of groundwater movement under complex conditions. The simulation method is divided into two categories: physical simulation and numerical simulation [22]. Numerical simulation is used very widely and can resolve many problems in the assessment of water resources under complex conditions. There are two numerical simulation methods commonly used in the assessment of water resources, i.e., finite differential method and finite element method [23]. Numerical method is not only suitable for the assessment of water resources in medium and large water source site with higher requirement and complex conditions, but also suitable for managing water resources, to guide rational development and utilization of water resources [24].

Correlative analytical method

Correlative analytical method is commonly used in the case where there are insufficient hydrogeological exploration and testing work as well as fewer available data, but there are relatively abundant data of groundwater level dynamics. In areas where there are abundant data, the method can be used as one method to assess water resources, so as to conduct analysis and comparison [26].

Method of allowable extraction and available amount

The definition of allowable extraction of groundwater defined by the department of geology and minerals is: ensured producible groundwater resources under economically reasonable extraction conditions without causing water quality degradation, bad geological phenomena (for instance surface subsidence and surface collapse), and unfavorable influence on the ecological balance system [26].

The definition of available amount (available water amount including groundwater and surface water) defined by the department of water conservancy is water amount that engineering facilities can provide in different level years and different guaranteed rates and in consideration of water demand requirements.

According to the definition of allowable extraction and available amount, in combination with the practice, under precondition of the unified assessment of groundwater and surface water as well as assessment of water resources by water-bearing system and water basin, the assessment method of allowable amount and available amount can be summarized as following two aspects:

- On the basis of comprehensive analysis of investigation data, the corresponding mathematical model has been set up. It is necessary to identify the basic characteristics of underground and surface water—bearing system as well as flow system, extending engineering of water lifting, water storage, water diversion, and water allocation, history and status as well as major problems of water resources development and utilization, and long-term change of water resources system under conditions of artificial extraction. According to the actual situation, it is also necessary to select suitable mathematical simulation method and parameters, to set up correct recognition model. It is most critical to depict accurately the hydraulic relation between aquifers and between groundwater and surface water, to set up feedback model with time-varying characteristics.
- To design specific extraction plan (not to design the flow field). The plan should be concrete, including well set or layout of pumping stations (single well or single pump) and extracted amount. The extraction plan is designed to find out basically the possible "optimal" scheme for decision-making rather than substituting decision-making.

1.2.2.2 Review of Water Resources Assessment Method

The results and methods of water resources assessment in China cannot meet the demand of sustainable economic development and sustainable utilization of water resources. The major problems exiting in present water resources assessment are mainly reflected in the following aspects [27].

- The impact of human activities on water resources. Human activities such as land use, urbanization, utilization of water resources interfere with the natural hydrological circulation, change the generation conditions of water resources, and influence the characteristics of water resources such as quantity, quality and distribution. Human activities also make it challenging to collect random and independent hydrological data. Human activities make the generation conditions of water resources kept in the process of continuous change, while the existing serial restoring calculation can only restore the reduced water amount and transferred water amount of water conservation engineering and cannot meet the preconditions of serial consistency.

- Impact of weather change on water resources. The water resources come mainly from atmospheric precipitation and highly depend on weather change. Some experts think that North China is a region sensitive to global warming. Because of aridification and greenhouse effect, there is possibly less precipitation, and the situation of water resources becomes severe. Therefore, to quantitatively study the weather change and its impact on water resources, taking corresponding countermeasures is an important problem that water resources assessment is facing.
- Assessment of available amount of water resources. The previous assessment results are expressed as amount of natural water resources (amount, time and space distribution, degree of development and utilization, etc.), and although they can macroscopically describe the status of natural water resources, they lack index of available amount and utilization degree and cannot meet the need of production and management. While the available amount is dependent on the quality, distribution, engineering design, and planning engineering [28], there is no commonly accepted unified calculation method and technical standard.
- Systematics of water resources. Surface water and groundwater are hydraulically connected subsystems of water resources. But many previous water resources assessments did not consider the interconnection and conducted water resource calculations separately by treating the surface water and groundwater as independent systems.
- Dynamics of water resources. In the large system of water resources, not only the quality and the quantity of surface water and groundwater change with time, but also the conversion between them is dynamic, particularly the development and utilization of water resources by human being made this conversion more complicated [29]. It is very necessary to conduct dynamic assessment and forecast. In traditional assessment method, surface water and groundwater are calculated and assessed in isolation, and it is impossible to realize dynamic assessment and forecast of water resources.
- In the current assessment of water resources, surface water can be studied in detail in time distribution, for example, interannual and annual variation. But in assessment of groundwater, using the average of many years does not provide the calculation results that allow the analysis of interannual and annual variation of total water resources.

1.2.3 Current Status of Research on Mine Seepage Theory and Numerical Simulation

1.2.3.1 Simulation of Groundwater Flow

Through development since many years, the research on the theory and method for groundwater flow simulation particularly numerical simulation has reached big progress. But in some aspects, for example in deposit hydrogeology, the accuracy of water inflow prediction in mine is still unsatisfactory. Because fracture water seepage is characterized by heterogeneity, anisotropy, and discontinuity, simulation of groundwater system by using seepage theory of porous media characterized by homogeneity and continuity produces certainly big error and is even beyond recognition [30].

The research on fracture water started in the middle of 1960s. Ando et al. [31] and Louis [32] used permeability tensor to set up seepage model of anisotropic fracture media and became the pioneers in the research field. After the 1970s, the research has advanced rapidly. Fracture network model has been continuously improved. Several representative models appeared: (1) seepage model of equivalent continuous media [33], (2) seepage model of discontinuous media [34], (3) seepage model of generalized double media [35], and (4) coupling model of seepage field and stress field of generalized double media [36]. The above-mentioned seepage models of fracture media have summarized and expressed the structural characteristics and water flow movement characteristics in permeable space of fractured rocks and have their own adaption scope and application conditions.

The redistribution of stress field under the influence of mining will induce damage and result in the violent variation of permeability in rock mass, showing characteristics of non-Darcy seepage. Factors influencing stress–permeability relation are numerous and complicated, and particularly, it is very difficult to describe quantitatively the increased amplitude of infiltration after the peak in rock mass [37]. At present, empirical relation (equation) of stress and permeability obtained from laboratory experiment is inserted into the coupling model of seepage—stress—damage [38], and it is the major approach to resolve the problem in mine inflow prediction.

1.2.3.2 Research on Special Variability of Hydrological Hydraulic Parameters

Traditional parameter zoning and interpolating cannot depict the heterogeneity of permeability coefficient in rock mass. The results of research indicate that most hydrological hydraulic parameters are spatially correlated, there is certain collaborative correlation among different parameters, and this spatial variation is different depending on the type of parameters, sampling method, and sampling measure.

In actual field conditions, water-bearing media shows intense spatial variability, so we must treat water-bearing media as a random variable [39].

At present, the permeability coefficient is treated as a random variable to construct permeability coefficient field. Mainly, the methods are as follows: (1) method of discrete independent parameter, (2) method of continuous correlative parameter, (3) discrete correlative parameter, and (4) condition simulation [40]. The application of random simulation in simulation of groundwater flow and pollutant migration in porous media has rapidly developed abroad [41], and its application has already started in China, but there are few cases of its application in resolution of actual problems in fracture media [42, 43]. Geostatistics is a science based on the theory of regional variable and taking variogram as a basic tool to study the natural phenomena distributed in space and showing certain structures and randomness [44–46]. So using geostatistics to study the spatial variability of parameters of hydrological and water resources environment system, we can reveal quantitatively the variation regularity of parameters of hydrological and water resources environment in different spatial directions and identify the direction of the maximum variation of different parameters. Particularly, geostatistics can give the optimized estimation and variance of regional variable. Any other estimation method does not have this character [47].

The research on spatial variability of hydrological and hydraulic parameters has become a hot subject of abroad scholars. Since abroad scholars started to study the spatial variability of hydrological and hydraulic parameters in 1970s of twentieth century, the initial research before 1980s basically remained in qualitative description of the spatial variability of parameters, and during the end of 1970s and the earlier 1980s, research moved into quantification. Delhomme [48] introduced firstly geostatistics into the field of hydrogeology and studied the spatial variability of permeability coefficient of aquifer. Gambolati and others used Kriging method to estimate the distribution of groundwater water head in Venice, Italy, taking this as a basis for the study of surface subsidence [49]. Delhomme [50] and Clifton [51] also used Kriging method to estimate the distribution of water conduction coefficient of aquifers in Normandie, France, and Avra aquifer in Arizona, USA. Since the middle of 1980s particularly 1990s, numerous abroad scholars have applied geostatistics to study the collaborative structure characteristics and spatial distribution characteristics. In 1985, De Smedt and others discussed the analysis of the spatial variability of conduction coefficient under different observation scales, deepened the research on spatial variability of hydrogeological parameters [52]. In 1988, Amleto and Murashige took the permeability coefficient of aquifer and phreatic water level as unstable regional variable, studied the spatial distribution of parameters in Potomac-Raritan-Magothy aquifer in New Jersey, USA, and applied universal Kriging in the research of the spatial variability of parameters [53]. However, in order to fully utilize other geological information and some natural information to increase the estimation accuracy of parameters, co-Kriging was applied preliminarily in the field of hydrogeology; for instance, Abou-Saif and Al-Kawas [54], Ahmed et al. [55], and Nolen-Hoeksema et al. [56] applied co-Kriging to study the spatial variability of hydraulic characteristic parameters. Since approximately 10 years, abroad scholars have obtained many important achievements in the research on the spatial variability of hydrological and hydraulic parameters. Dobermann et al. [57] have also obtained a series of research results in the scale-related analysis of soil properties of unsaturated zone of low land in tropical area. Goovaerts [58] not only analyzed the correlation of the spatial scale in the aspect of spatial forecast of geotechnical characteristic parameters, but also set up non-deterministic geostatistical model for the water-soil relationship (2001).

At the end of the 1980s in China, the research on the spatial variability was still limited in trend surface analysis; for example, Fan Jiajue studied in 1988 the spatial distribution characteristics of permeability parameters of aquifers in the alluvial fan of Hun River [59]. Up to the early 1990s, geostatistics obtained some preliminary results in soil physics, water conservancy, and hydrology and was not yet applied in the study of the spatial variability of hydrogeological parameters [60]. Until after 1993, Tinxi and Caolunbagen [61], and Liu Yanxi and others (1993; 1994) studied the specific water yield, the burial depth of limit evaporation of phreatic water, permeability coefficient, and characteristic parameters of unsaturated zone and conducted valuation prediction. Then, various Kriging methods for geostatistics have been applied in the research of the spatial variability of hydrogeological parameters [62].

1.2.4 Current Status of Research on the Theory and Technology of Rational Allocation of Water Resources

1.2.4.1 Basic Concept

From the basic concept, the rational allocation of water resources is how to utilize water resources, including the development, utilization, protection, and management of water resources [63]. Concretely speaking, the rational allocation of water resources is to adjust the time–space distribution of water resources through engineering and non-engineering measures according to the need of sustainable development, to emphasize on open source and saving of water, development and utilization and protection, to balance the current interest and long-term interest, to well deal with the relationship among the economic development, ecological protection, environmental control, and resources development, to use systematic method, decision-making theory, and computer technology to allocate in united way surface water, groundwater, reused water (reused sewage after treatment, i.e., intermediate water), invoked water (invoked water from outside), and brackish water, to pay attention to bringing benefits and abolishing harms, to coordinate well the contradiction of interests of different departments using water, to increase the regional integral water utilization efficiency, and to accelerate the sustainable utilization and regional sustainable development of water resources [64].

The rational allocation of water resources is realized through the integral system composed of engineering and non-engineering measures [65]. The reasonability of the water resources allocation is reflected in the resolution of the conflicts of supply and demand of water resources, competition of different water usage, upstream and downstream coordination, investment relation of different water conservancy projects, water usage benefit of economy and ecological environments, water usage of the current society and future society, mutual conversion of water sources, and fair and acceptable water resources allocation plan [66]. The rational allocation is the objective and the wish to allocate rare resources. Generally speaking, the result of the rational allocation is not the best for an individual or the main body, but is the best for the overall benefit and interest.

The optimized allocation is the method and approach used for searching rational allocation plan [67]. The general optimization that is realized by mathematical description, has to generalizes objectives that are often difficulty to quantify. These generalizations cause “distortion” of the original problem with results being far away from the actual requirements. With the scientific and technological development, different optimization methods will be developed and the optimization results will gradually approach the requirements of rational allocations.

1.2.4.2 The Scientific Basis of the Rational Allocation Water Resources

The objective basis for the rational allocation of water resources is the interdependent and interconstraint quantitative relationships between macroeconomic system, water resources system and environmental system, which are parts of the complex “economy—environments—society—resources–ecology” system. Their relationships are intensively reflected in the competiveness of water usage and investment. The competiveness in water usage results from conflicts in the objective of water usage, time and region because of insufficient water resources, poor water quality, and insufficient water supply capacity. Because the competiveness of water usage, the problem of the rational water allocation is induced between the national economic development and ecological environmental protection at the same time. It is also needed to resolve the problem of the rational water allocation among different national economic departments and different regions. The competiveness of water usage is resolved through engineering and non-engineering measures and both require investment. Because there are many approaches to resolve the competiveness of water usage and investment, different resolution plans have different influence on regional development mode, utilization, protection and control of water resources. Therefore, the optimized allocation of water resources is needed.

The allocation of water resources is realized through the optimized allocation system. The optimized allocation system consists of hardware and software [68]. The hardware includes engineering of water source, water supply network, facilities of water usage, water drainage network, and reused water facilities of sewage treatment. Software includes development scale, sequence of construction, strategy of optimized scheduling, economic mechanism, and administrative mechanism. Through these engineering and non-engineering measures, different types of water resources with a different regularity of input water and different quality will be allocated and treated for specific areas and specific period, forming efficient water supply with certain guarantee rate and water quality standard in assigned areas and assigned period, so as to increase at maximum the efficiency of overall and comprehensive utilization of water resources.

1.2.4.3 Relation Between Rational Allocation and Supply–Demand Balance of Water Resources

The analysis of the supply and the demand of water resources is the basis approach for allocation of water resources [69]. The major task of the analysis of supply and demand is to conduct long serial investigation and calculation or typical annual analysis of water supply, water usage, water consumption, water drainage of water resources in a water basin or in a region, to obtain index such as the satisfaction degree, surplus and deficiency, time—space distribution and the situation of water environments of different level years in the water basin (region), to definite the nature and the cause of water shortage, to determine the sequence of measures for resolution of water shortage, to provide basic information for the analysis of water resources supply and demand structure, utilization efficiency and rationality of engineering layout, analysis and calculation of marginal cost of potential tapping and increasing supply, pollution control, water saving, transferred water from the outside, and for the generation of allocation scheme of water resources.

Through repeated analysis of water supply and demand, water resources allocation involves water resources allocation scheme under combined conditions of water demand, water saving, water supply (water transfer), and protection of water resources. The generation of the scheme follows the thought of three balances [70]—full consideration of water saving, pollution control and potential tapping in the water basin, and consideration of water transfer from the outside of the water basin. On the basis of the analysis of current water supply and demand, and on the basis of combination and analysis of possible measures for various reasonable control of consumption, efficient increase of water supply, and active protection of ecological environments, multiple feedback of supply and demand is conducted and the balance is coordinated, striving to realize the rational allocation of water resources [71].

1.2.4.4 The Major Tasks of the Rational Allocation of Water Resources

The rational allocation of water resources is proposed aiming at the shortage of water resources and the competition of water usage. It can be realized through water allocation system. The resources and environmental, social, and economic attribute of water in itself decide that the rational allocation of water resources concerns rather wide content. The major tasks of its research include [72, 73] the following aspects:

Social economic development and demand of water resources
The following tasks should be conducted for social economic development and demand of water resources: to explore the scale and the direction of actual feasible social economic development in a water basin or a region; to seek rational distribution of production; to study water use structure, water utilization efficiency and corresponding technical measures under current situation; and to analyze and forecast the demand of water resources under conditions of future living standard improvement, development of different national economic departments and protection of ecological environments.

Quality of water environments and ecological environments
The aim is to evaluate the quality of the current water environments, to analyze the pollution degree of water environments, to formulate reasonable standards for water environment protection and control, to analyze the ratio and total amount of discharge of different pollutants during production, and to forecast the concentration and environmental capacity of major pollutants in rivers and lakes. The purpose is to conduct the research on the criteria for protection of ecological and environmental quality, the mechanism, and the quantity of ecological water consumption and to analyze the relation between ecological environmental protection and the development and utilization of water resources.

Patterns of water resources development and utilization and engineering layout
The following tasks should be conducted for designing patterns of water resources development and utilization and engineering layout: to carry out assessment of water resources development and utilization, analysis of water supply structure, analysis of available amount of water resources; to study united deployment of multiple water sources; to plan the reasonable scale and construction sequence of water conservancy projects; and to analyze the necessary investment, running cost, integrated benefits of flood control, electricity generation and water supply of the development and utilization of different water sources.

Analysis of supply and demand balance
The aim is to carry out analysis of supply and demand balance of water resources under the mode of different water conservancy engineering development and the mode of regional economic development and to determine the scope and available water supply of water conservancy engineering, the constitution of water sources for water supply, quantity of water supply, guarantee rate of water supply, water deficiency, process of water shortage, and distribution of damage induced by water shortage in each water-using unit.

Water resources management

The following tasks should be conducted for water resources management: to study the scientific management system matching the rational allocation of water resources, including to set up scientific management mechanism and approach; to formulate efficient policies and regulations; to determine reasonable fee of water resources, water price, standards and implementation method for collecting water charge; to analyze the influence of water price on social economic development and its inhibiting effect on water demand; and to train scientific management personnel of water resources.

Technology and method of water resources allocation

To study and develop model technique and method related to water resources allocation, for example, modeling mechanism and method, decision-making mechanism and method, simulation model, optimization model and evaluation model, management information system, support system for decision-making and application of GIS technology.

Integrating the practical experiences in previous regional water conservancy planning and management, the research methods for rational allocation of water resources include the following categories:

- To consider together the regional macroeconomic system, ecological environmental system, and water resources system, to focus on water demand, water supply, and water quality management, and to grasp quantitatively the interdependent and interconstraint relation among the three.
- To take the coordinated regional economic, environmental, and social development as research objective to study the strategy of the rational allocation of water resources and to reveal quantitatively the relation of mutual competition and mutual constraint among objectives.
- To adopt the decision-making method of multiple levels, multiple objectives and group decision-making to accommodate the influence of different optimized allocation schemes on upstream and downstream, left and right banks, different areas and different departments and to integrate each decision maker’s intention into the decision-making process.
- To take the analysis of the dynamic input and output of each macroeconomic department as basis and to reveal quantitatively the relationship among agriculture, industry, and tertiary industry, the relationship between economic development and the overall plan of a water basin, and the relationship among professional plans such as the development of each department and irrigation plan, hydraulic electric generating plan, urban life and industrial water supply, and water resources protection plan, etc.
- To maintain the balance of water demand and water supply in the decision-making of the rational allocation, the balance of sewage discharge and water pollution control, and the balance of the sources and the distribution of investment on water and at the same time the water ecological balance under natural conditions.

- To combine organically the optimization approach of decision-making of multilevels and multiobjective group with simulation technology of complex water resources system with multiple water sources and multiusers, to use the optimization approach to reflect various dynamic connections, and to use simulation approach to reflect the influence of uncertainty during economic development and hydrological continuous change of water abundance and dry-up on the optimized allocation scheme.
- To use the shadow water price derived from dynamic input and output model and water diversion principles derived from decision-making model of multiobjective groups as economic levers of the rational allocation of water resources. Implementation of the rational allocation scheme requires institutional controls such as administrative management and legal means including water intake permit.
- To set up decision-making support system of regional water resources allocation with the guide of the theory and method of the rational allocation. To take the system as the quantitative calculation tool for rational allocation so as to conduct dialogue with decision makers and also as water resources management information system of each area.

1.2.4.5 Principles and Objectives of Water Resources Allocation

Principles of water resources allocation

Macroscopically, according to the principles of economics of rare resources allocation, the rational allocation of water resources should follow the principle of high efficiency and fairness. In the advanced stage of water resources utilization, the principle of sustainable utilization of water resources should be also followed simultaneously, i.e., high efficiency, fairness, and sustainability, and must be the basic principle of rational allocation of water resources. Microscopically, allocation of water resources must also follow the principle “excellent water is for excellent usage” and the principle of minimum destruction in case of resources shortage [74, 75].

From the above-mentioned allocation principle, the rational allocation of water resources must start with the space, time, and objective of water use and water amount allocation.

Objective of water resources allocation

The general objective of water resources allocation should be to carry out transformation, planning, design, combination, arrangement, and management of the layout according to the natural and social situation of ecological system of water resources in a water basin or in a region by adopting scientific and technological methods and reasonable management system, attempting to achieve the requirement of sustainable development and sustainable utilization of water resources.

The concrete objectives of the rational allocation of water resources include the big output, the high efficiency, the optimal structure and function, strong anti-interference, and recovering and transforming capacity of the sustainable utilization system of water resources.

1.2.4.6 Model for the Rational Allocation of Water Resources

The model for the rational allocation of water resources can be defined as a computer model by pursuing the optimal function of sustainable utilization of the integral system as objective. The computer model is aimed at water resources system with water supply as the main objective and with system analysis theory, operational research, intellectual rule, and logical deduction as technical basis and combines suitably and regulates jointly different engineering measures and non-engineering measures.

The analysis of water resources system generally adopts two basic methods: One is optimization and the other simulation. The optimization uses commonly mathematical planning, looks at macroanalysis and spatial configuration of water resources, solves the studied optimized objective function and constraint equation set, and arrives at the results of optimization, i.e., Pareto solution. Simulation looks at microanalysis and the time configuration of water resources, conducts simulating calculation of the comparison scheme already drawn up or optimization scheme, gets different evaluation index values of the scheme, then performs evaluation, chooses the best, or verifies the optimized results.

Preference and verification of the optimized results. Commonly used optimization models include linear programming model, nonlinear programming model, dynamic programming model, and multiobjective programming model.

In a plan of water resources, the multiobjective programming model cannot produce the clear optimal solution given in the conventional model and can only obtain some “non-inferior solutions,” and the non-inferior solutions constitute non-inferior solution set. There are many solution methods approximately the multiobjective programming model, including:

- Evaluation function method;
- Interactive planning method;
- Mixed optimization method.

At present, to couple the optimization model of water resources allocation with the simulation model and to take the advantage of the two into account are becoming the trend for the best solution of the problem of the rational allocation of water resources.

1.2.5 Current Status of the Research on Water Resources Protection in Mining Areas

The earliest achievement made abroad in the protection of groundwater resources in mining area is the monograph “Change and Protection of Mining Hydrogeological Conditions” written by B.M Fomin in the former Soviet Union in 1983. The monograph discussed groundwater recession, exhaustion of water resources, and other problems related to groundwater and induced by mining and put forward suggestions on the comprehensive utilization of water resources.

China is a large mining country. Coal mines are mostly located in the northern region with water shortage. In recent years, in order to look for water and to save energy, research on different technologies of the comprehensive utilization of water resources has been conducted in many mining areas [76, 77]. The research is based on the current status of water resources utilization and investigation of hydrogeological conditions in mines, including the research on water quality and pollutants. Multiobjective decision economic management model is applied to put forward optimal regulation and control of future water resources utilization and to conduct corresponding forecast [78, 79]. Theoretically, the research gets close to attain the international level.

The earliest discussion on water resources protection in China was conducted in Yangquan Coal Administration, Shanxi Province. Because of sewer drainage in Yangquan mine, Niangziguan spring dried up. From 1981, some experts were organized to study the technological measures of mining and water resources protection. The report published in 1984 used the concept of "combination of water drainage and water supply", with which the people are now familiar. Then, in the joint key research project of the State Development Planning Commission, the Ministry of Geology and Mineral Resources, the Ministry of Coal Industry, Non-Ferrous Metals Corporation and the Ministry of Metallurgy, the study on "Karst and Rational Development and Utilization of Water Resources in North China" was conducted. The project, using drainage and supply technology, discussed the utilization and protection of water resources in northern mining region. In 1995, Wu Qiang and others put forward the theory of comprehensive utilization of mine water—"integration of water drainage, water supply and environmental protection" and conducted deepened study in Jiaozuo mining area [80, 81]. At present, application of mine water lays particular stress on improvement of water treatment technology and simply reused [82, 83], and because of the influence of factors such as policy, there is some distance from the realization of the comprehensive utilization of mine water in real significance.

1.2.6 *Application of New Technology in the Study of Hydrology and Water Resources*

1.2.6.1 Comprehensive Application of "3S" System

So-called 3S system [84, 85] is referred to the integration of GIS (geographic information system), RS (remote sensing system), and GPS (global positioning system). GIS is a computer system for collection, storage, management, analysis, display, and application of geographic information and is a general technology for analysis and processing of huge amount of geographic data, making analogue simulation of topography, geomorphology, river runoff, river diffusion, and river consumption possible in the study water basin, generating dynamic, visual, and 3D effect, with its strong functions such as digital mapping, graph storage, database or networking database, spatial analysis, and aiding decision-making, providing powerful technical support for the development of the subjects of hydrology and water resources.

The actual application of 3 systems in the field of research of hydrology and water resources further promotes the development of digital water basin and digital hydrology, is a milestone of the study and application of groundwater model, and can conduct intuitive, accurate, quantitative simulation, evaluation, and trend forecast of different geological hazards such as surface subsidence, ground fissure, seawater intrusion in littoral areas, and water inrush in roof and floor induced by coal mining in underground coal mines.

1.2.6.2 Application of Computer Technology

Groundwater model [86, 87] has advantages such as interface, generalization, visualization, intelligence of pre- and postprocessing, and standardization of output format and is characterized by man–machine interaction, data interface of geographic information system, automatic generation of regionalization of spatial parameters, rapid and accurate numerical algorithm, and advanced visualization of graph, has functions such as setting up of various spatial finite element net, a stereo 3D spatial model, 2D planar model, 2D section, or axial symmetric 2D model, also has functions such as simulation of unsteady flow or steady flow, free surface water-bearing system of multilayers, groundwater movement, and migration of chemical materials, and is up-to-date software with the most complete functions for simulation and analysis of groundwater. GMS is so far the most complicated and integral software of groundwater model, composed of MODFLOW, MODPATH, MT3DMS, RT3D, SEAM3D, FEMWATER, NUFT, UTCHEM, SEEP2D, PEST, and UCODE. It is mostly suitable to set up all categories of groundwater models and has advantages of good preprocessing program. GMS uses separate module processing for source sink term and different boundaries, good technical support and fast renovation, great amount of reference manual and source program codes that can be modified according to the project needs [88, 89].

1.2.6.3 Application of Geostatistics

When geostatistics, sequential stratigraphy, and Quaternary geomorphology are applied in recognition of the structure of groundwater system [90–92], we can determine 3D spatial distribution of different lithologies on the basis of regional discrete borehole data to provide 3D spatial data for setting up of 3D visualization platform of groundwater system, in combination with MODFLOW and FEFLOW to set up the model of 3D groundwater flow in real significance, to sufficiently use the information of each borehole and generation of computer technology, and to improve accuracy and efficiency.

1.2.6.4 Application of Multivariate Statistical Analysis

In modern research on hydrology and water resources, processing of observation data with multiple variables is often required, using various methods such as estimation and test provided by multivariate statistical analysis, principal component analysis, canonical correlation analysis, multivariate linear analysis, discriminant analysis, and cluster analysis, with the aid of multitudinous and fast data processing capacity of computer, research on the distribution and digital characteristics of multidimensional random variables, and correlation among variables and their related statistical characteristics can be realized [93–98].

1.2.6.5 Application of Hydrochemistry and Environmental Isotope Technique

Hydrochemistry and environmental isotope techniques are used to understand and determine the geological conditions in study areas, recharge, runoff, discharge, circulation and hydraulic connection in a water system [99–101] through the study of the composition, distribution of stable isotopes, rare elements and rare gas in water and evaluation law of water.

1.3 General Thinking, Content, and Technical Route of the Study

1.3.1 General Thinking

The general thinking is based on the analysis of historical available data, takes the investigation of hydrological data exposed at site as subject, in combination with complement exploration, to study the distribution of water resources (including surface water, groundwater and mine water), the status and variation trend of domestic water, production water and industry water in the mining area, from the view of water system, to assess qualitatively and quantitatively the distribution law, evaluation trend, development and utilization potential of water resources, to put forward the optimized allocation plan of water resources of future different level years in Shendong mining area, further to put forward technical approaches and technical route for improvement of development and utilization ratio of water resources and realization of sustainable development in the area.

1.3.2 Major Content

According to the major task, the key scientific problems to solve and expected objective of the study, the content of research, test, experiment, investigation, and calculation are as follows:

- To collect overall historical exploration and observation data related to the study and related to hydrology, meteorology, ecological environments, hydrogeology, geology, and coal resources in the study area and to collect the qualitative and quantitative demand on water resources from agriculture, life, and industries (particularly coal and electricity construction), and the future variation trend in recent years in the study area.
- To take the groundwater and surface water recharge, runoff, and discharge system with the surface divide of Ulan Mulun River water basin as boundary as the key study area, to divide the area into relatively independent hydrological system of recharge, runoff, and discharge of sublevel, to conduct systematic investigation of approximate level, yield, quality of mine water, groundwater, surface water, water supply well point, and different types of springs exposed in valley inside the study area, to analyze the burial and exposure conditions of the main aquifers, the mutual contact relation and hydraulic connection between aquifers and surface water bodies (perennial river, ravine with seasonal flow, reservoir and pond, etc.), to conduct hydrogeological mapping of key water source sites, to investigate and analyze water consumption and water deficiency in production, life, industries, and afforestation and the current status of mine water utilization, and to assess the impact of mining on water resources and environment geology.
- To set up the dynamic observation network of water resources in the study area (according to the *Technical Specification for Dynamic Long-Term Observation of Groundwater MT/T633～1996*), taking Ulan Mulun River water basin as unit, and to set up the observation network of rainfall infiltration conditions, surface water, groundwater, and mine water. The observation network will take the exposure points of well and springs as subject. In areas where there are insufficient control points and key water source sites, additional necessary exploration engineering will be complemented. Exploration engineering is mainly hydrogeological drilling and corresponding hydrogeological tests. Exploration boreholes will be used also as long-term hydrogeological observation boreholes. To observe principally the yield, level, chemical composition, flow net and hydraulic conditions, mutual conversion of different kinds of water, and their evolution trend.
- To conduct hydrogeological division, assessment and study of water resources system, subsystem and key water source sites based on investigation of water resources, hydrogeological test, hydrological information observation and exploration of major aquifers, in combination with collection, reorganization, analysis and study of historical hydrological and water resources data according to indexes such as abundance and deficiency, characteristics of recharge and

circulation, burial and development condition, hydrochemical type, availability, importance in ecology and environments, reliability of water resources of different types and in different areas, and their relation with coal mining.

- To set up database and information management system of water resources in mining area. The management system will have function of inquiry, processing, calculation, analysis, imaging, visualization, updating, modification, and optimization of information. Apart from serving water supply and environmental geological evaluation in mining areas, the database includes also data necessary for water hazard control in coal mines, for example, parameters of aquifer, parameters of rocks, data of transmission fracture zone in roof, and data of small structures.
- On the basis of the structural characteristics of roof rocks of the major minable seam and its spatial relation with aquifer, to set up the computer simulation model of mining and excavation process in mine, to simulate and analyze the disturbance effect of mining on water source site (aquifer) in different areas and under different burial conditions and different excavation modes to predict water inflow possible occurring during mining and its influencing factors, so as to provide technical data and theoretical support for formulating the plan of mine water control and utilization as well as protection of water resources, and finally to put forward the technical plan for protection of water while mining and comprehensive utilization of mine water.
- To set up random optimal management and decision management models for united dispatch of water resources (surface water, groundwater, mine water, etc.) in mining area. These models include the basic information such as the type of water resources, location of major water sources, water yield, water quality, water demand, hydrochemical requirements with the maximum assurance rate of water resources supply. The minimum cost of water supply is set as objective functions in the models, with ecological environmental protection, protection of water resources, groundwater level control and safe mining of coal resources as major constraints. The models simulate and calculate the optimized regulating and control plans of water resources for the coordinative development of life, ecology and production in the mining area (and to put forward the reliability level of different plans) to put forward the concrete measures for the unified coordination of water quality and quantity, the maximum integral economic, social, ecological environmental benefit in future years and under condition of limited water resources. The 3D numerical simulation model of the key water source sites and major aquifers, multiobjective economic management model for the optimization of the optimal development plan of water resources is established in the study area to assess the feasibility and reliability of the integral exploitation of water source sites in valley of the first level tributary of Ulan Mulun River.
- Through the study of the structure of the macro water system and water balance and dynamic conditions, the prediction, assessment and calculation of the quantity of water resources in key water source sites are conducted to evaluate the feasibility of recycling and the availability of mine water. Scheduling and optimal control models of water resources are used in combination with water

use plan of industrial and agricultural sectors in the mining area. The modeling results put forward the technical plan for the comprehensive utilization of water resources in the study area and assess the reliability of the plan.

The relation of interdependence of the major content of the project is shown in Fig. 1.1.

Thus, it can be seen that there is a closed interdependent relation among different research contents, and different research content not only has its relative

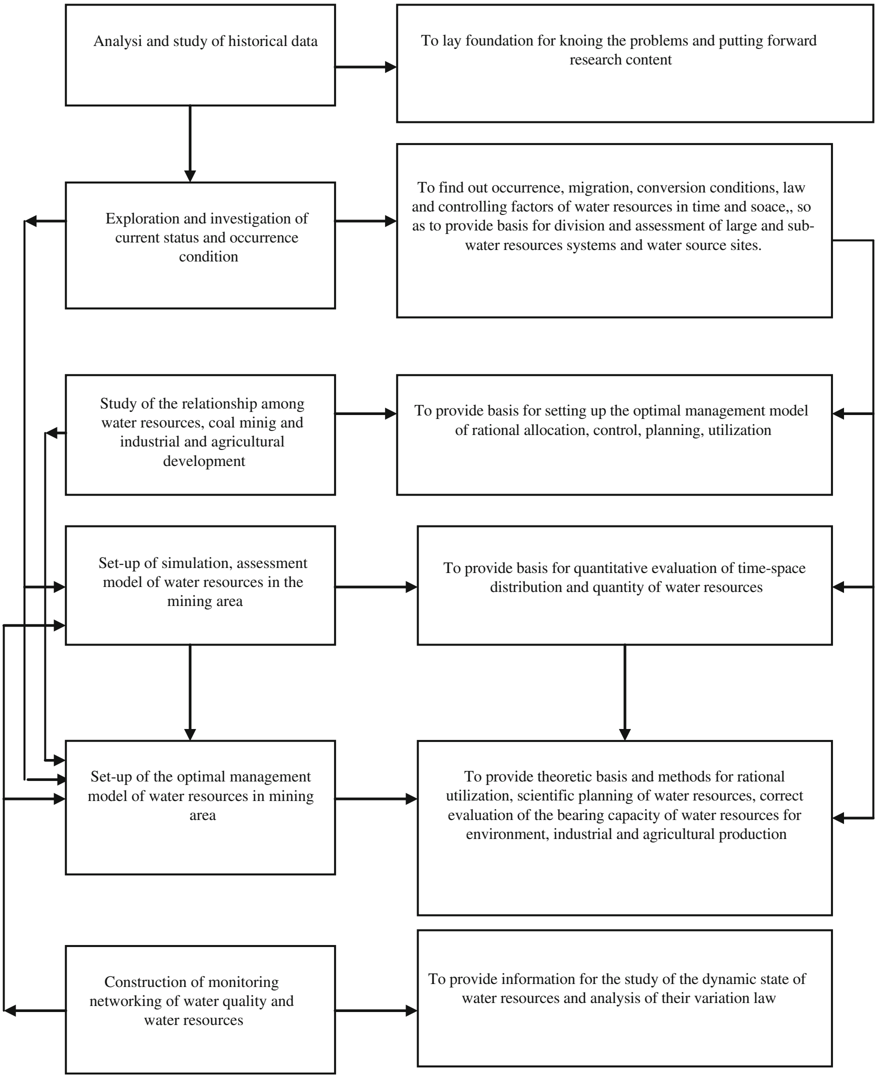

Fig. 1.1 Block diagram of the relationship of interdependence of research content of the project

independence and assumed the special response to a scientific problem, but also laid foundation for other research works.

1.3.3 Technical Route

The overall technical route of the research is shown in Fig. 1.2.

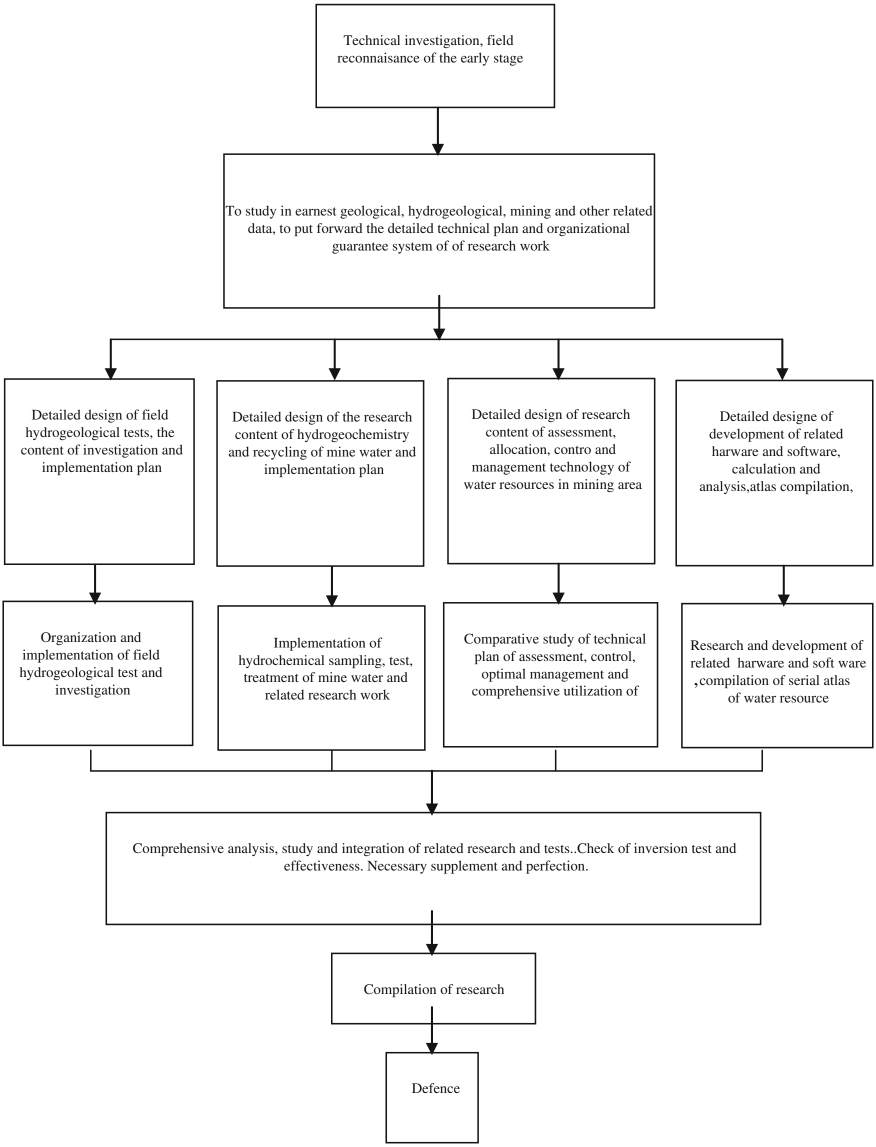

Fig. 1.2 Technical route of research work

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Chapter 2
Analysis of Supply and Demand of Water Resources in the Study Area

Analysis of supply and demand of water resources is to analyze and study the relationship between supply and demand of water resources in the study area. Through the analysis of supply and demand of water resources, the contradiction between the supply and the demand can be revealed; thus, the measures to solve the problems can be put forward. In this chapter, surface water, groundwater, mine water, and accumulated water in gob are taken as organic components of water resources system, and the total water resources are calculated and analyzed. At the same time, on the basis of the current status of the development and utilization of water resources in the area, the future water demand is predicted. This will provide scientific basis for rational allocation, optimal regulation, and control of water resources.

2.1 Assessment of Surface Water Resources

Surface water resources refer to the dynamic water yield of surface bodies such as river, lake, and reservoir, and their quantitative characteristics are the runoff volume of stream [1, 2]. The river and its tributaries in the study area are tributaries of Yellow River and are mainly recharged by rainfall. Controlled by rainfall, water level of streams rises and lowers sharply and varies a lot seasonally.

2.1.1 Surface Water Bodies in the Study Area

There are totally 47 existing surface water bodies (reservoirs and ponds) inside the study area, including ponds recorded in previous data and water bodies newly constructed and formed in recent years. There are 26 water bodies with relatively

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large surface area and volume, mainly distributed in 14 ravines and ravine branches (Gongnieergai ravine, Shujigounao, Hala ravine, Shimibula ravine, Gejia ravine, Bulian ravine, Huaer ravine, Sanbula ravine, Shuanggou ravine, Sha ravine, Xisha ravine, Liugen ravine, Tuolawanmingziliang), the volume of the largest water body is 2.2 million cubic meter, and it is Baolaigao reservoir located in Gongnieergai ravine. The total area of water surface is 590,794.6 m^2, and the total volume is 2,696,705 m^3. The details are shown in Table 2.1.

Surface water bodies in the study area are recharged by rainfall and phreatic water of Quaternary loose layer. Except for reservoirs, the volume of most water bodies is small. The content of organic matter and suspended solids is relatively high. Water quality is poor and cannot be used as water source of water supply. There are 3 relatively large reservoirs in the area, i.e., Baolaigao reservoir, Liugengou reservoir, and Gejiagou reservoir, and the capacity of reservoirs is relatively high; water quality is good. These 3 reservoirs are source of water supply in the area.

2.1.2 *Runoff Volume of Ulan Mulun River*

Ulan Mulun River is the main stream flowing through the study area. Gongnieergaigou, Huhewusugou, Buliangou, Huojitugou, Halagou, Liugengou, Kaokaolaigou, Tangjianggoue, Muhuagou, Zhugaigou, and Shuanggou constitute the tribute at both sides of the river and are mostly seasonal streams. Under a part of tributaries, groundwater seeps in the form of spring [3–5]. The distribution of surface drainage in the study area is shown in Fig. 2.1.

Through the collection of data of measured runoff volume of many years at Zhuanlongwan Hydrometric Station at the upstream of Ulan Mulun River and at Wangdaohengta Hydrometric Station at the downstream, the average runoff volume of many years in the water basin section in the study area was calculated. Correlation analysis was conducted by using simultaneous runoff series from 1992 to 2004, totally 11 years (missed in 1994 and 1995) at Zhuanlongwan Station and Wangdaohengta Station (Fig. 2.2), and the correlation coefficient is up to 0.92. According to this correlation, the runoff series at Zhuanlongwan Station was interpolated and extended (1961–1992, 1994, and 1995). The runoff from 1961 to 2004 (totally 44 years) was obtained at both stations. The annual and monthly average runoff after interpolation is shown in Table 2.2. From Table 2.2, it can be seen that the average annual runoff of water basin section of Ulan Mulun River in the study area was 117,000,000 m^3 for many years, but was distributed very unevenly in time, mainly concentrated in the period of thawing in March and in rainy season (July, August, and September), the runoff of these four months accounts for approximately 65 % of the annual total.

After processing of the measured annual runoff data of Ulan Mulun River at Wangdaohengta Hydrometric Station during 1961–2006 and interpolated annual runoff at Zhuanlongwan Hydrometric Station during the same period, the

Table 2.1 Statistics of surface water bodies in Shendong mining area (six mines and seven shafts)

No.	Location	Coordinates			Area of water surface/m^2	Water depth/m	Volume/m^3
		X/*m*	*Y*/*m*	*Z*/*m*			
1	North side of Shuanggou	438,312	4,348,998	1160	3,000	2.5	7500
2	Pond at the upstream of Shuanggou	438,384	4,348,231	1141	1,190.5	1.5	1785.8
3	Pond at Halagou	434,774	4,355,860	1194	2,400	2	4800
4	South branch of Sanbulagou	441,452	4,350,544	1198	230	1.2	276
5	Pond at Shujigougounao	430,944	4,344,658	1206	4,105	1.5	6157.5
6	Pond A at the south side of Tuolawan	428,425	4,343,010	1226	5,378.6	0.8	4302.9
7	Pond B at the south side of Tuolawan	428,365	4,342,881	1222	2,937.5	2.5	7343.8
8	Pond at the east branch of Mindziliangou	427,152	4,351,282	1187	357	0.5	178.5
9	Pond at Xishagounao	426,232	4,354,783	1165	100	0.5	50
10	Xishagou reservoir	423,570	4,355,911	1220	1,059.2	5	5296
11	Pond at the upstream of Xishagou	423,396	4,356,005	1229	1200	1.5	1800
12	Pond A at the upstream of Buliangou	420,049	4,357,447	1266	2,049.6	2	4099.2
13	Pond C at the upstream of Buliangou	421,249	4,357,654	1234	3,388.6	1.5	5082.9
14	Pond D at the upstream of Buliangou	422,747	4,358,045	1218	5,786.4	1.8	10,415.5
15	Pond at the convergence of Buliangou and Huaergou	421,838	4,357,577	1230	2,303.2	1.6	3685.1
16	Pond at the middle stream of Huaergou	421,706	4,357,124	1241	4,072.8	2	8145.6
17	Pond A at the middle stream of Buliangou	423,976	4,358,752	1204	4,636.2	1	4636.2
18	Pond B at the middle stream of Buliangou	424,330	4,359,057	1196	4,300	1	4300
19	Pond C at the middle stream of Buliangou	424,315	4,358,955	1194	5,800	2	11,600
20	2 artificial impounding reservoirs at rear Bulian village	426,959	4,360,804	1150	25,000	1.7	42,500
21	Pond at Shagou	429,814	4,359,247	1154	300	0.5	150

(continued)

Table 2.1 (continued)

No.	Location	Coordinates			Area of water surface/m^2	Water depth/m	Volume/m^3
		X/*m*	*Y*/*m*	*Z*/*m*			
22	Pond at the small branch of the middle stream of Gejiagou	433,688	4,361,965	1172	700	1	700
23	Gejiagou reservoir	432,385	4,361,589	1243	22,500	3	67,500
24	Pond at Shimibulagou	432,814	4,363,434	1258	8,000	1.8	14,400
25	Liugengou reservoir	427,634	4,365,003	1213	80,000	3.5	280,000
26	Baolaigao reservoir	420,232	4,377,371	1255	400,000	5.5	2,200,000
	Total				590,794.6		2,696,705

comparative curves were obtained as shown in Fig. 2.3. The runoff at the interval between two stations could be obtained as shown in Fig. 2.4.

Through data consultation, the average annual runoff of 121,000,000 m^3 for many years was also obtained at Xinmiao Hydrometric Station located in Beiniuchuan main stream, the maximum annual runoff was 287,000,000 m^3 (1979), and the minimum annual runoff was 32,000,000 m^3 (1956).

From the above-mentioned data, it can be known that the average annual runoff for many years of Ulan Mulun River in the water basin section in the study area was approximately 117,000,000 m^3, but very unevenly distributed in time, mainly concentrated in the period of thawing in March, July, August, and September, and the runoff in these four months accounts for approximately 65 % of the annual total.

2.1.3 Resources of Surface Water Bodies

Water bodies in the study area include mainly reservoirs, ponds, and lakes. According to the field investigation conducted in October and December 2006, consultation, and collection of previous data, inside the key study areas, there exist 47 water bodies of different sizes, including ponds recorded in previous data, 26 water bodies newly constructed and formed in recent years, located, respectively, in Gongnirergaigou, Shujigounaogou, Halagou, Shimibulagou, Gejiagou, Buliangou, Huaergou, Sanbulagou, Shuanggou, Shagou, Xishagou, and Liugengou Tuolawanmingziliang, totally 14 ravines, and ravine branches. Among these water bodies, Baolaigao reservoir located in Gongnieergaigou has the largest water surface area (400,000 m^2), and its water volume is 2,200,000 m^3. The total water surface area of all water bodies is 590,794.6 m^2, and the total volume is 2,696,705 m^3 (see Table 2.3).

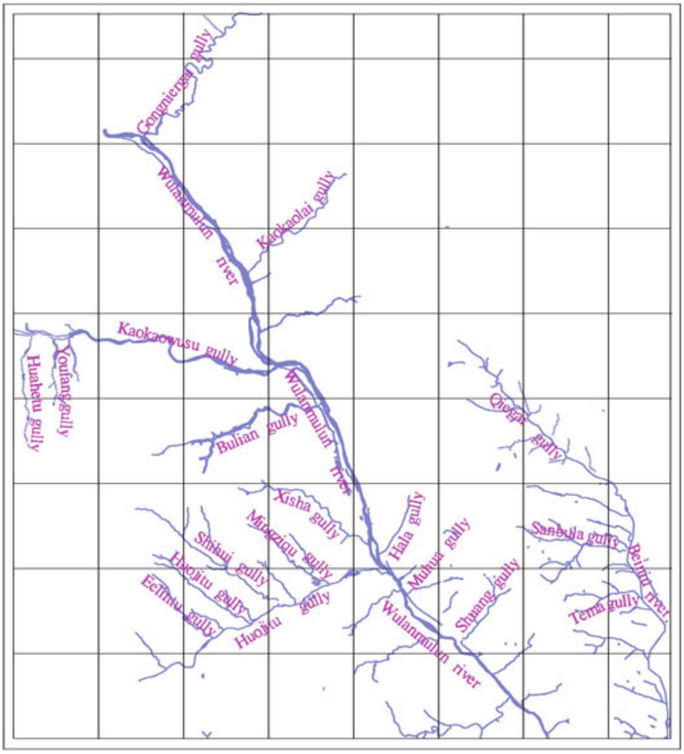

Fig. 2.1 Distribution of major surface water systems

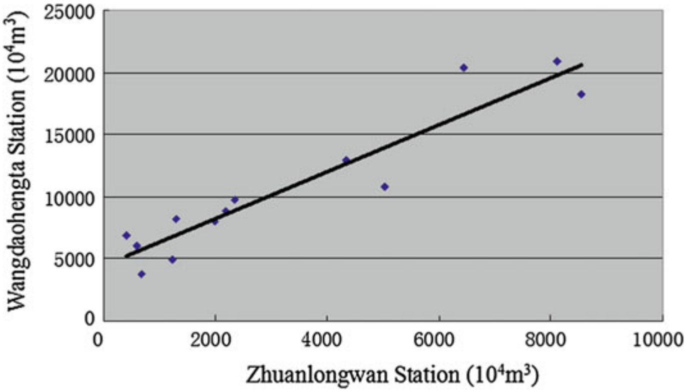

Fig. 2.2 Correlation analysis of simultaneous runoff series during 1992–2004 at Zhuanlongwan station and Wangdaohengta station

Table 2.2 Average annual and monthly runoff for many years at Zhuanlongwan Station, at Wangdaohengta Station, and in the study area (unit 10^4 m^3)

Month	1	2	3	4	5	6	7	8	9	10	11	12	Annual
A	301.2	479.6	2974.9	1,313.1	717.9	640.5	2834.4	4715.2	1763.7	1481.9	1079.3	446.6	18,350
B	107.3	170.8	1092.0	489.4	261.4	229.8	1084.9	1885.5	669.5	556.2	402.3	167.6	7116.7
C	193.8	308.8	1882.9	823.7	456.5	410.8	1749.5	2890.7	1094.2	925.7	677.3	282.0	11695.8

Note A—Wangdaohengta Station, *B*—Zhuanlongwan Station, *C*—runoff interval between the two stations

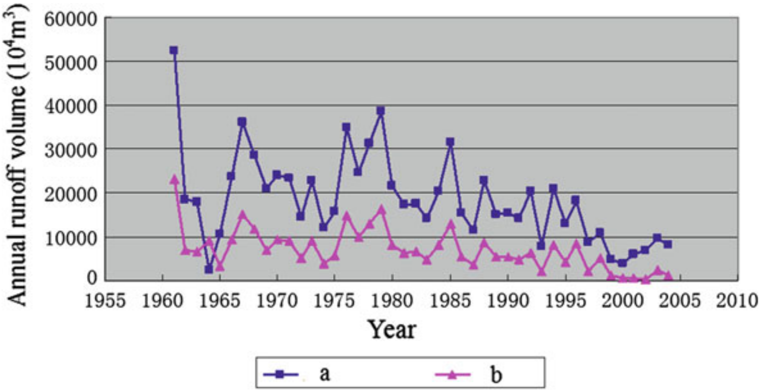

Fig. 2.3 Annual runoff curves of Ulan Mulun River at Wangdaohengta and Zhuanlongwan stations. *Note a*—annual runoff volume at Wangdaohengta station; *b*—annual runoff volume at Zhuanlongwan station

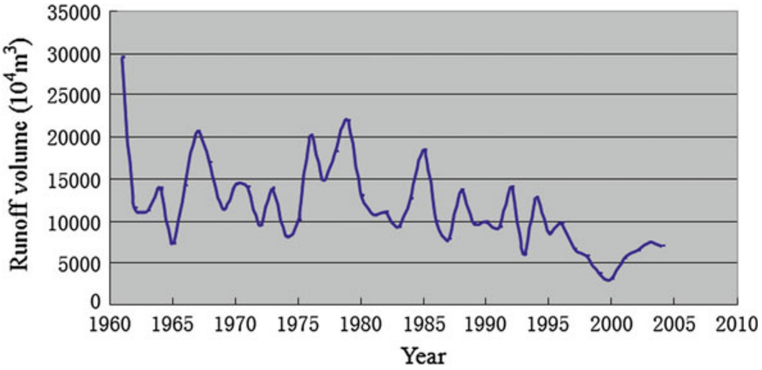

Fig. 2.4 Annual runoff curve of Ulan Mulun River at interval between Wangdaohengta and Zhuanlongwan stations

2.1.4 Total Surface Water Resources

Through statistical analysis of the calculated runoff volume of rivers and water volume of each water body in the study area, we can conclude that the total surface water resources in the study area 1,19,700,000 m^3 (see Table 2.4).

Table 2.3 Statistics of water bodies (reservoirs, ponds, and lakes) in the study area (area unit m^2, volume unit m^3)

Name	Daliuta	Huojitu	Shangwan	Bulianta	Halagou	Shigetai	Ulan Mulun	Total
Area	6820.5	12,421.1	2,716.2	57,336.8	31,500	80,000	400,000	590,794.6
Volume	14,361.8	17,804.2	7,324.5	94,464.5	82,750	280,000	2,200,000	2,696,705

Table 2.4 Statistics of surface water resources in the study area (unit 10^9 m^3)

Name	Runoff volume of Ulan Mulun River	Volume of surface water bodies	Total surface water resources
Water volume	1.17	0.027	1.197

2.2 Assessment of Groundwater Resources

2.2.1 Influence of Different Precipitation on the Recharge of Groundwater Resources

Atmospheric precipitation is the important recharge source of groundwater in the area. Recharge of groundwater from rainfall infiltration is a very complicated process and is controlled by rainfall intensity, evaporation intensity, burial depth of groundwater level, soil texture, and water content of aeration zone [6, 7].

2.2.1.1 Statistical Analysis of Meteorological Data in the Study Area

In order to get the characteristics of meteorological factors in the study area, the area where Shangwan mine is located was taken as the typical area, meteorological data at Shangwan Meteorological Station were collected, the meteorological factors at each meteorological station include rainfall and evaporation, and every factor was accurate to month.

Analysis of variability of meteorological factors

On the basis of existing meteorological data at each meteorological station, the corresponding values were listed from big to small and the occurrence frequency was calculated. The following equation was adopted when calculating the occurrence frequency:

$$P = \frac{m}{n+1} \times 100\,\%$$

The average value corresponding to 95 % frequency year of each meteorological factor at the meteorological station in the study area was calculated.

Analysis of variability of precipitation data

The meteorological data in the study area were averaged, i.e., $\bar{X} = \frac{1}{n}\sum_{i=1}^{n} x_i$, where x expresses the measured value of a meteorological factor; the number of values is n; and $\bar{x}$ expresses the average of measured values of a meteorological factor.

The standard deviation of meteorological factors is noted as σ; the equation $\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}$ is used to calculate this value, and the variability coefficient is noted as c; the calculation is $c = \frac{\sigma}{\bar{x}}$, and according to the conventional processing of water resources, variability coefficient is classified into $c \leq 0.1$—weak variability, $0.1 < c \leq 1$—medium variability, and $C > 1$—strong variability.

On the basis of the above-mentioned method, the calculated variability degree of the year of 95 % rainfall frequency at Shangwan Meteorological Station is listed in Table 2.5.

Variability analysis of evaporation data

Evaporation variation degree of different frequency years corresponding to the statistical analysis of precipitation data at each meteorological station in the study area is shown in Table 2.6.

From the variability analysis of annual precipitation and evaporation of 95 % frequency, it can be seen that the variation degree of precipitation in the area is medium and the evaporation variation is weak. The average of the frequency year was used to conduct calculation, which is relatively safe for the assessment of groundwater resources.

Calculation of precipitation and evaporation

Precipitation and evaporation are factors to be observed at each meteorological station. According to the investigation, the diameter of vessel used for the measurement of both precipitation and evaporation at each meteorological station is 200 mm. Because the device for the measurement of precipitation is different, the measured quantity is different from the actual value, and there exists conversion coefficient between them. WMO and CIMO put forward pit-type rain gauge at fifth congress in 1969. This rain gauge is called commonly as standard rain gauge. The precipitation in the study area must be multiplied by coefficient of 1.134.

As regards the measurement of evaporation, at present, WMO and CIMO put forward that evaporation pond of 20 m^2 is taken as temporary international standard and consider that evaporation pond is the best among the existing evaporators. Previous research indicates that in aeolian sand area of Ordos basin, when converted to the amount of evaporation in waters of large area, the amount of evaporation (evaporation pan AM 200) provided by meteorological station has to be multiplied by the coefficient of 0.43. In the dissertation, this coefficient is adopted to convert the evaporation data.

Results of sorting out and analysis of meteorological factors

On the basis of the above-mentioned analysis, the results of the converted precipitation and evaporation of 95 % frequency year at Shangwan Meteorological Station are given in Table 2.7. This is taken as the basic data for calculation to provide the basis for numerical simulation of rainfall infiltration.

Table 2.5 Variability analysis of annual precipitation of 95 % frequency

Month	1	2	3	4	5	6	7	8	9	10	11	12	Annual total
Average	0.66	4.98	12.76	12.91	26.99	39.67	82.43	113.29	40.13	17.72	3.36	1.51	356.41
Standard deviation	0.73	5.13	12.41	14.04	23.96	19.56	41.65	59.58	20.44	12.02	4.76	2.06	88.92
Variation coefficient	1.12	1.03	0.97	1.09	0.89	0.49	0.51	0.53	0.51	0.68	1.42	1.37	0.25
Variation degree	A	A	B	A	B	B	B	B	B	B	A	A	B

Note A—strong, B—medium

Table 2.6 Analysis of evaporation variability corresponding to precipitation of 95 %

Month	1	2	3	4	5	6	7	8	9	10	11	12	Annual total
Average	43.8	61.8	137.9	277.5	402	380.3	342.1	253.9	203.8	146.6	77.9	46.6	2374.1
Standard deviation	9.7	16.5	37.2	36.9	57.6	44.2	48.8	44.3	24.6	32.2	15.6	8.1	173.7
Variation coefficient	0.2	0.3	0.3	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.1
Variation degree	B	B	B	C	C	C	C	B	C	B	B	B	C

Note B—medium, C—weak

Table 2.7 Analysis results of precipitation and evaporation as well as precipitation-free days of 95 % frequency year

Factor	1	2	3	4	5	6	7	8	9	10	11	12
Precipitation	0.7	5.7	14.5	14.6	30.6	45	93.5	128.5	45.5	20.1	4.3	1.8
Evaporation	18.8	26.6	59.3	119.3	172.8	163.5	147.1	109.2	87.6	63	33.5	20

2.2.1.2 Numerical Model of Water Content Migration in Aeration Zone in the Study Area and Determination of Rainfall Infiltration Coefficient

Mathematical model

Basic equation of water content migration is one-dimensional in the unsaturated zone [8, 9] because water content migration in aeration zone of the calculated area mainly consists of vertical movement. If the origin of coordinates is chosen at the bottom of the calculated section, and axis z is positive upward the selected fundamental equation is [10, 11]: Fig. 2.5

$$\text{Aeration zone: } \frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h,z)\left(\frac{\partial h}{\partial z}+1\right)\right]$$

$$\text{Saturated zone: } \frac{\partial^2 h}{\partial z^2} = 0$$

$$\text{Connection condition: } d(t) = H + h_a - h(0,t)$$

$$\text{Initial condition: } h(z,0) = h_0 \quad 0 \le z \le H$$

$$\text{Surface condition: } \left|-k\frac{\partial h}{\partial x} - k\right| \le E, \quad h_A \le h \le h_S$$

$$\text{Lower boundary condition: } h = h(0,t) \quad t > 0$$

where

H	thickness of the calculated section
$d(t)$	thickness of the aeration zone
H	pressure head (negative pressure in aeration zone)
$K(h)$	unsaturated permeability
h_a	air entry value
E	maximum potential of evaporation and infiltration under local meteorological conditions
h_A, h_S	allowable maximum and minimum pressure heads on soil surface.

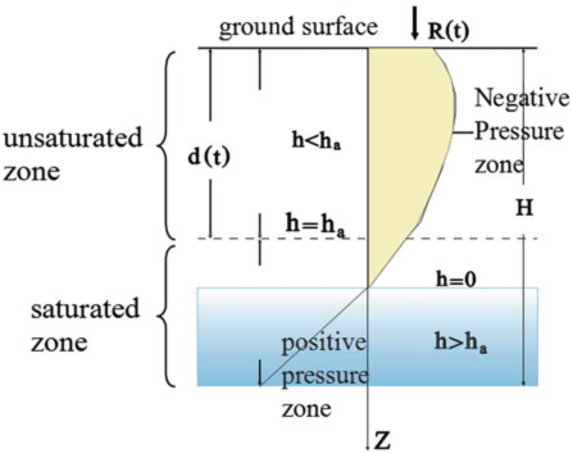

Fig. 2.5 Conceptional model of phreatic water surface infiltration and evaporation

Solution of mathematical model

The software HYPDRUS-1D (Fig. 2.6) developed by American Geotechnical Laboratory was issued to solve the above-mentioned mathematical model. When solving this model, it is unnecessary to consider the positive and negative signs of precipitation and evaporation, and if it is OK to follow the hints on the interface, positive and negative signs are automatically adjusted by program.

Finite difference numerical simulation is used to solve the mathematical model.

$K(h)$ and in the equation are calculated by using the empirical formula proposed by Van Genuchten in 1980, and the empirical formula has good fitting accuracy for both adsorption curve (main) and desorption curve (main).

The empirical formula is as follows:

$$K(h) = \frac{K_s\left[1 - (\alpha|h|^{n-1}[(1+\alpha|h|^n)]^{-m}\right]^2}{[(1+\alpha|h|^n)]^{m/2}}$$

$$\theta = \theta_r + (\theta_s - \theta_r)[(1+\alpha|h|^n)]^{-m}$$

where α, n_a, and m are all fitting parameters, $m = 1 - 1/n$, herein $n > 1$. When fitting the moisture adsorption curve, parameters θ_s, θ_r, α_w, and n_w are used, when fitting the moisture desorption curve, parameters θ_s, θ_r, α_d, and n_d are used. θ_s is the percentage of saturated water content, and θ_r is the percentage of residual water content.

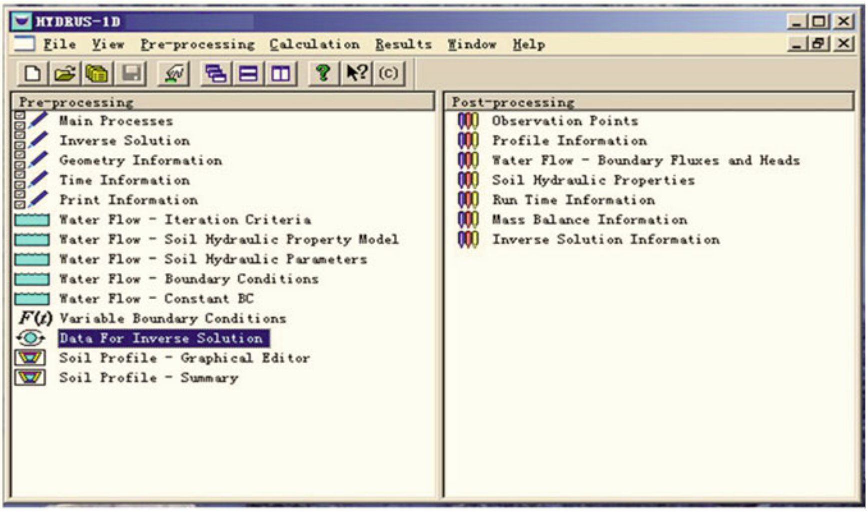

Fig. 2.6 Interface of software HYDRUS-1D

Acquisition of parameters
Because of the variability and the constitutive complexity of parameters of aeration zone, at present, there is not a reasonable mathematic model to describe the complexity and constitutive property and to calibrate its fundamental equation [12, 13]. Then, even in situ undisturbed samples are collected to measure the physical parameters; the representativeness of such physical parameters is questionable. Through the consultation of data and use of predecessors' researches, on the basis of the actual categories of lithology of aeration zone indicated by borehole data in the study area, the triangle coordinate graph of soil texture classification of the Ministry of Agriculture, USA (Fig. 2.7), was selected to determine the parameters. Practice shows that because of the variability and constitutive characteristics of parameters of aeration zone, and the parameters selected in this way are macroscopically more representative. The parameter value of each lithology is shown in Table 2.8 (unit of K_S: m/d).

According to the above-mentioned thinking, on the basis of the lithological characteristics of aeration in different areas where coal mines are located, the study area is roughly divided into four subareas (Fig. 2.8).

On the basis of known Ks data, the corresponding lithological parameters are found out (Table 2.9). Calculation can be done by inputting these parameters into the model.

The upper boundary is an open boundary and is recharged by precipitation, irrigation water, discharge of evaporation, and crop rising (because the data regarding crop are lacking, only the discharge of evaporation is considered). The precipitation and the evaporation are calculated on the basis of the results of the sorted out meteorological data at Shangwan Meteorological Station and time

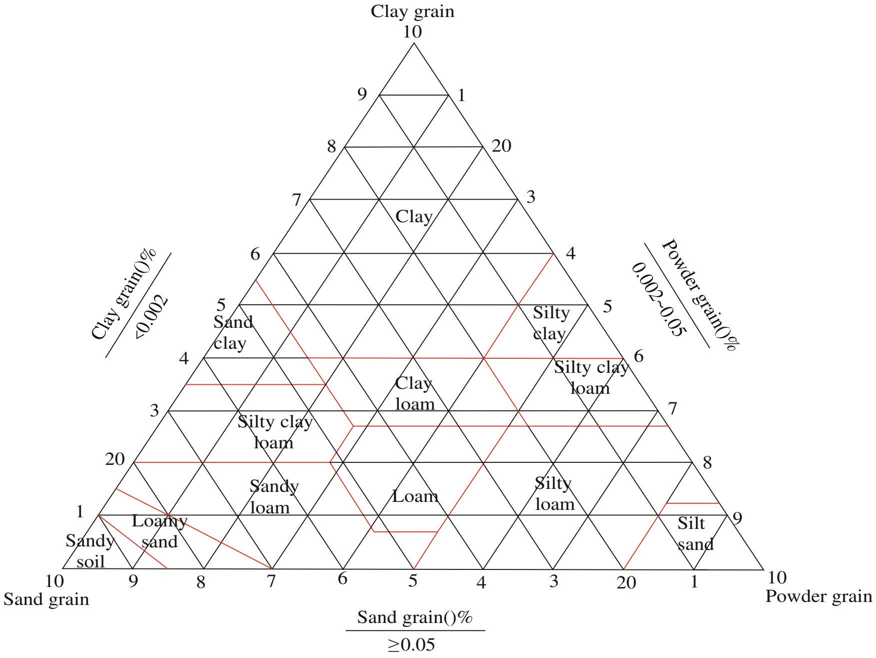

Fig. 2.7 Triangle coordinate graph for soil texture classification of the Ministry of Agriculture, USA

Table 2.8 Parameters of basic lithology in aeration zone, used by the Ministry of Agriculture, USA (suitable to van Genuchten model)

English name	K_S	θ_r	θ_S	α	n	θ_m
Clay	0.0048	0.068	0.38	0.8	1.09	0.38
Silty clay	0.0048	0.070	0.36	0.5	1.09	0.36
Silty clay loam	0.0168	0.089	0.43	1.0	1.23	0.43
Sandy clay	0.0288	0.100	0.38	2.7	1.23	0.38
Silty	0.0600	0.034	0.46	1.6	1.37	0.46
Clay loam	0.0624	0.095	0.41	1.9	1.31	0.41
Silty loam	0.1080	0.067	0.45	2.0	1.41	0.45
Loam	0.2496	0.078	0.43	3.6	1.56	0.43
Sandy clay loam	0.3144	0.100	0.39	5.9	1.48	0.39
Sandy loam	1.0610	0.065	0.41	7.5	1.89	0.41
Loamy sand	3.5020	0.057	0.41	12.4	2.28	0.41
Sandy soil	7.1280	0.045	0.43	14.5	2.68	0.43

Fig. 2.8 Subareas of precipitation and infiltration

Table 2.9 Lithological parameters of different subareas of precipitation

Subarea	K_S	θ_r	θ_S	α	n	θ_m
Subarea 1	1.0610	0.065	0.41	7.5	1.89	0.41
Subarea 2	7.1280	0.045	0.43	14.5	2.68	0.43
Subarea 3	0.1080	0.067	0.45	2.0	1.41	0.45
Subarea 4	0.2496	0.078	0.43	3.6	1.56	0.43

interval. In consideration of fewer rainy days in the study area, in order to make the water content in the upper boundary not less than the residual water content, artificial restraint condition is given to the upper boundary, i.e., the negative pressure is not higher than 5 m.

The lower boundary is taken as the known hydraulic head. In HYDRUS-1D, the pressure head is adopted (it is positive below the artificially set water level). Assuming the burial depth is phreatic water surface, the water content is taken as the saturated water content. The outflow in the lower boundary is due to the recharge of the phreatic water surface, while the inflow is due to the evaporation of the phreatic water surface.

Water content distribution values under the initial status of the section are input, and at that time, the program can automatically convert the water content values to the negative values according to the characteristic curves of water content.

The calculation results are input to the water content of the section. Because the measured water content data of the section are lacking, when calculating the regional section, firstly an artificial approximate section is given, under condition where the input of the upper boundary is zero, running is made for 29 years, and the water content section at the end is taken as the initial water content of the section for the calculation of the water content of regional section.

Time subdivision is adopted, and the initial time step is 0.1 d. The time step is automatically adjusted by program according to the convergence of calculation. If a specific time step reaches the iteration number 03 required by the convergence, then the time increment of the next time step may be multiplied by a constant bigger than 1 (generally 1.1–1.5). If the iteration number is 47, then the time increment of the next time step is multiplied by a constant smaller than 1 (generally 0.3–0.9). At a specific time step, when the number of iterations converged at any time level exceeds the given maximum value (generally 10–50), the iteration at this time level is terminated, the length of the time step is changed into t/3, and the iteration process restarts. The minimum time step is 0.001 d, and the maximum time step is 1 d. The fixed space step length is 10 cm.

Because the migration mechanism of soil water is different during freezing period and unfreezing period, in the area, the freezing depth of the surface soil is up to 1.1 m during January, February, September, and December, and in analog calculation, the evaporation and precipitation are not considered for these four months. Only the rainfall infiltration intensity of the unfreezing period is calculated (1 March to 31 October).

1. **Calculation results**

After calculation, the infiltration coefficient of accumulated rainfall of 95 % frequency years in four subareas is shown in Table 2.10.

2.2.2 *Assessment of Regional Groundwater Resources*

2.2.2.1 Scope of Balance Area

The study area is located in the junction of Yijinhuoluo County at the south of Ordos and Shenmu County of Shaanxi Province, and its geographical coordinate is east longitude from 110°4′ to 110°11′ and north latitude from 39°20′ to 39°30′. The north, the east, and the south are all watershed boundaries. The west of the study area is the artificially depicted water head boundary, as shown in Fig. 2.9.

Table 2.10 Rainfall infiltration coefficient in four subareas

Subarea no.	1	2	3	4
Area (km^2)	232.2	362.9	205.7	51.0
Rainfall infiltration coefficient	0.23	0.30	0.15	0.2

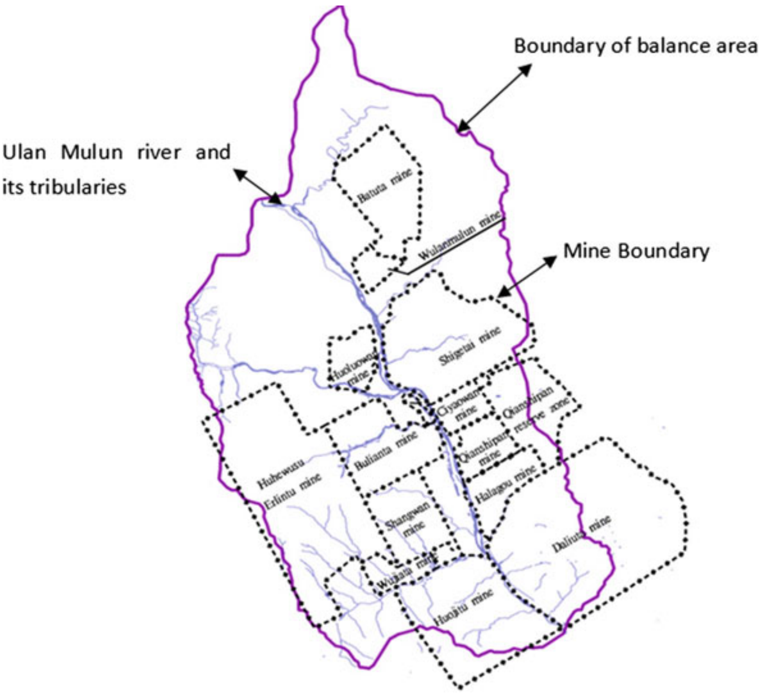

Fig. 2.9 Sketch of the scope of the balance area

2.2.2.2 Selection of Balance Period

For the study of regional water balance, generally it is necessary to select a complete hydrological year as the balance period, and median water year is the best for the hydrological year [14]. Through the analysis of the guarantee rate of the precipitation during 1975–2006 in the study area, the year 2004 with precipitation guarantee rate of 50 % was selected to conduct the study of water balance. The analysis on the concrete precipitation guarantee rate is as follows:

On the basis of the precipitation data of many years (calculation of precipitation will be stated in detail in the following section), the precipitation series, from small to large, R_1, R_2, …, R_i, …, R_n, can be obtained. The guarantee rate (accumulated frequency) of the precipitation R_i is as follows:

$$p_i = \frac{i}{n+1}$$

where

p_i occurrence frequency larger or equal to the precipitation R_i
i serial number of precipitation
n number of years for statistics.

Table 2.11 Average precipitation guarantee rate of the study area

No.	Year	Precipitation	Guarantee rate	No.	Year	Precipitation	Guarantee rate
1	1997	120.72	3.03	17	2004	357.65	51.52
2	1999	126.80	6.06	18	2002	359.03	54.55
3	1993	139.21	9.09	19	1977	377.29	57.58
4	2000	178.33	12.12	20	2001	388.16	60.61
5	1989	201.88	15.15	21	1985	392.87	63.64
6	1987	213.39	18.18	22	1976	402.90	66.67
7	1986	214.86	21.21	23	1992	407.16	69.7
8	1981	242.28	24.24	24	1988	417.53	72.73
9	1980	247.28	27.27	25	1984	426.93	75.76
10	2006	281.40	30.30	26	1995	429.12	78.79
11	1983	284.00	33.33	27	1998	436.54	81.82
12	1990	308.51	36.36	28	1979	452.50	84.85
13	1991	326.63	39.39	29	1978	490.75	87.88
14	2005	327.12	42.42	30	1994	541.55	90.91
15	1982	334.22	45.45	31	2003	542.98	93.94
16	1975	351.47	48.48	32	1996	674.09	96.97

Guarantee rate of precipitation of different years, calculated on the basis of the above-mentioned formula, is shown in Table 2.11.

Because the average rainfall of the median water year can approximately represent the regional rainfall of many years, and rainfall is the most important source of recharge in the study area, the year with the precipitation guarantee rate of 50 % was selected as the balance period for the study of water balance. From Table 2.11, it can be seen that there are 32 annual rainfall data in total for the analysis of precipitation guarantee rate. The precipitation guarantee rate of 2004 was 51.52 %, approaching almost 50 %, which is the rate for typical median water year. The 2004 rate could approximately represent the average rainfall of many years.

2.2.2.3 Calculation of Balance Terms

The balance terms of the study area include the term of recharge and the term of discharge. The term of recharge consists of mainly rainfall infiltration and the recharge of lateral runoff. The term of discharge consists mainly of spring flow, mine water inflow, and base flow drained to Ulan Mulun River.

Term of recharge

The term of groundwater recharge consists mainly of rainfall infiltration and the recharge of lateral runoff.

(a) Rainfall infiltration recharge

Rainfall infiltration is the most important recharge source in the study area. Rainfall infiltration is mainly influenced by rainfall, surface lithology, burial depth of water level, and other geological conditions. The solution procedure of annual rainfall infiltration is as follows [15, 16]:

Step one: interpolation and extension of data of rainfall station

The study has collected totally the rainfall data observed at four rainfall stations located in the study area, including Shangwan Station, Shigetai Station, Daliuta Station, and Wangdaohengta Station. The observation series at Shangwan Station was from January 1975 to December 1992 and from January 1967 to December 1988 at Shigetai Station, and because Daliuta Station was set up late, there was only observation series from June 1977 to October 1988, while the observation series at Wangdaohengta Station was long from 1975 to now. Because four rainfall stations are close to each other, landform and cause of precipitation are similar, and Wangdaohengta Station was used as reference station to interpolate and extend the rainfall series at other stations by using regression analysis.

Regression analysis is a method to conduct prediction from the correlation of things. On the basis of possessing great amount of observation data, mathematical statistics method is used to establish the function expression (called as regression equation) of the regression correlation between the dependent variable and independent variable. In regression analysis, to seek the correlation of variable versus another variable is monadic regression analysis [17].

To set up the correlation between the observation series at Wangdaohengta Station and that of Shigetai Station, a unitary linear trend line was drawn (as shown in Fig. 2.10). The established unitary parameters and linear regression equation are shown in Table 2.12. The observation series at Shigetai Station was extended to 2006 by using unitary linear regression method (see Table 2.13).

To set up the correlation between the observation series at Wangdaohengta Station and that at Daliuta Station, unitary linear trend line was drawn (as shown in

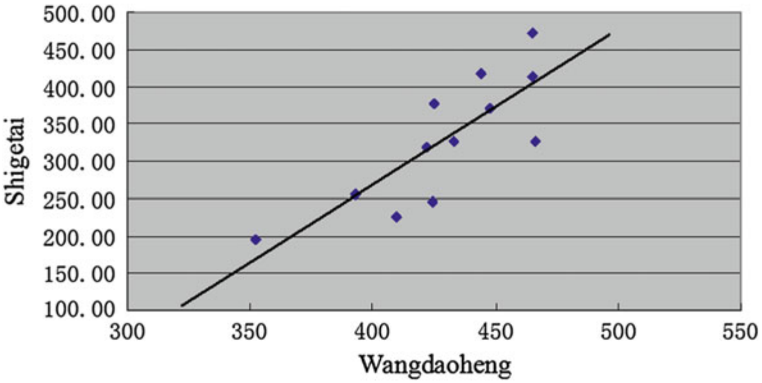

Fig. 2.10 Correlation of precipitation between Wangdaohengta and Shigetai stations

Table 2.12 Unitary-related parameters and equation

Equation $Y = 2.0826X - 564.61$	Correlation coefficient $R = 0.81$

Note 1 X—data at Wangdaohengta, Y—calculated data at Shigetai

Table 2.13 Extended results of precipitation at Shigetai Station (unit mm)

Year	Wangdaohengta	Shigetai	Year	Wangdaohengta	Shigetai
1975	433.2	326.3	1991	422.2	314.7
1976	447.7	371.7	1992	462.8	399.2
1977	425.2	377.4	1993	323.0	108.1
1978	465	471.5	1994	523.4	525.4
1979	433.4	483.8	1995	467.4	408.8
1980	409.5	224.8	1996	589.4	662.8
1981	393.2	256.3	1997	213.4	119.9
1982	422.2	318.7	1998	471.1	416.6
1983	424.1	245.8	1999	219.7	122.7
1984	444.1	417.5	2000	342.5	148.7
1985	466.2	327.2	2001	447.0	366.3
1986	352.2	194.8	2002	432.5	336.1
1987	497.6	242.2	2003	524.1	526.9
1988	464.8	412.5	2004	431.8	334.7
1989	344.3	152.4	2005	366.8	299.3
1990	390.1	247.8	2006	344.0	251.9

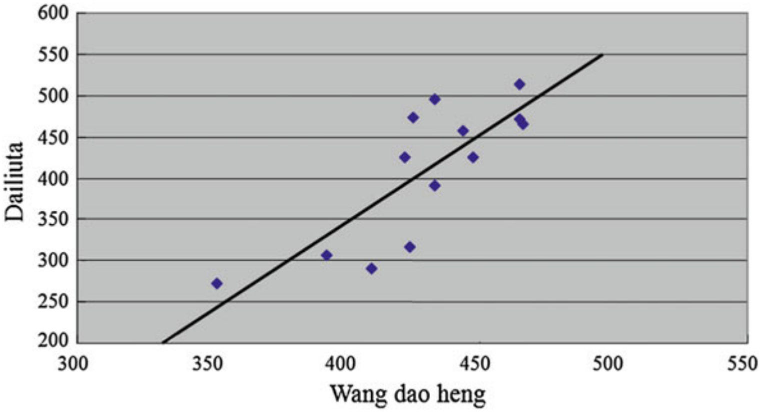

Fig. 2.11 Correlation of precipitation between Wangdaohengta and Daliuta stations

Fig. 2.11). The established unitary-related parameters and unitary linear regression equation are shown in Table 2.14. The observation series of Daliuta Station was extended to 2006 by using unitary regression method (Table 2.15).

Table 2.14 Unitary-related parameters and equation

Equation $Y = 2.125X - 504.2$	Correlation coefficient $R = 0.81$

Note 1 X—data at Wangdaohengta, Y—calculated data at Daliuta

Table 2.15 Extended results of precipitation at Daliuta Station (unit mm)

Year	Wangdaohengta	Daliuta	Year	Wangdaohengta	Daliuta
1975	433.2	391	1991	422.2	393
1976	447.7	424.5	1992	462.8	479.3
1977	425.2	474.2	1993	323.0	182.2
1978	465	470.4	1994	523.4	608
1979	433.4	495.0	1995	467.4	489
1980	409.5	291.4	1996	589.4	748.3
1981	393.2	306.6	1997	213.4	150.7
1982	422.2	426.1	1998	471.1	496.9
1983	424.1	317.3	1999	219.7	157.3
1984	444.1	457.0	2000	342.5	223.6
1985	466.2	465.2	2001	447.0	445.7
1986	352.2	271.7	2002	432.5	414.9
1987	497.6	331.2	2003	524.1	609.5
1988	464.8	513.9	2004	431.8	413.4
1989	344.3	227.4	2005	366.8	275.3
1990	390.1	324.8	2006	344.0	226.8

To set up the correlation between the observation series at Wangdaohengta Station and that at Shangwan Station, unitary linear trend line was drawn, as shown in Fig. 2.12. The established unitary-related parameters and unitary linear regression equation are shown in Table 2.16. The observation series of Shangwan Station was extended to 2006 by using unitary regression method (as shown in Table 2.17)

Step two: calculation of average rainfall in the study area

Rainfall is the most important source for the recharge of groundwater in the study area. Therefore, the amplitude of rainfall controls the balance and dynamics of the water system in the study area, determining the amount of groundwater resources [18].

The precipitation measured at rainfall stations is used to calculate the regional average rainfall. Thiessen's polygon method was used to discretize the region, so as to make the spatial distribution of rainfall of each unit approximately uniform, and to determine the rainfall of each calculated unit on the basis of the water amount measured at existing rainfall stations. The formula for calculating the regional average rainfall by using Thiessen's polygon method is as follows:

$$\overline{P} = \frac{1}{A}\sum_{i=1}^{n} p_i a_i$$

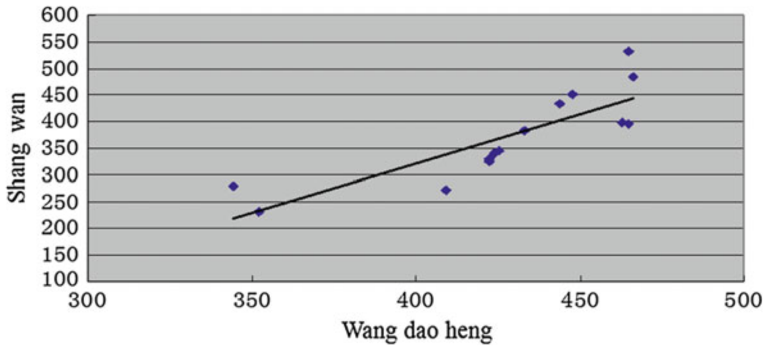

Fig. 2.12 Correlation of precipitation between Wangdaohengta and Shangwan

Table 2.16 Unitary-related parameters and equation

Equation $Y = 1.8443X - 416.94$	Correlation coefficient $R = 0.84$

Note 1 X—data at Wangdaohengta, Y—calculated data at Shangwan

Table 2.17 Extended results of precipitation at Shangwan (unit mm)

Year	Wangdaohengta	Shangwam	Year	Wangdaohengta	Shangwan
1975	433.2	382.4	1991	422.2	325.3
1976	447.7	450.6	1992	462.8	397.2
1977	425.2	345	1993	323.0	178.8
1978	465	531.6	1994	523.4	548.4
1979	433.4	383.4	1995	467.4	445.1
1980	409.5	271.4	1996	589.4	670.1
1981	393.2	194.7	1997	213.4	111.7
1982	422.2	330.9	1998	471.1	451.9
1983	424.1	339.6	1999	219.7	123.4
1984	444.1	433.6	2000	342.5	214.7
1985	466.2	484.6	2001	447.0	407.5
1986	352.2	230.7	2002	432.5	380.7
1987	497.6	230.2	2003	524.1	549.7
1988	464.8	394.5	2004	431.8	379.4
1989	344.3	279.9	2005	366.8	259.5
1990	390.1	409.8	2006	344.0	217.5

where

$\overline{P}$ regional average rainfall (mm)

A regional area

a_i area of number i Thiessen's polygon, i.e., area of number i calculated unit, $i = 1, 2, \ldots, n$

Table 2.18 Annual average precipitation in the study area (unit mm)

Year	Average precipitation	Year	Average precipitation
1975	351.47	1991	326.63
1976	402.90	1992	407.16
1977	377.29	1993	139.21
1978	490.75	1994	541.55
1979	452.49	1995	429.12
1980	247.28	1996	674.09
1981	242.28	1997	120.72
1982	334.22	1998	436.54
1983	284.01	1999	126.80
1984	426.93	2000	178.33
1985	392.87	2001	388.16
1986	214.86	2002	359.03
1987	213.39	2003	542.98
1988	417.53	2004	357.65
1989	201.88	2005	327.12
1990	308.51	2006	281.40

p_i water amount of number i Thiessen's polygon, i.e., water amount of number i calculated unit, $i = 1, 2, \ldots, n$
n number of Thiessen's polygons in the area.

The average precipitation calculated by the above-mentioned formula is shown in Table 2.18.

Step three: Calculation of annual recharge from rainfall infiltration

According to zoning of rainfall infiltration coefficient in the study area (Fig. 2.8) and calculated rainfall infiltration coefficient in each subarea (Table 2.10), the annual recharge from rainfall infiltration in the study area was determined. The calculation formula is as follows:

$$Q_{\text{atmospheric}} = \alpha \cdot P \cdot F$$

where
Q recharge from rainfall infiltration ($10^8 \text{m}^3/\text{a}$)
α rainfall infiltration coefficient
P precipitation (m)
F calculated area (km^2).

The calculation based on the above formula arrived at the annual recharge from rainfall infiltration in each subarea, and then, the recharge of four subareas from rainfall infiltration was summed to arrive at the annual recharge from rainfall infiltration of the whole area, as shown in Table 2.19.

Table 2.19 Calculation results of the recharge from rainfall infiltration in the study area

Subarea no.	1	2	3	4	Whole area
Recharge from rainfall infiltration ($10^4 m^3$)	1826.16	4311.13	1095.48	364.80	7597.57

(b) Lateral recharge

At boundary where there is lateral runoff, the calculation section was cut perpendicular to the direction of groundwater flow, and Darcy formula was used:

$$Q_{\text{lateral}} = K \cdot I \cdot H \cdot L$$

where

K average permeability coefficient of aquifer at the calculated section;
I hydraulic slope of groundwater at the calculated section, which is taken from the groundwater level contour map;
H the average thickness of aquifer at the calculated section;
L length of the calculated section.

According to the above formula, with reference to related geological data and maps, the calculated total lateral recharge in the balance area is 4,821,900 m^3.

Term of discharge

The term of groundwater discharge consists mainly of the flow of springs, mine inflow, and base flow drained to Ulan Mulun River.

(a) Discharge of springs

In feeder drains in the study area, groundwater converts mainly to surface water in the form of spring. The annual flow of springs in the tributaries of Ulan Mulun River is shown in Table 2.20.

From the table, it can be seen that the total flow of springs in the tributaries of Ulan Mulun River in 2004 was 33,272,200 m^3.

(b) Mine inflow

There are six mines and seven shafts in the study area, which are, respectively, Daliuta mine, Huojitu shaft, Shangwan mine, Bulian mine, Halagou mine, Shigetai mine, and Ulan Mulun mine. The monthly inflow during balance period in these mines is shown in Table 2.21.

In addition, according to the report of water inflow in Shigetai, the total inflow in the mine was 1,257,000 m^3 in 2004. Therefore, we can know that the total inflow in 2004 in the balance area was approximately 12,434,000 m^3.

Table 2.20 Annual average flow and runoff of the main tributaries of Ulan Mulun River

Water system	No.	Tributary	Annual average flow (m^3/s)	Annual average runoff (10^4 m^3)
Ulan Mulun water basin	1	Gongniergaigou	0.264	834.12
	2	Kaokaolaigou	0.185	584
	3	Shigetaigou	0.05	157.7
	4	Halagou	0.070	219
	5	Buliangou	0.017	53.6
	6	Liugengou	0.087	274.7
	7	Shanggou	0.013	41.0
	8	Tangjianggou	0.023	72.5
	9	Budaihaogou	0.032	100.9
	10	Huojitugou	0.18	567.6
Other tributaries and dispersed springs			0.134	422.1
Total			1.055	3327.22

Table 2.21 Statistics of monthly inflow of coal mines (except Shigetai mine) in 2004 (unit m^3/h)

Time	Mine					
	Daliuta	Huojitu	Bulianta	Shangwan	Ulan Mulun	Halagou
2004.01	598.5	138	188.42	65	103.26	18.87
2004.02	686	146	188.79	80	100.49	20.62
2004.03	306.7	208	186.7	82	98.73	23.49
2004.04	433	219	193.2	76	252.06	23.75
2004.05	517	557	191.55	93	190.51	20.02
2004.06	392	239	196.5	89	260.74	48.7
2004.07	604.4	279	198.1	95	273.22	23.68
2004.08	322.9	294	237.6	96.5	268.42	22.78
2004.09	332.6	304	242.1	93.7	221.3	23.02
2004.10	422	262	314.1	93.2	260.71	22.23
2004.11	657.3	245	337.5	72	245.19	22.46
2004.12	336	258	467	81	239.86	24.65
Total	The total inflow in six mines is 11,177,000 m^3 in 2004					

(c) Base flow of Ulan Mulun River

From the above section, it is known that the runoff at the interval of Ulan Mulun River from Zhuanlongwan to Wangdaohengta was 69,860,400 m^3 in 2004. The runoff consists mainly of tributary flow drained to the river and base flow of the river. Therefore, the total runoff minus the tributary flow was the base flow of the river in 2004. According to the field investigation, the total flow of the tributaries of Ulan Mulun River was approximately 33,272,200 m^3. So, the base flow of Ulan Mulun River was 36,588,200 m^3.

2.2.2.4 Balance Analysis and Assessment of Groundwater Resources

According to the above content, the recharge term in the study area consists mainly of rainfall infiltration and recharge from lateral runoff. The discharge term consists mainly of spring flow, mine inflow, and base flow drained to Ulan Mulun River.

$$\text{Groundwater balance equation: } Q_{\text{recharge}} - Q_{\text{discharge}} \Delta\varepsilon$$

$$\text{In the balance area: } Q_{\text{recharge}} = Q_{\text{rainfall}} + Q_{\text{lateral runoff}}$$
$$\mathrm{Q}_{\text{discharge}} = Q_{\text{spring}} + Q_{\text{inflow}} + Q_{\text{baseflow}}$$

where

Q_{recharge}	total recharge of groundwater during the balance period in the balance area
$Q_{\text{discharge}}$	total discharge of groundwater during the balance period in the balance area
$\Delta\varepsilon$	variation of water storage volume during the balance period
Q_{rainfall}	recharge from rainfall infiltration
$Q_{\text{lateral runoff}}$	recharge from lateral runoff in the balance area
Q_{spring}	spring discharge in the tributaries of Ulan Mulun River
Q_{inflow}	total mine inflow in the balance area
$Q_{\text{base flow}}$	base flow drained to Ulan Mulun River.

From the above formulas, it can be obtained that during the balance period in the whole balance area, the rainfall infiltration was 75,975,700 m^3, the recharge from the lateral runoff was 4,821,900 m^3, the discharge of springs was 33,272,200 m^3, the mine inflow was 12,434,000 m^3, the base flow of Ulan Mulun River was 36,588,200 m^3, the total recharge was 80,797,600 m^3, and the total discharge was 82,294,400. The variation of water storage volume during the balance period is $\Delta\varepsilon = -1{,}496{,}800\ m^3$ in Table 2.22.

Thus, it may be concluded that there was a negative base in 2004 in the balance area, and groundwater storage was reduced by approximately 1,496,800 m^3.

Table 2.22 Calculation results of groundwater balance in the study area

Balance factor	Recharge		Balance factor	Discharge	
	(10^4 m^3)	(%)		(10^4 m^3)	(%)
Rainfall infiltration	7597.57	94.03	Discharge of springs	3327.22	40.43
Lateral runoff	482.19	5.97	Mine inflow	1243.4	15.1
			Base flow of Ulan Mulun River	3658.82	44.5
Total recharge	8079.76	100	Total discharge	8229.44	100

Table 2.23 Total water resources in the study area (unit 10^9 m^3)

Name	Surface water resources	Groundwater resources	Repeated volume	Total water resources
Water yield	1.197	0.80798	0.6986	1.3064

2.3 Total Water Resources

Atmospheric precipitation, surface water, and groundwater are three kinds of water bodies closely correlated with natural water circulation [19]. In case of the study area, surface water is mainly river runoff, which is recharged by atmospheric precipitation and groundwater discharge including springs and base flow of Ulan Mulun River, whereas the discharge is mainly in form of water surface evaporation and soil infiltration. Groundwater is gravitational water stored in aquifer, recharged by infiltration of atmospheric precipitation and lateral runoff, discharged in the form of springs, base flow drained to Ulan Mulun River, and mine drainage. The total water resources are the addition of surface water resources and groundwater resources; then, the repeated volume of mutual conversion is deducted. Therefore, the key for the calculation of total water resources is how to determine the repeated volume between surface water and groundwater [20]. For the analysis and determination of the repeated volume between surface water and groundwater, the characteristics of water resources in the study area must be defined clearly, i.e., the surface water resources are the sum of local river runoff and resources of the surface water bodies, groundwater resources are the sum of the recharge from infiltration of atmospheric precipitation and lateral runoff, and the repeated calculated volume between surface water and groundwater is the water volume recharging groundwater then discharging in form of spring and river base flow finally feeding into Ulan Mulun River, that is the sum of spring discharge and base flow drained to Ulan Mulun River.

On the basis of the previous calculation results of surface water resources and groundwater resources and the analysis of the repeated volume between surface water and groundwater, we can calculate the total water resources in the study area, which is 130,640,000 m^3 (see Table 2.23).

2.4 Current Status of Water Resources Development and Utilization

2.4.1 *Current Status of Water Supply Engineering*

Water supply engineering already developed and utilized is divided into two systems, i.e., tap water and water supply engineering of reused water, and the reused water engineering includes reused water engineering for afforestation and reused water engineering for industry.

2.4.1.1 Tap Water Supply Engineering

The tap water supply engineering includes Kaokaolai Water Treatment Plant, Halagou Water Treatment Plant, hole for forced surface drainage in Ulan Mulun mine, Daliuta underground water treatment engineering, Huojitu large-diameter well, water supply engineering using water source in Xiaoliuta, Shigetai Water Treatment Plant. At present, there are five concentrated networking water sources for water supply, i.e., Kaokaolaigou, Gongnieergaigou, Halagou, and clear water from hole for surface forced drainage in Ulan Mulun mine and underground clear water in Daliuta mine.

Tap water supply engineering is shown in Table 2.24. From the table, it can be known that until the end of 2005, the existing maximum water supply capacity of water supply engineering in the dry area was 37,500 m^3/day, and water supply capacity during dry season was 30,800 m^3/day.

2.4.1.2 Reused Water Engineering

It includes reused water engineering for afforestation and reused water engineering for industry. Among the reused water engineering for afforestation, there are Daliuta sewage treatment works, Heitangou sewage treatment works, Daliuta underground water treatment works, and Huojitu underground water treatment works. Reused water engineering is underground reused water engineering in each coal mine.

Reused water supply engineering is shown in Table 2.25.

From Table 2.25, it can be seen that till the end of 2005, the reusable water yield of the reused water engineering in the study area was 56,331 m^3/day; already reused water yield was 25,193 m^3/day; the surplus water yield was 31,138 m^3/day; of which the reused yield of reused water engineering for afforestation was 10,900 m^3/day; the water yield already reused was 6700 m^3/day; the surplus was 4200 m^3/day; the reused water yield of reused water engineering for industry was 44,778 m^3/day; the water yield already reused was 14,388 m^3/day; the surplus was 30,390 m^3/day.

2.4.2 *Current Status of Water Supply*

Since recent years, with the extension and the increase of tap water and reused water engineering, water supply has also been increased. According to the investigation and the analysis of the collected data (see Table 2.26), the total water supply in the study area increased from 47,293 m^3/day in 2003 to 62,693 m^3/day in 2005 with an increase of 15,400 m^3/day. Tap water supply increased from 27,300 m^3/day in 2003 to 37,500 m^3/day in 2005 with an increase of 10,200 m^3/day. Reused water supply capacity increased from 19,993 m^3/day in 2003 to 25,193 m^3/day in 2005 with an increase of 5200 m^3/day.

Table 2.24 Current status of tap water supply engineering in the study area until the end of 2005 (unit m^3/day)

Water source		Water yield		
		Supply capacity		Note
		Maximum	Dry period	
Concentrated networking water supply source	Kaokaolaigou	18,000	15,000	Major water source accounts for 64 % of production and domestic clear water supply in Shendong mining area
	Halagou	5500	2000	Accounts for 21 % of clear water supply in Shendong mining area
	Gongnieergaigou	3000	3000	Water is stored in reservoir from April 2006, and water supply capacity is 8900 m^3/day
	Underground clear water in Daliuta	2000	2000	After treatment on the surface, clear water from gob is supplied to tap water pipe net
	Clear water from surface forced drainage hole in Ulan Mulun mine	4000	4000	Added to the water supply pipe of Kaokaolai water treatment plant
Independent water supply source	Huojitu large-diameter well	1000	1000	Supply production and domestic water in Huojitu mine and Lijiaban community
	Shigetaigou	1000	1000	There is Shigetai water treatment plant, supplying production and domestic water in Shigetai mine
	Xiaoliuta water source	2000	2000	Major drinking water source in Ulan Mulun mine
	Bulianta water well	1000	800	Supplement water source of Bulianta mine
Total		37,500	30,800	

2.4.3 Current Status of Water Consumption

With the major mines put into production successively, enlargement of production scale and rapid development of corresponding supporting facilities in the mining area, water consumption in the mining area shows growth trend year by year. According to the investigation and the analysis of the collected data (see Table 2.27 and Fig. 2.13), it can be seen that in the study area, the total water consumption

Table 2.25 Current status of water supply of reused water engineering in the study area in 2005 (unit m^3/day)

Reused water engineering		Available reused water amount	Water amount already reused	Surplus water amount
Industry	Daliuta mine water	10,153	6920 (including 2000 for afforestation)	3233
	Huojitu mine water	5641	2700 (including 400 for afforestation)	2941
	Bulianta mine water	16,487	3100	13,387
	Ulan Mulun mine water	7296	1400	5896
	Shangwan mine water	2236	1068	1168
	Halagou mine water	2197	400	1792
	Shigetai mine water	3,168	1200	1968
Industry	Subtotal	44,778 (repeated volume deducted, i.e., 2400 for afforestation from mine water treatment plant)	14,388 (take out 2400 used in afforestation)	30,390
Afforestation	Heitangou sewage	2000	2000	0
	Daliuta sewage	6500	2300	4200
	Daliuta mine water treatment plant	2000	2000	0
	Huojitu mine water treatment plant	400	400	0
	Subtotal	10,900	6700	4200
Total		56,331	25,193	31,138

increased from 32,248 m^3/day in 2000 to 49,477 m^3/day in 2005, with an increase of 17,229 m^3/day. Tap water consumption increased from 20,822 m^3/day in 2000 to 28,377 m^3/day in 2005, with an increase of 7555 m^3/day. Reused water

Table 2.26 Statistics of water supply during 2003–2005 (unit m^3/day)

Water supply engineering	2003	2004	2005
Tap water	27,300	32,000	37,500
Available water supply during dry period	20,800	27,000	30,800
Reused water	19,993	21,500	25,193
Total	47,293	54,500	62,693

Table 2.27 Statistics of water consumption during 2000–2005 (unit m^3/day)

Engineering	2000	2001	2002	2003	2004	2005
Tap water	20,822	21,260	20,966	22,761	23,622	28,377
Reused water	11,426	12,543	15,100	17,900	19,300	21,100
Total	32,248	33,803	36,066	40,661	42,922	49,477

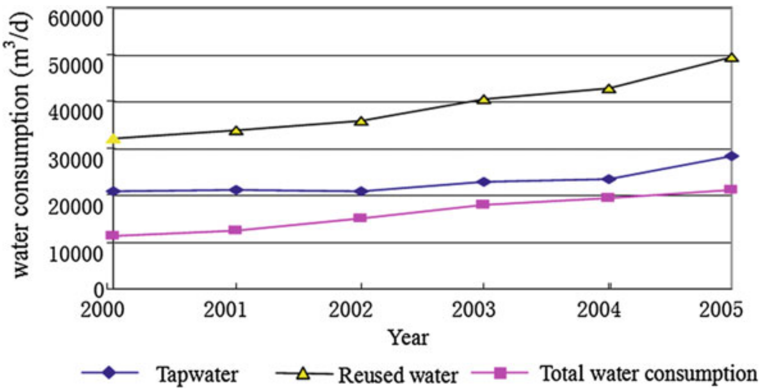

Fig. 2.13 Variation of water consumption during 2000–2005 in the study area

consumption increased from 11,426 m^3/day in 2000 to 21,100 m^3/day in 2005, with an increase of 9674 m^3/day.

2.4.4 Analysis of the Current Status of Supply—Demand Balance of Water Resources

Calculation and analysis of regional water supply and demand balance refer to the process of conducting calculation and analysis of the surplus and the shortage with regard to supply and demand of water resources in regional scope. It is based on the regional current status and the development trend of water supply and demand and provides support for decision-making in the rational development and utilization of

Table 2.28 Analysis of the current status of water supply and demand balance (unit m^3/day)

Water amount		2003	2004	2005
Tap water	Water supply	27,300	32,000	37,500
	Water demand	22,761	23,622	28,377
	Surplus and shortage	+4,539	+8,378	+9,123
Tap water during dry period	Water supply	20,800	27,000	30,800
	Water demand	22,761	23,622	28,377
	Surplus and shortage	−1,961	+3,378	+2,423
Reused water	Water supply	19,993	21,500	25,193
	Water demand	17,900	19,300	21,100
	Surplus and shortage	+2,093	+2,200	+4,093
Total water resources	Water supply	47,293	55,500	62,693
	Water demand	40,661	42,922	49,477
	Surplus/shortage	+6,632	+12,578	+13,216

the regional water resources and regional, economic, social, ecological, sustainable, and coordinated development [21].

According to the statistics of current water supply and demand, the current status of water supply and demand balance was analyzed as shown in Table 2.28.

From Table 2.28, it can be seen that from 2003 to 2005, the total water supply could meet the total water demand and there was surplus in the study area. In 2005, the water surplus was 13,216 m^3/day. During the dry period in 2003, there was water shortage, and the shortage was 1961 m^3/day, in 2004 and 2005; the water surplus was not large relatively. From the table, it can be seen also that the reused water supply was larger than the demand. In 2005, the reused water surplus was 4093 m^3/day. From this, it can be known that the use of mine water is the effective approach to solve the problem of water in coal chemistry and other industries in the study area. At present, the situation of water supply with quality using three systems, i.e., tap water supply system, reused water supply system for industries, and reused water supply system for afforestation, has been formed preliminarily.

At present, the general current status of supply and demand of water resources in Shendong mining area is as follows: the source of tap water is mainly the surface water in Kaokaolaigou, Gongnieergaigou, Halagou, Shigetaigou, clear water from surface forced drainage hole in Ulan Mulun mine, clean water from Daliuta mine; the actual water supply amount is less than 50 % of the designed water supply capacity; and there is a large potential of water supply. The two existing sewage treatment plants are mainly used to treat reused water for afforestation, and the reused rate of sewage in these two plants is 9 % and 37.8 %, respectively, which is relatively low. For reused water in six production mines in the study area, the reused rate of water is 15.5 % in Daliuta mine and 46.1 % in Huojitu mine. In other mines, mine water is not reused except reused in underground production, and therefore, there is big potential of development and utilization.

2.5 Prediction of Future Water Demand

Prediction of water demand is to calculate the water demand in a future time interval according to the variation pattern of historic data of water demand by using scientific, systematic and empirical methods and to predict qualitatively and quantitatively the trend of water demand. Analysis of water supply and demand balance refers to the process of conducting calculation and analysis of the surplus and the shortage with regard to supply and demand of water resources in regional scope [22]. The aim of conducting prediction of water demand and analysis of supply and demand balance of water resources is to provide decision-making basis and support for planning, management, and macrocontrol of regional water resources. In the study, GM (1, 1) model was used to predict the water demand in the study area, and on the basis of this, the water supply and demand balance of the planned period was studied and analyzed.

In the planning, the year 2005 was taken as reference year and the planned period was divided into short term and long term. The short term is from 2006 to 2015 and the long term from 2016 to 2020.

2.5.1 Water Demand Prediction Based on GM (1, 1) Model

Water demand prediction is to estimate and infer the future water demand by considering the change of actual conditions and environments and using proper method. Water demand prediction is influenced by multiple factors, and it is very difficult to describe accurately and quantitatively the influence of different factors on water demand. There is known information and also unknown and undefined information. It is a gray system. So, it is very suitable to predict water demand on the basis of the time sequence characteristics of historic water demand and by using gray system model GM (m, n) to dig the inherent information in the integral gray volume based on its dynamic memory feature. The gray prediction method is to use the gray system principle to process the data of time sequence, to use the generated series with strong regularity to set up the gray model, and finally to conduct prediction. This method can set up model and conduct prediction under conditions of shortage of data and information, has relatively high accuracy, and is simple and practical [23]. In the dissertation, on the basis of available data, GM (1, 1) was selected to predict the water demand in the study area.

2.5.1.1 Basis of Prediction

The major basis of the water demand prediction are "The Tenth Five Year Plan and The Development Plan in 2010 in Shendong Mining Area" and "The Eleventh Five Years Plan and The prospect Objective to 2020 for Coal Industry in Shendong

Branch of China Shenhua Coal Corporation," the overall planning of the mining area, other related policies, law and regulations. According to the eleventh five-year plan and the prospect objective planning of Shendong, Shendong Coal Corporation will continue to take the development as the subject, economic benefit as center, science and technology as guide, market as support, use advanced production technology and world top equipment, rely on advanced management and production organization mode, further improve production efficiency, make bigger and stronger strut industries such as coal, coal electricity and coal chemistry, realizing the sustainable development in the mining area. The commercial coal production of "six mines and seven shafts" will be 67,000,000 t in 2005. The planned annual commercial coal production will be 77,000,000 t in 2008 and 101,000,000 t in 2015 and 2020. The third stage of electricity generation project of Shangwan thermal power plant will be put into production in 2007; the second stage of Daliuta thermal power plant will be put into production in 2009. With coal liquefaction project put into production, a serial projects related to coal liquefaction will be constructed. At the same time, Daliuta community, Shangwan community, and other communities are on the way of construction step by step, and the scope of community is enlarged continuously. In addition, from the historic data of water demand, it can be seen that from 2000 to 2005, tap water demand increased by 6.4 % annually and reused water demand increased by 8.9 % annually. It can be predicted that with the planning and the construction of the mining area, water demand will increase continuously.

It must be illustrated here that the reused water for afforestation in the study area is mainly treated sewage. The current reused water comes mainly from Daliuta sewage treatment plant, Heitangou sewage treatment plant, Daliuta mine water treatment plant and Huojitu mine water treatment plant. The maximum treatment capacity of reused water from afforestation is 10,900 m^3/day, making the ecological environments in the study area improved. In the future, with the setup of other sewage treatment plants, i.e., Ulan Mulun sewage treatment plant, Kalagou sewage treatment plant, Shigetai sewage treatment plant, Majiata sewage treatment plant, reused water engineering in Shanwan mine and reused water engineering of oxidation pond in Bulianta mine, the maximum treatment volume of reused water for afforestation will reach 26,420 m^3/day. Because the water used in afforestation is mainly the treated sewage, and the principle of zoning and nearby supply is implemented, its future water demand and water supply and demand balance are not analyzed in the following section and only are analyzed the future water demand and water supply and demand balance for tap water reused water for industries in Table 2.29.

2.5.1.2 Gray System Theory

Gray system is a system with a part of known information and a part of unknown information between white system and black system. The gray system theory [24] is a theory to study and solve the analysis, modeling, prediction, decision-making, and

Table 2.29 Current status of the study area, planned reused water engineering in construction for afforestation, and designed treatment volume (unit m^3/day)

Name	Hitangou sewage treatment plant	Daliuta sewage treatment plant	Daliuta mine water treatment plant	Huojitu mine water treatment plant	Sahngwan mine water treatment plant	Bulianta oxidation pond
Treatment volume	2000	6500	2000	400	3000	2000
Name	Halgou sewage treatment plant	Majiata sewage treatment plant	Shigetai sewage treatment plant	Sewage treatment plant of Lijiaban ecological park	Ulan Mulun sewage treatment plant	Total
Treatment volume	480	480	960	3600	2500	26,420

control of the gray system and was put forward by a famous Chinese scholar, Professor Deng Julong in 1982.

“Prediction of future” is essentially gray problem. Gray prediction, an important component of the gray system theory and also a branch used the most actively, has been applied in many fields and produced good results. Based on the difference of data acceptance and rejection as well modeling mode, gray prediction is divided into three categories: series prediction, catastrophe prediction, and system prediction. Among the gray models, GM (1, 1) and its modified types are the most applied, and GM (1, 1) model refers to gray prediction model with first-order equation and variable.

Usually, GM (1, 1) model has better results for short-term prediction, and for long-term prediction, it shows the phenomenon of “floating upward” in predicted value. This is because GM (1, 1) model is based on gray module. In the gray module, the plane intercalated between the upper bound and the lower bound of the future predicted value is called as gray plane. The gray plane is expanded in the form of trumpet, i.e., the farther the future moment is, the bigger the gray interval of the predicted value. Therefore, although GM (1, 1) model can conduct long-term prediction, but from the gray plane, several data only predicted in short term have predicted value with actual significance and higher accuracy, and the farther data reflect only a trend. In order to increase the accuracy of GM (1, 1) model for long-term prediction, it can be imagined to shrink the gray plane. To shrink the gray plane means to make the full use of the known information, at the same time to add continuously new information, so as to enhance the whiteness of the gray plane. GM (1, 1) model is set up on the basis of this thinking.

GM (1, 1) model

GM (1, 1) model is a model set up with known series, which is used to predict a value called as gray number, and then, this predicted value is supplemented after the known series. At the same time, in order to not increase the length of the series, the first datum of the previous modeling is deducted, and the equal dimension is maintained. GM (1, 1) model is set up again to predict the next value. In this way, the new supersedes the old and prediction is made one by one. The replacement is made in order of precedence until achieving the predicted objective or reaching the expected accuracy. Its use during prediction can supplement and utilize new information on time, enhance the whiteness of the gray plane, and shrink the gray interval of the predicted value. In each step of prediction, the gray parameters are modified one time, the model is improved, and so the gray parameters are corrected continuously and the model is improved progressively; thus, the predicted value is produced dynamically.

The steps of modeling of GM (1, 1) model are as follows:

(a) Assume there exists the original series $x^{(0)}$, and there are n observation values: $x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n)$

(b) In order to reduce the error, firstly the original series is smoothed:

$$\bar{x}^{(0)}(1) = \left(3x^{(0)}(1) + x^{(0)}(2)\right)/4$$

$$\bar{x}^{(0)}(k) = \left(x^{(0)}(k-1) + 2x^{(0)}(k) + x^{(0)}(k-1)\right)/4 \quad (k = 2, 3, \ldots, n-1)$$

$$\bar{x}^{(0)}(n) = \left(x^{(0)}(n-1) + 3x^{(0)}(n)\right)/4$$

(c) The smoothed series is accumulated at one time and generated:

$$x^{(1)}(k) = \sum_{i=1}^{k} \bar{x}^{(0)}(k) \quad (k = 1, 2, \ldots, n)$$

Obtain the generated series: $x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n)$

(d) With regard to the series $x^{(1)}$, the differential equation in the form of whitening is formulated for the predicting model:

$$\frac{\mathrm{d}x^{(1)}}{\mathrm{d}t} + a\,x^{(1)} = u$$

where a, u are parameters for estimation, a is development gray number, and u is endogenously controlled gray number.

(e) Take $\bar{a}$ as the vector of the parameters for estimation, and use the principle of the least square method to solve a and u:

$$\bar{a} = \begin{bmatrix} a \\ u \end{bmatrix} = (B^T B)^{-1} B^T Y$$

where

$$Y = \left[x^{(1)}(2), x^{(1)}(3), \ldots, x^{(1)}(n)\right]$$

$$B = \begin{bmatrix} -(x^{(1)}(1) + x^{(1)}(2))/2 & 1 \\ -(x^{(1)}(2) + x^{(1)}(3))/2 & 1 \\ \vdots & \vdots \\ -(x^{(1)}(n-1) + x^{(1)}(n))/2 & 1 \end{bmatrix}$$

Solve GM (1, 1), and obtain

$$\hat{x}^{(1)}(k+1) = \left(\mathrm{x}^{(0)}(1) - u/a\right)e^{-ak} + u/a(k = 1, 2, \ldots, n)$$

The following formula restores the predicted data, and we can obtain the predicted value:

$$\hat{x}^{(0)}(k+1)\hat{x}^{(1)}(k+1)\hat{x}^{(1)}(k) \quad (k = 1, 2, \ldots, n)$$

Here, when k = 1, 2, …, n, $\hat{x}^{(0)}$ (k) is the fitted value of the original data series $\mathrm{x}^{(0)}$ (k) (k = 1, 2, …, n), and when $k > n, \hat{x}^{(0)}(k)$ is the predicted value of the original data series $\mathrm{x}^{(0)}$ (k) (k = 1, 2, …, n).

For the original series, the dynamic processing of equal dimension gray number is made: i.e., $x^{(0)}$ (1) is removed, and $\hat{x}^{(0)}(n+1)$ is added; we obtain:

$$x^{(0)}(2), x^{(0)}(3), \ldots, \hat{x}^{(0)}(n+1)$$

The above steps 1–7 are repeated by taking this as the new original series until to obtain the final prediction results.

(f) Check of the model accuracy:

After modeling, the model needs to be checked to determine whether the accuracy of the model meets the requirements and to judge if the model can be used in prediction. The common testing method is as follows:

(1) Residual error test:

Residual error: $\varepsilon(k) = \mathrm{x}^{(0)}(k)\hat{x}^{(0)}(k)$

Relative error: Δk = |ε (k) |/$x^{(0)}$ (k)

In concrete modeling, the allowable relative error Δk can be determined according to the real situation.

(2) Posterior error test:

To seek the mean value of the original series: $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x^{(0)}(i)\ i = 1, 2, \ldots, n$
To seek the variance and the mean square error:

$$S_1^2 = \sum_{i=1}^{n} (x^{(0)}(i) - \bar{x})^2\ S_1 = \sqrt{\frac{S_1^2}{n-1}}$$

The mean value of the residual error ε is as follows: $\bar{\varepsilon} = \frac{1}{n}\sum_{i=1}^{n} \varepsilon(i)$
To seek the variance and the mean square error:

$$S_2^2 = \sum_{i=1}^{n} (\varepsilon(i) - \bar{\varepsilon})^2\ S_2 = \sqrt{\frac{S_2^2}{n-1}}$$

To calculate the variance ratio: $C = S_2/S_1$
To calculate the probability of small error: $P = \{|\varepsilon(i) - \bar{\varepsilon}| < 0.6745\mathrm{S}_1\}$
On the basis of the calculated results of C and P, the model accuracy is assessed comprehensively according to Table 2.30.

Case analysis
The existing tap water consumption during 2000–2005 was taken as the original value to predict the water demand in different years of the planned period, to verify the feasibility of GM (1, 1) model, and to simulate and to predict whether the predicted results can reach the accuracy requirement. According to the above steps of modeling, Visual Basic programming was used to conduct simulation and prediction as well as calculation. The results are shown in Fig. 2.14 and Tables 2.31 and 2.32. From the simulation results in Table 2.32, it can be seen that P is bigger than 0.95, C is smaller than 0.35, and the fitting accuracy meets the standard of class one. Because it is dynamic prediction, C value of each year of the prediction results shown in Table 2.32 is different. From the prediction results in Table 2.31, it can be seen that both C and P meet the standard of class one indicated in accuracy assessment given in Table 2.30. When the development gray number a of GM (1, 1) is smaller than 0.3, the model can be used in medium- and long-term predictions. Parameter a given by the above calculation is all smaller than 0.1. According to the principle of posterior error test, the posterior error ratio is the smaller the better. In addition, it is shown in Fig. 2.14 that the fitting results are good. Thus, GM (1, 1) model has some practical value and can be used in long-term prediction.

Table 2.30 Assessment of model accuracy

Accuracy class	P	C
Class one: good	>0.95	<0.35
Class two: qualified	>0.80	<0.50
Class three: barely	>0.70	<0.65
Class four: unqualified	≤0.70	≥0.65

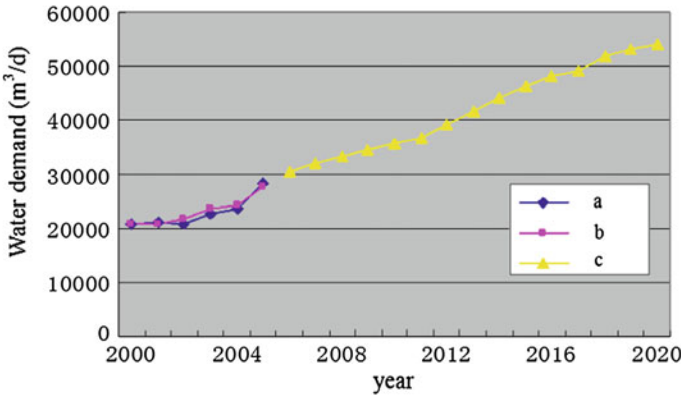

Fig. 2.14 Fitting and predicted results of tap water consumption and demand. *Note a*—initial value; *b*—fitted value; *c*—predicted value

Table 2.31 Simulation results of current water consumption

Year	Original value (m^3/day)	Fitting value (m^3/day)	Residual error	Relative error (%)
2000	20,822	20,822	0	0
2001	21,260	20,817	443	2.09
2002	20,966	21,639	−673	−3.21
2003	22,761	23,500	−739	−3.25
2004	23,622	24,120	−498	−2.11
2005	28,377	27,714	663	2.34
C = 0.12, P = 1				

2.5.2 Prediction of Water Demand

According to the step of the above GM (1, 1) model, the amount of tap water and reused water for industry in the study area during 2000–2005 was taken as the original value to predict the demand of tap water and reused water for industry in different future years, and the results are given in Table 2.33 and Fig. 2.15.

From the predicted results, it can be known that the water demand shows the trend of increase year by year. Tap water demand will increase from 30,600 m^3/day in 2006 to 54,203 m^3/day in 2020, increasing 23,603 m^3/day. The reused water for industry will increase from 18,007 m^3/day in 2006 to 31,062 m^3/day in 2020, increasing 13,055 m^3/day. The total water demand in the study area will increase from 48,607 m^3/day in 2006 to 85,265 m^3/day in 2020, increasing 36,658 m^3/day.

Table 2.32 Prediction results of tap water demand during planning period

Year	Predicted value (m^3/day)	Development gray number *a*	*C*	*P*
2006	30,600	−0.097	0.107	1
2007	32,100	−0.098	0.108	1
2008	33,205	−0.094	0.102	1
2009	34,500	−0.09	0.128	1
2010	35,800	−0.086	0.128	1
2011	36,590	−0.0825	0.138	1
2012	39,234	−0.0836	0.15	1
2013	41,536	−0.0830	0.164	1
2014	44,213	−0.0810	0.174	1
2015	46,457	−0.0788	0.186	1
2016	48,189	−0.0771	0.2	1
2017	49,253	−0.0758	0.212	0.99
2018	51,860	−0.0747	0.224	0.98
2019	53,062	−0.0739	0.236	0.98
2020	54,203	−0.0730	0.248	0.95

Table 2.33 Prediction of water demand during planning period (unit m^3/day)

Year	Tap water (m^3/day)	Reused water for industry (m^3/day)	Total water demand (m^3/day)
2006	30,600	18,007	48,607
2007	32,100	18,804	50,904
2008	33,205	19,554	52,759
2009	34,500	25,584	60,084
2010	35,800	26,026	61,826
2011	36,590	26,565	63,155
2012	39,234	27,048	66,282
2013	41,536	27,632	69,168
2014	44,213	28,012	72,225
2015	46,457	28,546	75,003
2016	48,189	29,006	77,195
2017	49,253	29,654	78,907
2018	51,860	30,123	81,983
2019	53,062	30,535	83,597
2020	54,203	31,062	85,265

2.5.3 Planning of Water Supply Engineering

According to the "*Eleventh Five Years Plan and the Prospect Objective to 2020 of Coal Industry of Shandong Branch of China Shenmue Coal Group Corporation,*" during the planned period in the study area, water supply engineering already

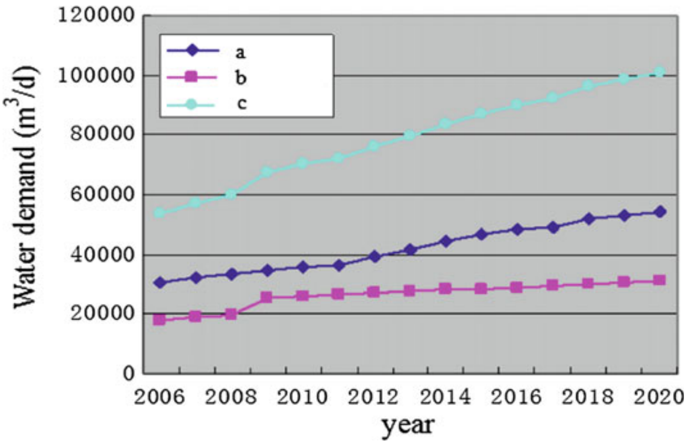

Fig. 2.15 Variation of predicted water demand with time. *Note a*—tap water; *b*—industrial reused water; *c*—total water demand

constructed and in construction includes Majiata infiltration gallery and Majiata pit water source engineering. Water supply engineering to construct include Bulianta underground water treatment plant and water storage engineering of rear Bulian pit.

1. Majiagou pit impoundment utilization engineering: supply cooling water of Shangwan thermal power plant and water for coal washing in Shangwan coal washery. A sand dam will be constructed in Ulan Mulun River. Water will be collected during wet season, detained then stored in Majiata pit of 2,500,000 m^3 with water supply yield of 10,000 m^3/day. The area of the water blocking pit is 2,000,000 m^2, 20 m deep, and effective volume is 2,500,000 m^3. The depth of stored water is 4 m; the available water volume is 600,000 m^3. The engineering will be completed at the end of August 2006 and will meet the water demand for cooling in the third stage of Shangwan thermal power plant and coal washing in Shangwan coal mine.
2. Bulianta underground water treatment plant: A new underground water sump will be constructed in Bulianta mine, and a borehole will be drilled on the ground surface to inject water. The water drained from forced drainage boreholes will be transported through surface pipeline to the water injecting borehole, through which the water will be transported to the newly constructed sump. After being detained and filtrated, the clear water will then be transported through the underground water pipeline to the surface water treatment plant. The treated water will be merged into the water supply pipe network from the high pool in Bulianta, the treated water will be merged into the water supply pipe network. Its water supply yield will be 10,000 m^3/day. It is planned that the treatment plant will be constructed and put into production in 2008.
3. Rear Bulian pit: In rear Bulian mining district, near the junction of Huhewusugou and Ulan Mulun River, there is a pit with an effective volume of

approximately 3,400,000 m^3 and used to store the inflow of the pit, and at the same time, an infiltration canal may be constructed at the downstream river channel of Wuhesugou to introduce water into the pit. The water supply yield will be 10,000 m^3/day. It is planned to put into production in 2009.

Through the above plans of water supply engineering, with regard to water supply engineering, from 2008 the tap water supply yield will increase 10,000 m^3/day. With regard to reused water supply engineering for industry, from 2006 the reused water supply yield will increase 10,000 m^3/day, and from 2009, as rear Bulian pit impoundment will come into use, the reused water supply for industry will increase additionally 10,000 m^3/day. In addition, through the transformation of Halagou underground reused water engineering, in 2009 the reused water supply yield will increase again by 2000 m^3/day.

The prediction data of water supply yield rooted mainly in the "*Eleventh Five Years Plan and the Prospect Objective to 2020 of Coal Industry of Shendong Branch of China Shenhua Coal Group Corporation,*" and at the same time, the water supply engineering inside six mines and seven shafts was added. The results are shown in Table 2.34 and Fig. 2.16. From the table and the figure, it can be seen that the tap water supply yield will increase, then decrease, and increase from 49,800 m^3/day to 52,900 m^3/day in 2010, increasing 3,100 m^3/day. From 2011 to 2015, the tap water supply yield will be 50900 m^3/day, decreasing 2000 m^3/day compared to 2010. From 2015 to 2020, the tap water supply yield will be 47,900 m^3/day, decreasing 3000 m^3/day again compared to 2015. This is mainly because there is a decreasing trend of the water yield of springs in the study area. From the other point of view, this illustrates that coal mining results in the reduction of water yield of springs; surface water is converted into mine inflow and accumulated water in gob. Therefore, it is very necessary to enhance the development and utilization of mine water.

As a whole, the reused water yield for industry shows increasing trend and will increase from 20,390 m^3/day in 2006 to 36,390 m^3/day in 2010, increasing 16,000 m^3/day from 2011 to 2020. The reused water yield for industry will be 36,390 m^3/day, and as mentioned above, this is mainly resulted from the enhanced development and utilization of mine water, i.e., because several reused water engineering will come into use.

Generally speaking, the total water supply in the study area increases from 70,190 m^3/day in 2006 to 89,290 m^3/day in 2010, increasing 19,100 m^3/day from 2011 to 2015. The total water supply will be maintained at 87,290 m^3/day. After 2016, the total water supply will decrease again 3000 m^3/day and will be 84,290 m^3/day in 2020. This resulted mainly from the reduction of tap water supply capacity, with regard to the percentage of different water supplies. The percentage of tap water will be decreased, i.e., decreasing from 71 % in 2005 to 56.8 % in 2020. But the percentage of reused water for industry will increase, correspondingly increasing from 29.1 % in 2006 to 43.2 % in 2020. From this, it can be seen that in the future planning period, the utilization ratio of mine water resources will increase. This can not only relief the contradiction between the water supply and the

Table 2.34 Prediction of water supply during future level years in Shendong mining area

Source		Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Water source of tap water supply	Source of networking water supply	Kaokaolaigou water source	17,000	17,000	16,000	15,000	15,000	13,000	13,000	13,000	13,000	13,000	10,000	10,000	10,000	10,000	10,000
		Daliuta underground water treatment plant	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
		Underground clear water in Ulan Mulun mine	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
		Underground water treatment plant in Bulianta mine	0	0	6000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
	Independent water supply source	Water source in Halagou	5000	4500	3000	0	0	0	0	0	0	0	0	0	0	0	0
		Gongniergaigou reservoir	8900	9000	9000	9000	9000	9000	9000	9000	9000	9000	9000	9000	9000	9000	9000
		Subtotal of networking tap water yield	43,900	43,500	47,000	47,000	47,000	45,000	45,000	45,000	45,000	45,000	42,000	42,000	42,000	42,000	42,000
		Water source in Shigetai	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
		Water source in Xiaoliuta	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
		Seepage well in Huojitu	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
		Buliangou seepage channel	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
		Subtotal of independent source	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
		Total of tap water yield	49,800	49,400	52,900	52,900	52,900	50,900	50,900	47,900	47,900	47,900		47,900		47,900	47,900
Source of reused water supply for industry		Daliuta shaft (underground reused water)	1920	1920	1920	1920	1920	1920	1920	1920	1920	1920	1920	1920	1920	1920	1920

(continued)

Table 2.34 (continued)

Source	Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
	Underground water treatment plant in Daliuta mine (industrial reused water)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
	Underground water treatment plant in Huojitu mine (underground reused water)	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300
	Halagou mine (underground reused water)	400	400	1400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400
	Shangwan mine (underground reused water)	1070	1070	1070	1070	1070	1070	1070	1070	1070	1070	1070	1070	1070	1070	1070
	Bulianta mine (underground reused water)	3100	3100	3100	3100	3100	3100	3100	3100	3100	3100	3100	3100	3100	3100	3100
	Ulan Mulun mine (underground reused water)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
	Shigetai mine (underground reused water)	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
	Majiata seepage channel and pit water source	6000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
	Rear Bulian pit	0	0	0	6000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
	Subtotal of industrial reused water	20,390	24,390	25,390	32,390	36,390	36,390	36,390	36,390	36,390	36,390	36,390	36,390	36,390	36,390	36,390
Total water yield of all sources year by year		70,190	73,790	78,290	85,290	89,290	87,290	87,290	87,290	87,290	87,290	84,290	84,290	84,290	84,290	84,290

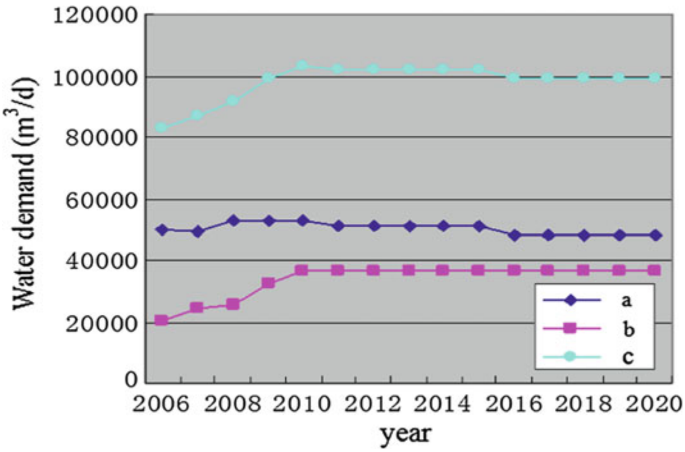

Fig. 2.16 Variation of predicted water supply versus time. *Note a*—tap water supply; *b*—industrial reused water supply; *c*—total water supply

demand of water resources, but also save capital and improve the economic and social benefits of enterprises.

2.5.4 Analysis of Future Water Supply and Demand Balance

2.5.4.1 Analysis on Future Water Supply and Demand Balance

On the basis of the predicted results of tap water supply and demand, water supply and demand balance of future different level years during the planning period were analyzed (Table 2.35 and Fig. 2.17).

From the table and the figure, it can be seen that the tap water demand in the study area shows the trend of yearly increase, whereas the water supply shows the trend of increase firstly and then it decreases. From 2006 to 2015, the water supply can meet the requirements of water demand, the water supply in 2006 is 49,800 m^3/day, water demand is 30,600 m^3/day, the surplus is 19,200 m^3/day; the water supply in 2008 is 52,900 m^3/day, and the water demand is 33,250 m^3/day, the surplus is 19,695 m^3/day; the water supply in 2010 is 52,900 m^3/day, the water demand is 35,800 m^3/day, the surplus is 17,100 m^3/day; the water supply in 2015 is 50,900 m^3/day, the water demand is 46,457 m^3/day, the surplus is 4443 m^3/day. From 2016 to 2020, the water supply cannot meet the requirement of water demand, the water supply is 47,900 m^3/day, the water demand is 48,189 m^3/day, and the shortage is 289 m^3/day. The water supply in 2020 is 47,900 m^3/day, the water demand is 54,203 m^3/day, and the shortage is 6303 m^3/day.

Table 2.35 Water supply and demand balance of different years of the planning period in the study area (unit m^3/day)

Year	2006	2007	2008	2009	2010	2011	2012	2013
Water supply	49,800	49,400	52,900	52,900	52,900	50,900	50,900	50,900
Water demand	30,600	32,100	33,205	34,500	35,800	36,590	39,234	41,536
Surplus and shortage	19,200	17,300	19,695	18,400	17,100	14,310	11,666	9364

Year	2014	2015	2016	2017	2018	2019	2020
Water supply	50,900	50,900	47,900	47,900	47,900	47,900	47,900
Water demand	44,213	46,457	48,189	49,253	51,860	53,062	54,203
Surplus and shortage	6687	4443	−289	−1353	−3960	5162	−6303

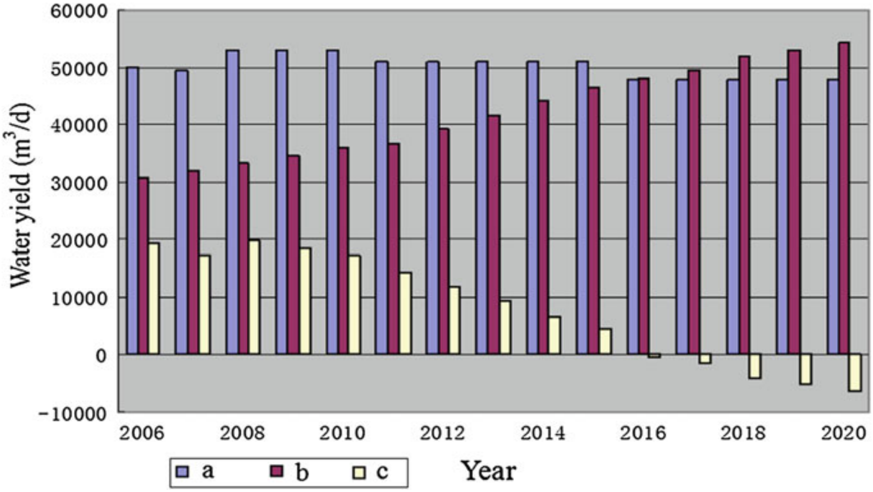

Fig. 2.17 Histogram of analysis on tap water supply and demand balance of different level years in the study area. *Note a*—water supply; *b*—water demand; *c*—surplus and shortage

This situation mainly resulted from two causes. As regards water demand, with the further development of coal and coal-related industry in the study area, with the progressive construction of Daliuta community and Shangwan community as well as different mining areas, with the continuous enlargement of house estate scope, the water demand shows the trend of yearly increase. As regards the water supply, the available yield of water supply source inside the study area shows the trend of decrease, for example the water yield of Kaokaogou water source. Shendong Corporation is exploiting continuously potentialities, firstly broadening the water supply capacity of the existing water sources, secondly increasing the utilization ratio of mine water conversion into tap water, thus easing the imbalance between the supply and demand of water resources in short term from 2006 to 2015. For the long term, i.e., after 2015, because the growth rate of water demand surpasses greatly the increased water yield of the tap water supply plan in the study area, the imbalance becomes obvious between the supply and demand of water resources.

2.5.4.2 Analysis on Industrial Reused Water Supply and Demand Balance

On the basis of the predicted results of industrial reused water demand and supply, the supply and demand balance of different level years during the planning period was analyzed (Table 2.36 and Fig. 2.18).

The industrial reused water demand shows the trend of yearly increase in the study area, so does the industrial reused water supply from 2006 to 2010 and will be constant from 2010 to 2020. According to the planned industrial reused water supply, the water supply can meet the water demand, the water supply in 2008 is 25,390 m^3/day, the water demand is 19,554 m^3/day, the surplus is 5836 m^3/day; the water supply in 2010 is 36,390 m^3/day, the water demand is 26,026 m^3/day, the surplus is 10,364 m^3/day; the water supply in 2015 is 36,390 m^3/day, the water demand is 28,546 m^3/day, the surplus is 7844 m^3/day; the water supply in 2020 is 36,390 m^3/day, the water demand is 31,062 m^3/day, the surplus is 5328 m^3/day.

From the above data, tables, and figures, it can be known that the industrial reused water, i.e., utilization ratio of reused mine water, will increase continuously during the planning period, while the industrial reused water supply can meet the requirement of the demand. This is mainly resulted from the fact that development and utilization of mine water are enhanced and several industrial reused water engineering put into use. In addition, there is big potential to exploit the industrial reused water in the study area. Firstly, the water supply has not yet reached its maximum capacity. Secondly, there is relatively large surplus in water supply. Therefore, in the future, we can also enhance the reused and treatment of mine

Table 2.36 Industrial reused water supply and demand balance of different level years during the planning period in the study area (unit m^3/day)

Year	2006	2007	2008	2009	2010	2011	2012	2013
Water supply	20,390	24,390	25,390	32,390	36,390	36,390	36,390	36,390
Water demand	18,007	18,804	19,554	25,584	26,026	26,565	27,048	27,632
Surplus and shortage	2383	5586	5836	6806	10,364	9825	9342	8758

Year	2014	2015	2016	2017	2018	2019	2020
Water supply	36,390	36,390	36,390	36,390	36,390	36,390	36,390
Water demand	28,012	28,546	29,006	29,654	30,123	30,535	31,062
Surplus and shortage	8378	7844	7384	6736	6267	5855	5328

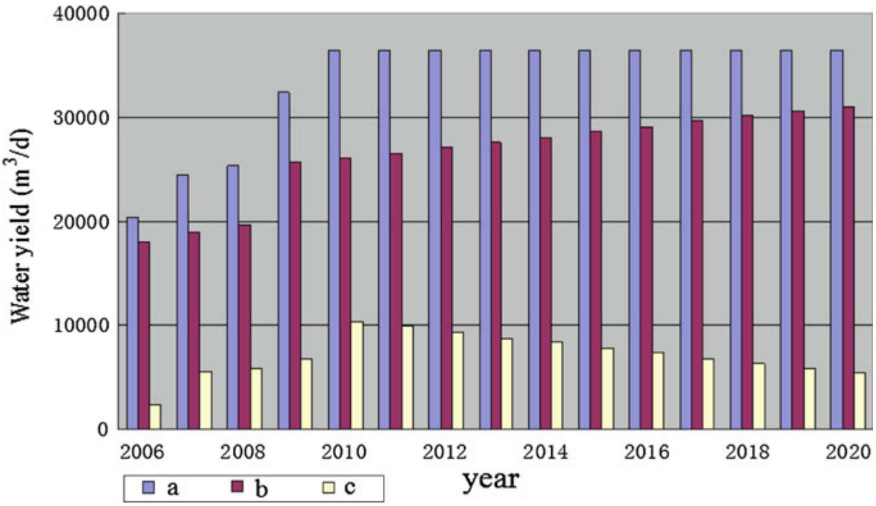

Fig. 2.18 Histogram of analysis on future industrial reused water supply and demand of different level years in the study area. *Note a*—water supply; *b*—water demand; *c*—surplus and shortage

water, improve further the reused ratio of mine water, substitute groundwater or surface water with mine water as much as possible, and protect the limited water resources, thus easing effectively the imbalance of the supply and the demand of water resources in the study area and simultaneously improving economic benefit.

2.6 Prediction of Mine Inflow

2.6.1 Current Status of Mine Inflow in Different Mines of the Study Area

In Daliuta mine, Huojitu shaft, Shangwan mine, Bulianta mine, Halagou mine, Shigetai mine, and Ulan Mulun mine, the annual mine inflow is 1470.5 m^3/h, and the total annual inflow is 12,667,000 m^3, as shown in Table 2.37. The largest annual average inflow occurs in Bulianta mine up to 504.3 m^3/h, and the total annual average inflow is 4418,000 m^3. The smallest annual average inflow occurs in Halagou mine and is 80.82 m^3/h, and the total annual average inflow is 707,800 m^3. The inflow in mines tends to increase year by year as in Fig. 2.19.

Table 2.37 Annual average inflow in mines

Name	Daliuta	Huojitu	Shangwan	Bulianta	Halagou	Shigetai	Ulan Mulun	Total
Annual average flow (m^3/h)	338.3	136.8	87.8	504.3	80.8	155	167.5	1470.5
Total annual average inflow (10^4 m^3)	296.6	108.8	76.3	441.8	70.8	125.7	146.7	1266.7

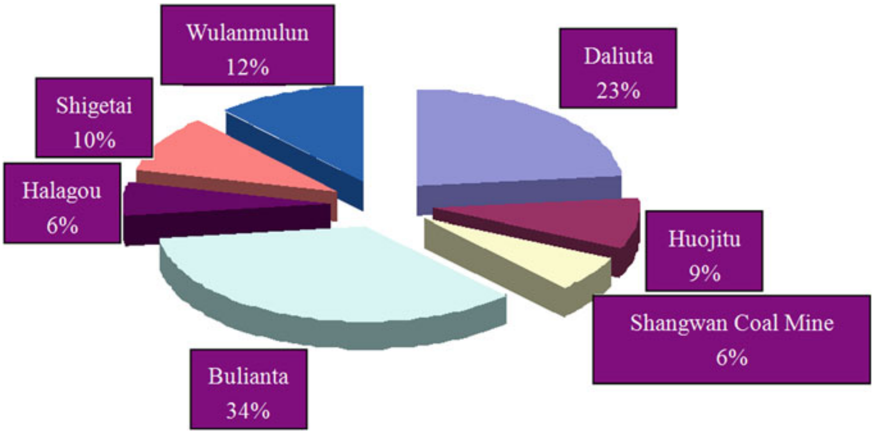

Fig. 2.19 Percentage of inflow of each mine in the total inflow

2.6.2 *Current Status of Water Filling in Gob of Different Mines in the Study Area*

Great amount of fractures in gob create good conditions for storage and flow of groundwater, link up the overlying aquifer or enhance hydraulic connection, and become passage for aquifer water to enter gob. Fractures and void in caved rocks become large space for storage of groundwater [25, 26]. Generally, the following formula is used to calculate the accumulated water yield in gob:

$$Q = KMS/\cos\alpha$$

where

Q accumulated water yield in gob;

M mining height of seam;

S horizontal projected area of gob;
α seam dip;
K water filling coefficient.

M, S, α are all fixed values. Therefore, the value of K is the critical parameter for which the calculation of accumulated water yield is accurate.

After a seam is mined out, a part of gob volume is filled by the volume part increased due to broken and expanded fallen rocks (called residual broken and expanded volume of rocks, equal to the total volume after the collapse of rocks minus the volume before the collapse of rocks), and the rest part of the volume is transferred to the ground surface through the shifting down of the overburden layers, ultimately manifested as surface subsidence [27, 28]. Therefore, the following relational expression is set up:

$$V = V_1 + V_2$$

where
V mined-out volume;
V_1 subsided volume;
V_2 residual broken and expanded volume of rock in collapsed zone.

Water accumulating volume V' of gob should be equal to the sum of void volume among rock fragments in collapsed zone, i.e.,

$$V' = V_2 = V - V_1$$

And the water filling coefficient is as follows:

$$K = (V - V_1)/V = (MS - SH)/(MS) = 1 - H/M$$

$$K = 1 - H/M$$

Because no surface subsidence volume of gob is available to the study, when determining the water filling coefficient of gob in Shendong mining area, we adopted empirical analogue method to get water filling coefficient. On the basis of calculation of water accumulating area and accumulated water yield in gobs of working faces 31305 and 31306 in Bulianta mine, the water filling coefficient was defined as 0.3. The calculation results of accumulated water yield of gob of working faces 63104 and 63106 in Ulan Mulun mine resulted in the water filling coefficient of 0.32. In combination with K value of 0.25–0.5 given in the fifth section Mine Water Control of "*Coal Mine Safety Manual*" (edition 1992), when calculating the accumulated water in gob of Shendong mining area, we defined the water filling coefficient as 0.30. According to this coefficient, we calculated the accumulated water yield of gob in major mines of Shendong mining area, as shown in Table 2.38.

Table 2.38 Water accumulating area and accumulated water yield of gob in different mines in the study area

Mine	Horizontal projected area of gob (10^4 m^2)	Calculation formula	Accumulated water yield (10^4 m^3)
Daliuta	5396.7	$Q = KMS/\cos\alpha$ where Q—accumulated water yield in gob M—mining height of seam S—horizontal projected area of gob α—seam dip K—water filling coefficient	1623.9
Huojitu	1094.9		329.4
Bulianta	2977.0		895.8
Shangwan	2115.5		636.6
Shigetai	486.9		146.5
Halagou	436.2		131.3
Ulan Mulun	555.6		167.2
Total	13,062.8		3930.7

The total water accumulating area of gob in Daliuta, Huojitu, Shangwan, Bulianta, Halagou, Shigetai, and Ulan Mulun is 130,628,000 m^2, and the total accumulated water yield is 39,307,000 m^3. With the continuous increase of mine water inflow and accumulated water yield in gob, as water resources, mine water has big potential for the development and utilization.

2.6.3 Basis of Prediction

Through the comprehensive analysis of historic mine inflow and production, the variation law between mine water inflow and some production factors such as mining area, roadway length, and mining depth was found out. The relationship between production factors and water inflow, one expressed by mathematical equation, can be used to predict water inflow in mines with similar geological and hydrogeological conditions.

The water richness coefficient in the hydrogeological analogue method was used to predict mine water inflow [29].

$$K_p = \frac{Q}{P}$$

whereK_p—water richness coefficient, referring to the ratio of mine water inflow $Q(t)$ to exploitation quantity $P(t)$ during the same period (usually one year).

It can be seen that water richness method is an analog expression based on the relation between exploitation quantity and water inflow in mine. If after interpolation of value K_p we want to predict the water inflow of the mine with similar conditions and the exploitation quantity, then we get:

$$Q' = K_p P'$$

K_p varies often a lot in different mines even in the same mine but during different periods. The reason is that it is related to the variation of natural conditions (geological and hydrogeological conditions) and artificial factors (mining method, mining intensity, etc.), in order to make the predicted results as much as possible close to the objective reality. In practice, we select other water richness coefficients to conduct prediction on the basis of the actual situation and data of the predicted mine, for example:

$$K_F = \frac{Q}{F} K_V = \frac{K}{V} K_L = \frac{Q}{L}$$

where F, V, L—mined-out area, mined-out volume, and roadway length;

K_F, K_V, K_L—water richness coefficient of mined-out area, water richness coefficient of volume, and roadway length.

According to the water-gushing characteristics of major active mines in Shendong mining area, through the analysis of the historic water-gushing data and data about production factors influencing water gushing, the study tends to set up the relation between coal production and water inflow to predict mine water inflow, that is, to set up the relation curves between historic total annual water inflow and accumulated coal production in different coal mines, to draw the trend line of the relation curves, and to use the fitting equation of the trend line to obtain the mine water inflow corresponding to coal production in future years as in Figs. 2.20, 2.21, 2.22, 2.23, 2.24, 2.25 and 2.26.

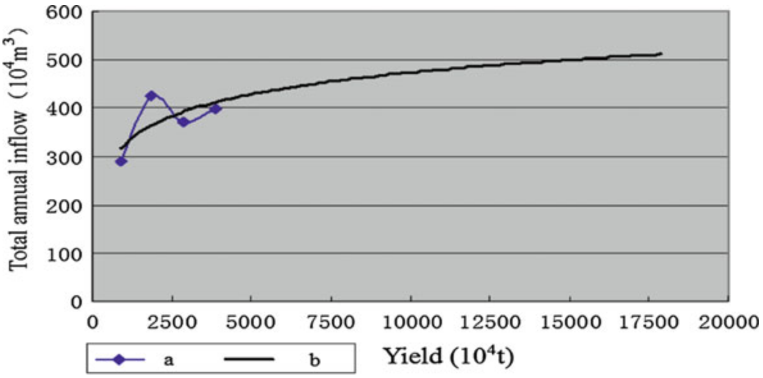

Fig. 2.20 Correlative curve between coal production and mine water inflow and trend line of Daliuta mine. *Note a*—relational curve; *b*—log (relational curve); *c*—accumulated production (10^4 t)

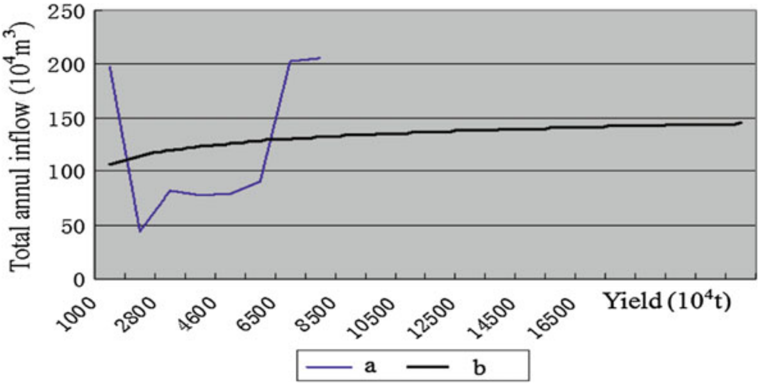

Fig. 2.21 Correlative curve between coal production and mine water inflow and trend line of Huojitu shaft. *Note a*—relational curve; *b*—log (relational curve); *c*—accumulated production (10^4 t)

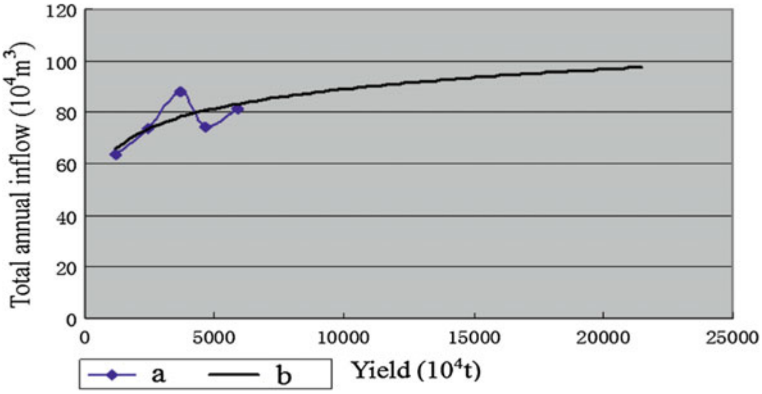

Fig. 2.22 Correlative curve between coal production and mine water inflow and trend line of Shangwan mine. *Note a*—relational curve; *b*—log (relational curve); *c*—accumulated production (10^4 t)

2.6.4 Prediction of Mine Water Inflow

By using the above-mentioned method, the correlative curves between coal production and water inflow in major mines of Shendong mining area and the trend lines were plotted respectively. The equation of the trend line was derived.

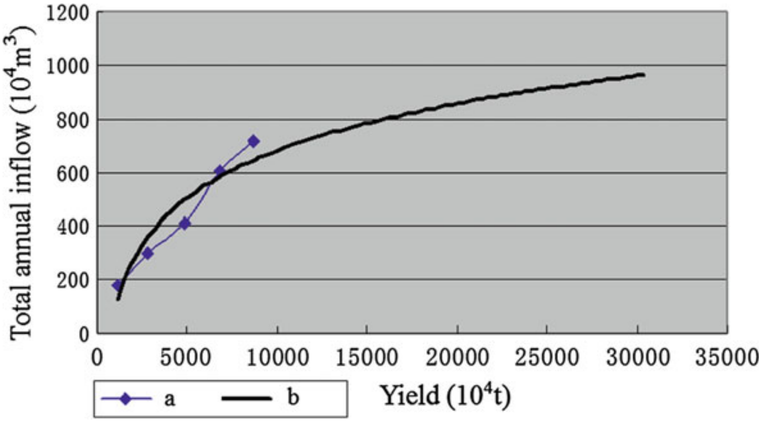

Fig. 2.23 Correlative curve between coal production and mine water inflow and trend line of Bulianta mine. *Note a*—relational curve; *b*—log (relational curve); *c*—accumulated production (10^4 t)

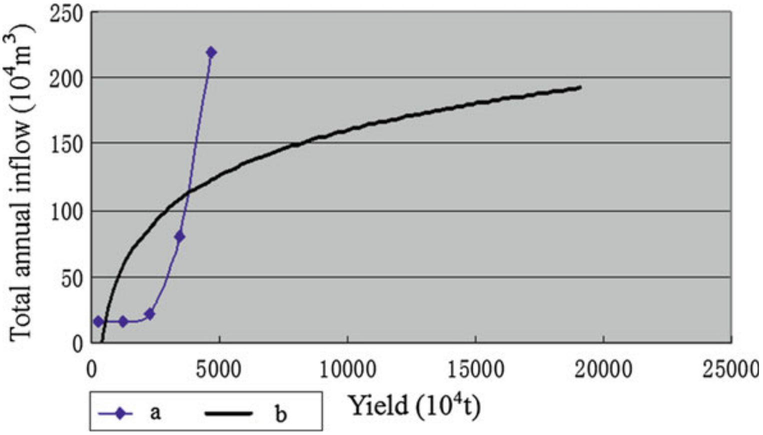

Fig. 2.24 Correlative curve between coal production and mine water inflow and trend line of Halagou mine. *Note a*—relational curve; *b*—log (relational curve); *c*—accumulated production (10^4 t)

1. **Daliuta mine**
   The fitting equation of the trend line is as follows: $Y = 65.108\ln(x) - 126.1$
2. **Huojitu shaft**
   The fitting equation of the trend line is as follows: $Y = 12.502\ln(x) + 105.78$

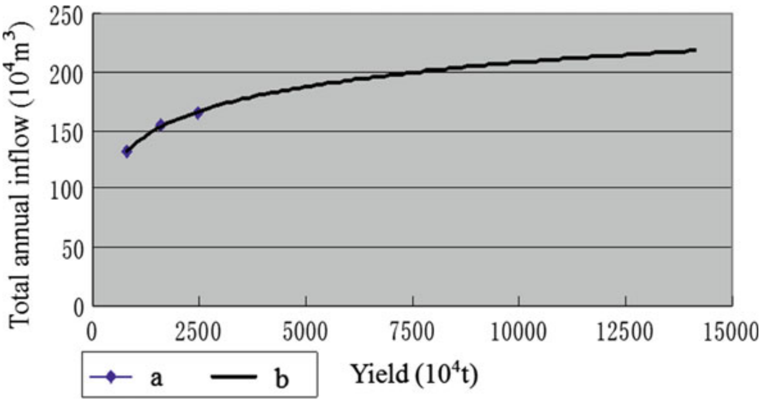

Fig. 2.25 Correlative curve between coal production and mine water inflow and trend line of Shigetai mine. *Note a*—relational curve; *b*—log (relational curve); *c*—accumulated production (10^4 t)

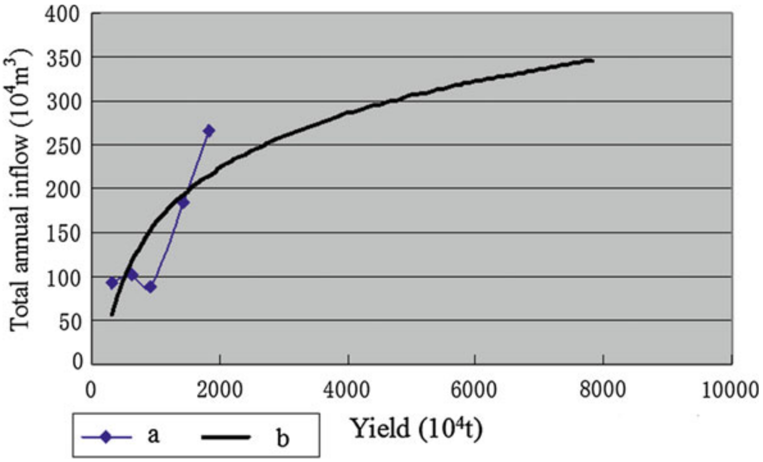

Fig. 2.26 Correlative curve between coal production and mine water inflow and trend line of Ulan Mulun mine. *Note a*—relational curve; *b*—log (relational curve); *c*—accumulated production (10^4 t)

3. **Shangwan mine**
   The fitting equation of the trend line is as follows: $Y = 10.957\ln(x) - 11.852$
4. **Bulianta mine**
   The fitting equation of the trend line is as follows: $Y = 252.72\ln(x) - 1647.2$
5. **Halagou mine**
   The fitting equation of the trend line is as follows: $Y = 49.429\ln(x) - 294.84$

Table 2.39 Predicted water inflow of major active mines in Shendong mining area during 2008–2020

Year		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Daliuta	Water inflow (m^3/day)	12,017	12,298	12,541	12,756	12,947	13,119	13,276	13,421	13,555	13,679	13,795	13,905	14,007
	Total annual water inflow (10^4 m^3)	439	449	458	466	473	479	485	490	495	499	504	508	511
Huojitu	Water inflow (m^3/day)	5848	5905	5954	5997	6035	6070	6101	6129	6156	6180	6203	6224	6244
	Total annual water inflow (10^4 m^3)	213	216	217	219	220	222	223	224	225	226	226	227	228
Shangwan	Water inflow (m^3/day)	2335	2382	2423	2459	2491	2520	2547	2571	2593	2614	2634	2652	2669
	Total annual water inflow (10^4 m^3)	85	87	88	90	91	92	93	94	95	95	96	97	97
Bulianta	Water inflow (m^3/day)	17,686	18,987	20,081	21,026	21,857	22,599	23,270	23,881	24,442	24,961	25,444	25,896	26,320
	Total annual water inflow (10^4 m^3)	646	693	733	767	798	825	849	872	892	911	929	945	961
Halagou	Water inflow (m^3/day)	3359	3670	3922	4135	4319	4481	4625	4756	4875	4984	5086	5180	5268
	Total annual water inflow (10^4 m^3)	123	134	143	151	158	164	169	174	178	182	186	189	192

(continued)

Table 2.39 (continued)

Year		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Shigetai	Water inflow (m^3/day)	4204	4358	4485	4593	4686	4769	4844	4927	5001	5069	5130	5187	5240
	Total annual water inflow (10^4 m^3)	153	159	164	168	171	174	177	180	183	185	187	189	191
Ulan Mulun	Water inflow (m^3/day)	5876	6477	6960	7364	7712	8017	8288	8532	8755	8959	9148	9323	9486
	Total annual water inflow (10^4 m^3)	214	236	254	269	281	293	303	311	320	327	334	340	346
Total (m^3/day)		51,324	54,077	56,368	58,330	60,048	61,575	62,950	64,217	65,377	66,447	67,440	68,367	69,235

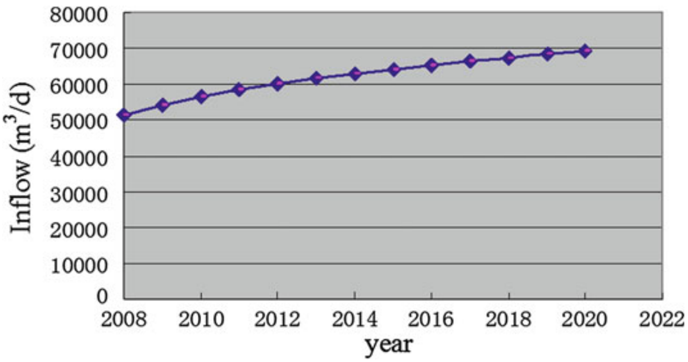

Fig. 2.27 Variation of mine water inflow in major active mines of Shendong mining area

6. **Shigetai mine**
   The fitting equation of the trend line is as follows: $Y = 29.842\ln(x) - 66.844$
7. **Ulan Mulun mine**
   The fitting equation of the trend line is as follows: $Y = 90.402\ln(x) - 464.15$

According to the fitting equations of the trend line of water inflow in different mines, water inflow of mines in future years was calculated, as shown in Table 2.39.

From Table 2.39, it can be seen that mine water inflow in major active mines of Shendong mining area shows the trend of increase year by year (Fig. 2.27 and the total mine water inflow increases from 51,324 m^3/day in 2008 to 69,235 m^3/day in 2020).

2.7 Summary

1. Through the investigation and study of all available and potentially used water resources such as surface water, groundwater, surface water bodies, mine water inflow during mine construction and production, and accumulated water in gob in different mines of Shendong mining area, it is concluded that:
   - The surface water system in the study area is mainly a seasonable water flow system composed of Ulan Mulun River and its tributaries. The tributaries are Shanggou, Halagou, Buliangou, Huojitugou, Liugengou, Gongnieergaigou, Kaokaolaigou, etc. The major spring field at the eastern bank of Ulan Mulun River, i.e., Gongnieergaigou, Kaokaolaigou, Hlagou, and Liugengou, has relatively thick loose layer, strong and medium water abundance, and relatively stable spring flow and is the major water supply source in the area. Water intake mode is direct water intake from springs.

  - The main stream and the river valley of Ulan Mulun River do not have themselves concentrated water supply conditions and cannot be used as permanent water sources in the mining area. But local river islands have some exploitation potential as independent small-scale water source. The annual runoff of more than 1,000,000 m^3 in different tributaries such as Liugengou and Budaihaogou, if used as water intake source, can increase tap water yield by 6000–8000 m^3/day.
  - Shalawusu Formation and burnt rock are the major aquifers in Shendong mining area, and both are unified aquifer with unified water level and good hydraulic connection. The phreatic water in Quaternary loose aquifer is the recharge source of phreatic water of underlying burnt rock fractures. Shalawusu Formation is mainly distributed in Kaokaolaigou, Liugengou, Halagou, Gongnieergaigou, and other valleys, mostly overlaid by aeolian deposit and strongly watery. The burnt rock is mostly distributed in the form of strip in valleys such as Muhegou, Shanggou, and Halagou, approximately 50–100 m wide, 20–50 m thick, and strongly watery. Inside different mines of the study area, except for several spring fields at the eastern bank of Ulan Mulun River, the aquifer of loose porous phreatic water is thin and discontinuous, except for high water abundance in local section, and has mostly weak and medium water abundance. The water abundance is strong in the first terrace of Ulan Mulun River, medium in floodplain and second terrace, and weak in the third and fourth terraces. In floodplain of Ulan Mulun River, there exist some temporary water intake points with certain exploitation potential, for example, Shigetai river island, floodplain of Buliangou mouth, and floodplain of Huhewusugou mouth.
  - The annual water inflow of Daliuta mine, Huojitu shaft, Shangwan mine, Bulianta mine, Halagou mine, Shigetai mine, and Ulan Mulun mine in the study area is 1470.5 m^3/h, the total is 12,667,000 m^3, and it shows the trend of increase year by year. The total water accumulating area of gob is 130,628,000 m^2, and the total accumulated water volume is 39,307,000 m^3. As water resources, mine water has great exploitation and utilization potential.
  - Because of the existence of gob, the groundwater runoff in the area is influenced not only by topography, landform, and tectonics, but also by gob, i.e., migrates toward gob. At the same time, gob is the discharge field of the shallow groundwater in the area. The form and dynamic variation of groundwater change, resulting in the change of the conversion relation and converted volume of “three waters” in natural conditions.
  - With the water drainage of mines and the conversion of horizontal runoff and discharge of Quaternary loose aquifer into vertical seepage, groundwater level drops, and spring flow reduces.

2. Assessment of water resources in the study area

- Surface water consists mainly of the main stream of Ulan Mulun River, the average annual volume of runoff in many years in the drainage basin section of

Ulan Mulun River is approximately 117,000,000 m^3, but very unevenly distributed in time, mainly concentrated in frost-free period March and rainy seasons July, August, and September, the volume of runoff of these four months accounts for approximately 65 % of the annual total.

- For the assessment of groundwater resources, water balance is studied by selecting 2004 with 50 % rainfall guarantee rate. The calculation results show that the total recharge is 80,797,600 m^3 in the whole balance area during the balance period, the total discharge is 82,294,400 m^3, and in 2004, the balance is negative; groundwater storage volume is decreased by 1,496,800 m^3. The total calculated water resources in the study area are 130,640,000 m^3.
- The static water storage volume of groundwater in three water source places, i.e., Kaokaolagou, Halagou, and Liugengou, is, respectively, 1.05×10^8 m^3, 1.13×10^7 m^3, and 1.72×10^7 m^3, and the annual rainfall recharge is, respectively, 7.37×10^6 m^3/a, 3.79×10^6 m^3/a, and 2.98×10^6 m^3/a.
- Statistics and analysis of future water supply engineering in the study area were carried out, then future water demand and water supply were predicted, and on this basis, future water supply and demand balance of the study area were analyzed and studied, thus providing decision-making basis for the planning and macroadjustment and control of water resources.
- GM (1, 1) model was used to predict the water demand during the planned period in the study area. From the prediction results, it can be known that different water demands show the trend of yearly increase. The tap water demand increases from 30,600 m^3/day in 2006 to 54,203 m^3/day in 2020, increasing 23,603 m^3/day. Industrial reused water consumption increases from 18,007 m^3/day in 2006 to 31,062 m^3/day in 2020, increasing 13,055 m^3/day. The total water demand in the study area increases from 48,607 m^3/day in 2006 to 85,265 m^3/day in 2020, increasing 36,658 m^3/day.
- In combination with "the Eleventh Five Years Plan" of Shendong Mining area, the water demand during the planning period was analyzed and predicted. The total water supply increases from 70,190 m^3/day in 2006 to 89,290 m^3/day in 2010, increasing 19,100 m^3/day; from 2011 to 2015, the total water supply will be maintained at 87,290 m^3/day; after 2016, the total water supply will be reduced by 3000 m^3/day; in 2020, it will be 84,290 m^3/day. This resulted mainly from the reduced tap water supply capacity. In regard to the percentage of different water supplies, the percentage of tap water supply will be decreased, decreasing from 71 % in 2006 to 56.8 % in 2020, while the percentage of industrial reused water supply will be increased, correspondingly increasing from 29.1 % in 2006 to 43.2 % in 2020. From this, it can be seen that in the future planning period, the utilization ratio of mine water resources will be increased, thus not only easing the imbalance of water supply and demand of water resources, but also saving the capital and improving the economic and social benefits of enterprise.
- Through the analysis of water supply and demand balance during the planning period, it can be known that from 2016 to 2020, the water supply cannot meet the requirement of water demand. The shortage will be 6303 m^3/day in 2020.

The industrial reused water supply from 2006 to 2020 can meet the requirement of water demand.

- According to mine inflow characteristics in different major active mines of Shendong mining area, on the basis of data analysis of historic water inflow and production factors influencing water inflow, the relation curves between historic total annual water inflow and accumulated coal production in different mines were established and the trend line of the relation curves was drawn. The fitting equation of the trend line was used to acquire the mine water inflow corresponding to coal production in future years. Different major mines in Shendong mining area show basically the trend of yearly increase. The total mine inflow increases from 51,324 m^3/day in 2008 to 69,235 m^3/day in 2020.

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Chapter 3
Groundwater System in the Study Area

The research of groundwater is one of the research focuses on hydrogeology, as an inseparable entirety groundwater of the same system has often the same recharge source, close hydraulic connection, and the same time–space evolution process. Water in different systems generally does not have hydraulic connection nor has weak hydraulic connection [1].

3.1 Generalities of Groundwater System

3.1.1 Concept of Groundwater System

Groundwater system is a basic groundwater unit, and it has an assembly of input and output of water yield, water quality, and migration [2].

Abroad with regard to the definition of "groundwater system," there are following sayings: Professor Englund of Free University Amsterdam, Holland, thought that "groundwater system" can be regarded as an organic entity with continuous metabolization of energy of four dimensions in time and space, mainly characterized by the following:

- Mode of boundary type,
- Volume,
- Structure,
- Resistance or transfer capacity of potential energy,
- Outflow system,
- Connection between adjacent systems,
- Mode of water quality type, and
- Development of groundwater system.

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Lall C. Hayes of the Water Resources Department of US Geological Survey thought “the term groundwater system refers to the part of the earth crust from phreatic level to the bottom of fractured zone, it is the place where groundwater occurs and moves, composed of aquifer (as passage for groundwater movement) and enclosing layer (impeding groundwater movement).” In addition, some hydrogeologists think “groundwater system refers to the rock aggregation with some properties, can freely contain and migrate water, and is adjacent to rocks which cannot contain and migrate water.” American scholar Dooye thought in 1967 that the definition of groundwater system is “the real or abstract structure, device, plan or process, input and output of substance, energy, information reflected in definite time and their evolution relation [3].”

Wu Yanqin defines groundwater system as the combination of rock aggregation with certain properties and porous water. This kind of water can migrate freely. This kind of rock aggregation has porosity, permeability, and water-giving property, and is adjacent to impermeable and void-free rock. Such water–rock entirety can reflect the input and output of substance, energy, information, and their evolution relation [4]. Chen Mengxiong [5, 6], senior academician of Chinese Academy of Sciences, thinks that “aquifer system is a group of water-bearing formations with fixed boundary, interconnecting or hydraulically connected, of the same age or different ages. Groundwater flow system refers to the groundwater body composed of flow plane group from source to convergence and having the same time–space evolution. Groundwater system is an intricate unified body of some independent units, controlled by natural and artificial factors, having interconnection and mutual influence of different levels, four dimensional nature in time–space distribution and individual features, continuous movement and evolution.” This unified body has following characteristics [7, 8]:

- Groundwater system is composed of independent but interconnected and mutually influenced subsystems or secondary systems of different levels.
- Groundwater system is a component of hydrological system, closely related to rainfall and surface water system, converting each other. The evolution of groundwater system is controlled to a great extent by input and output system of surface water.
- Each groundwater system has its individual features and evolution law, including its individual aquifer system, water circulation system, hydrodynamic system, and hydrochemical system.
- Aquifer system and groundwater system represent two different concepts: The former has fixed boundary, while the boundary of the latter is free and variable.
- Time–space distribution and evolution law of groundwater system are controlled by natural conditions and changed due to the influence of social environments, particularly human activities.

3.1.2 Characteristics of Groundwater System

3.1.2.1 Hierarchy of Groundwater System

Groundwater system is composed of three parts: geological body, input system, and output system. Each part consists of many components, and each component includes some smaller factors. These components and factors are called subsystem. A groundwater system may have some subsystems of lower level. The subsystems of lower level belong to and support the subsystems of higher level or systems. The ordered structure of the relative size of groundwater system is called hierarchical structure, reflecting that groundwater system is composed of substance of different size and various levels. A groundwater system may have shallow groundwater subsystem, medium deep groundwater subsystem, and deep groundwater subsystem. Each subsystem may include subsystem of lower level and is independent but interconnected and mutual influenced. The change of status of a subsystem induces certainly the change of status of adjacent subsystem.

3.1.2.2 Integrality and Unity of Groundwater System

Groundwater system is composed of some subsystems. The subsystems have their individual composition characteristics and behavior mode, but they must be unified and coordinated in the integrality of groundwater system, and take the optimal integral function of groundwater system as criterion rather than search for the optimal function of a subsystem.

The integrality of groundwater aqueous system is manifested its unified hydraulic connection: Water existing in the same water-bearing system is a unified integrality, and recharge and discharge at any part of water-bearing system influence the whole water-bearing system. That is to say, water-bearing system responds to the external stimulation. Therefore, water-bearing system is an independent and unified unit of water balance and may be used to study water yield balance even salinity balance and heat balance.

The integrality of groundwater flow system is manifested in its unified flow, along the direction of flow, salinity, heat, and water yield that revolves regularly, showing unified ordered structure in time and space. Therefore, the flow system is the ideal frame and tool to study the time–space evolution of water yield and water quality.

The factors outside groundwater system and having important influence on groundwater system are called environments of groundwater system. On the one hand, environments input substance, energy and information, accept the output of the system, and maintain the movement and continuous renewal of the system. On the other hand, the action of environments influences the structure, ordering, and function of groundwater system.

3.1.3 Theoretic Basis for Water Resources Assessment of Groundwater System

Groundwater system has often the following characteristics:

- Stability—for example, when a small disturbance is applied to a groundwater system (for instance, pumping of single well), the status of the system changes immediately (for instance, inducing cone of depression). But once the disturbance is removed, after certain time, the system is recovered to its original status, which can be expressed quantitatively.
- Controllability (observability)—if water level does not continue to drop, it can be controlled through pumping less and stop pumping, and the change of water level of the system can be observed.
- Sensibility—when a model is used to simulate a groundwater system, if the parameters are improperly recognized, the simulation results will induce big deviation.

The theoretic basis for the assessment of sustainable exploitation and utilization of groundwater resources roots in the systematic analysis. The systematic analysis occurred at the end of the 1940s and is known by the word due to highly effective work of Rand Corporation USA [9]. The systematic analysis is an assistive technology for decision making. It uses systematic method to put forward different feasible plans and strategies with regard to a studied problem, and to conduct qualitative and quantitative analysis, evaluation, and coordination to help decision maker to improve the clearness of understanding the studied problem, so that the decision maker chooses action plan [10]. Generally, the steps of the systematic analysis are as follows:

- Identify problems and determine the objectives;
- Collect data, explore the feasible plan;
- Set up model;
- Assess comprehensively; and
- Check and verify.

The systematic is a scientific method for decision making, while decision making is an important part of management activity. Management activity is composed of the repeated activities of decision making—implementation activity of decision—feedback—make decision again. Thus, good and bad decisions decide directly success or failure of management activity. From this, it can be seen that the groundwater management cannot do without the systematic analysis. The systematic analysis here referred to is completely different from that some people call the description of aquifer as systematic analysis of groundwater system [11, 12].

The flowchart of the systematic analysis of groundwater system is shown in Fig. 3.1. One of the major objectives of groundwater development is to provide water sources for industrial, agricultural, and urban domestic water. In order to

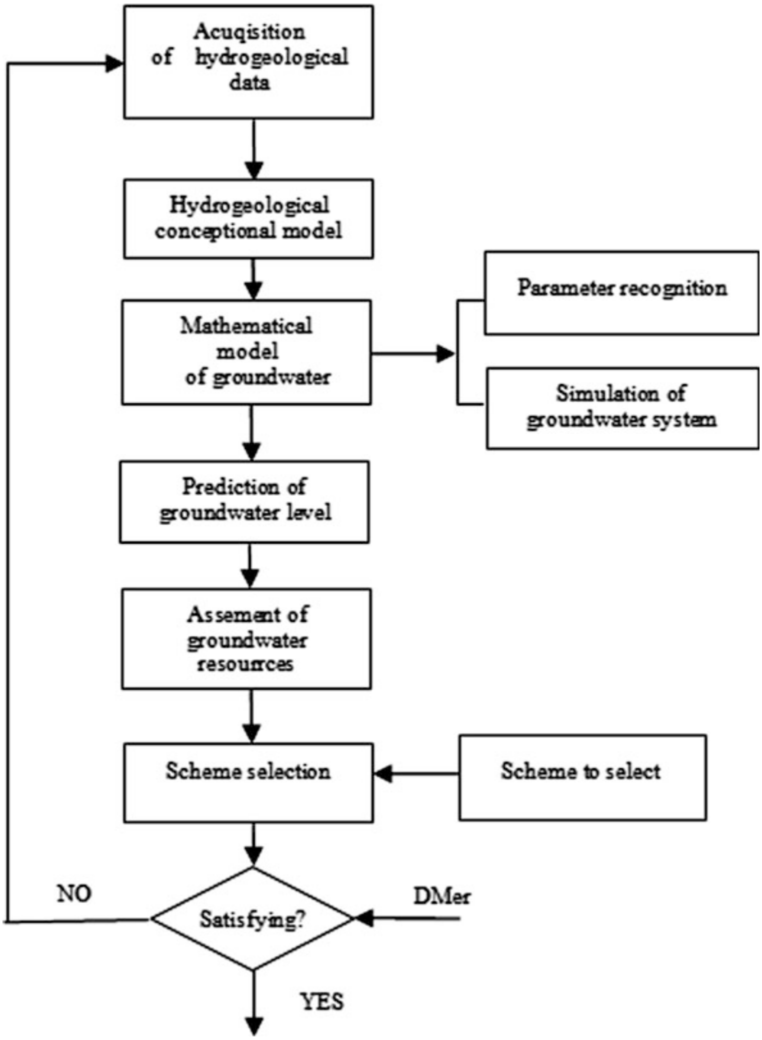

Fig. 3.1 Flowchart of groundwater system analysis

manage scientifically and reasonably groundwater resources, it is necessary to conduct in time and space the comprehensive assessment of the sustainable development and utilization of groundwater resources. The comprehensive assessment of the sustainable development and utilization of groundwater resources is to conduct overall scientific analysis and estimation in the aspects of the quantity, quality, characteristics of time–space distribution, environment and utilization conditions, social and economic benefit, and environmental impact of the water resources of a system [13].”

If we want to conduct comprehensive assessment of the sustainable development and utilization of the groundwater in a system, on the basis of collection of different hydrogeological data, first we must conduct necessary depiction of its hydrogeological conditions; that is, we set up the hydrogeological conceptual model. Then on the basis of this, we set up the mathematical model which can describe accurately or approximately the characteristics of flow movement of the system and solve it. Assessment and management of groundwater resources by using numerical method are carried out usually in two stages. The first stage is to solve inverse problem, i.e., to recognize the parameters of the model. The second stage is to solve direct problem and to conduct assessment and management of groundwater resources. The assessment of groundwater resources in general refers to the exploited quantity of groundwater. Through the assessment and the study of groundwater resources, the feasible ordered scheme set can be output for decision maker to choose. If the decision maker is unsatisfactory to the output assessment information, it is necessary to conduct further analysis and feedback on the results until the output scheme is satisfactory.

3.2 Analysis of Groundwater System and Hydrogeological Conditions

3.2.1 Generalities of Aquifer System Conditions

According to the previous exploration data and results of supplement drilling in the study area, the groundwater in the area is mainly porous phreatic water in Quaternary loose deposit and fracture water in Mesozoic clastic rocks. According to the combination of lithofacies paleogeography and lithological characteristics of different aquifers, the aquifers in the study area are divided into six water-bearing formations, Shalawusu Formation, and the burnt rocks are two major aquifers in Shendong mining area.

The characteristics and the distribution scope of aquifers are shown in Table 3.1.

According to “Hydrogeological Manual” and the characteristics of aquifers in Shendong mining area, the watery property of aquifers in the area is divided into three levels, i.e., strongly watery, medium watery, and weakly watery. The division standards are shown in Table 3.2.

3.2.1.1 Hydrogeological Characteristics of Shalawusu Formation

Shalawusu Formation was formed in Pleistocene and is a set of river and lake deposit, loose, uncemented. Lithologically, it is main fine sand and medium sand.

Table 3.1 The characteristics and distribution of aquifers in the study area

Type	Aquifer	Lithology	Distribution
Porous phreatic aquifer in Quaternary loose deposit	Holocene alluvial phreatic aquifer	Yellow fine sand in the upper, medium, fine sand, and gravel and pebble layers in the middle and the lower	Flood land composed of debris of Ulan Mulun River, Beiniuchuan, and relatively large tributaries, terrace of first and second levels, distributed in stripe, variable in width, 200–500 m, about 5.65–12.45 m thick
	Phreatic aquifer in upper Pleistocene Shalawusu Formation	Tawny fine sand with sludge lenses in the upper, medium, coarse sand in the lower, locally high gravel content, and mostly sand and gravel layer in the bottom. Loose in structure, apt to be recharged by rainfall, in depressions and river channel composed of underlying loess aquiclude (or bedrock), forming local water-rich section	Mainly distributed in spring field such as Kaokaolaigou, Liugengou, Halagou, and Gongnieergaigou, also distributed in other valleys, mostly overlaid by eolian deposit. The layer is alluvial and lacustrine deposit, distributed in stripe and sheet, generally 10–30 m thick. Relatively strongly watery
	Lower Pleistocene sand and gravel aquifer	Brown yellow silty fine sand, medium, and fine sand in the upper, salt and pepper pebble and gravel layer with medium and coarse sand in the middle and the lower, gravel diameter 2–300 mm. Components are quartz, chert and volcanic rock. Generally sorted, cemented to semicemented	Discontinuously distributed in the study area
Fracture aquifer of Mesozoic clastic rocks	Fracture phreatic aquifer in Middle Jurassic Zhiluo Formation	Composed of a set of yellow green, grayish yellow medium coarse sandstone, silty fine sandstone and mudstone, strongly weathered, fractures developed	Widely distributed in the study area, about 15–20 m thick, weakly watery
	Confined aquifer in Middle and Lower Jurassic Yan'an Formation	Coal-bearing strata, interbed of medium coarse sandstone, fine sandstone, siltstone. Fine sandstone and coarse sandstone are argillaceously or calcareously cemented.	Widely distributed, about 90–250 m thick, aquicludes and aquifers occur alternately. Poor vertical recharge. Weakly watery

(continued)

Table 3.1 (continued)

Type	Aquifer	Lithology	Distribution
		Bedding plan fractures and intergranular pores are developed. Fracture confined water	
	Void and fracture aquifer of burnt rock	Burnt rock is resulted from spontaneous combustion of coal seams, and surrounding rock was heated and deformed due to spontaneous combustion of coal seams. Brittle, hard. Rock broken. Fractures and voids developed. Fractures are 3–50 mm wide. Fracture rate 7–31 %. Good connectivity among fractures and voids	Mostly distributed as stripes in valleys such as Muhegou, Shanggou, and Hlagou. About 50–100 m wide, about 20–50 m thick. Strongly watery

Table 3.2 Division standards of aquifer watery property

Watery level	Strongly watery	Medium watery	Weakly watery
Water inflow of single well (m^3/d)	>800	100–800	<100

It is yellow brown silty fine sand with sludge lenses in the upper section and medium coarse sand in the lower section. The bottom has high gravel content in local sections and is a sand and gravel layer. It has horizontal and diagonal bedding and is loose and well-sorted. In the center of paleo-groove and low-lying place, the deposit is the thickest, thinning progressively toward two sides. Some pinched out at drainage divide. Generally, it is 10–30 m thick. The depth of water level of aquifer is shallow, approximately 3–9 m. The permeability coefficient is generally 0.88–17.5 m/d. The water inflow of single well is mostly 1000 m^3/d. It is mainly recharged by rainfall. Under the control of topographic and geomorphologic conditions, the natural flow field runs from high relief to ravine and the flow direction is consistent with land slope and has diversity, while it is controlled by regional landform at deep part. The flow direction is consistent with landform slope and has diversity, but at deep part is controlled by regional landform. The water is discharged to ravine in form of depression spring, locally flows off from Shalawusu Formation or the burnt rocks, and the two latters have close hydraulic connection. It is mainly distributed in spring fields such as Muhegou, Liugengou, Halagou, Gongnieergaigopu and other ravines. The most part is overlaid by eolian deposit. The layer is alluvial and lacustrine deposit, so often occurs as stripe or sheet, and is strongly watery.

3.2.1.2 Hydrogeological Characteristics of the Burnt Rock

The burnt rock is red and gray white rock masse collapsed and deformed under fritting action of different degrees in overlying formation during spontaneous combustion of coal. The fritting and destruction degrees depend on the distance of roof rocks to the spontaneously burnt seam and the thickness of seam.

In section, the burnt rocks may be divided into three zones:

- Quasi-melted rock zone: roof of the spontaneous burning seam. Because it is near the fir source, plastic and rheological deformation occurs in rock. This "quasi-melting" variation produces residuals such as slag. The burnt rock is in parti-color such as violet gray and blue gray, porous, rough on surface, irregular in shape, hard, and 1–3 m thick.
- Sintered rock zone: above quasi-melted rock. Because of strong baking, the formation is purplish red, brick red, and locally white, there is no plastic deformation or a little of plastic deformation, and the texture and the structure of rock are changed slightly. The hardness is high. Fractures are developed, and the opening is good. It is 10–30 m thick.
- Baked rock zone: above sintered rock, far from the spontaneous burning seam. The zone is light red and has clear bedding, and the hardness increases slightly. Fractures are mainly closed. It is approximately 20 m thick.

The actual observation indicates that the thickness and distribution of zones are relatively complex, but in most section, the third zone is predominant.

The watery property of water-bearing zone of the burnt rocks in the area is controlled by monoclinal structures and fluctuating fold structures in the floor, and has evident zoning. The size and watery properties of different subareas are different. The storage capacity of groundwater is variable. When extinction boundary is located at the pitch side of formation, the monoclinal structural water storage zone of the burnt rocks is formed; conversely, the water discharge structure is formed. If there exists low-lying basin structure in the floor of the burnt rock area, then the basin-shaped structural water-bearing area of the burnt rocks is formed. Often, these two states exist simultaneously, that is, the case at working face #205 in Huojitu mine.

Fracture, voids, and pores are developed in the burnt rocks. Fractures are 3–50 mm wide. Fracture ratio is 7–31 %. The connectivity is good among fractures, pores, and voids. In the study area, it is mostly distributed as stripe in ravine, for example, in Muhegou, Shanggou, and Halagou, approximately 50–100 m wide, approximately 20–50 m thick, and strongly watery.

3.2.1.3 Hydrogeological Characteristics of the Flood Land and Terrace of Ulan Mulun River

Flood plain

Lithologically, Quaternary alluvial sand is in the upper, sand and gravel in the lower, poorly sorted. Fine sand and mud sand filling resulted in poor permeability. The permeability coefficient of the aquifer is 5–10 m/d, the specific yield is 0.1–0.15, and the radius of influence is 60–100 m. Under natural conditions, the major recharge sources are lateral runoff of groundwater, rainfall, and infiltration of surface water during flood period. Under mining conditions, natural recharge may be increased, seepage of surface water may be identified, and evaporation is reduced. The watery property is medium.

The flood plain of Ulan Mulun River is unsuitable to be used as a concentrated water supply source. But according to the characteristics of flood plain, actual investigation, and study, there exist some temporary water-intaking points with certain exploitation potential in the flood plain. Examples of these flood plains include Shigetai river island located from the mouth of Shigetaigou to the mouth of Huhewusugou with a dimension of approximately 4 km long and maximum 450 m wide, flood plain at the mouth of Buliangou, Ulan Mulun flood plain located at 500 m to the south of the mouth of Buliangou, flood plain at the mouth of Huhewusugou, and Ulan Mulun flood plain at the downstream of the mouth of Huhewusugou.

Terrace

(a) **Terrace of the first order**

The terrace of the first order of Ulan Mulun River is distributed from the flood control dam to the eastern boundary of Bulian mine, locally absent; the face width of the terrace is 0–550 m; the deposit is 10.69–15.02 m thick; the thickness of the aquifer is 3–8 m; the water inflow of single well is more than 1000 m^3/d; the permeability coefficient is 3–10 m/d. It is strongly watery.

(b) **Terrace of the second order**

The terrace of the second order of Ulan Mulun River is distributed in the band from the railway to Songma highway; the face width of the terrace is 70–80, 10–15 m higher than the terrace of the first order; the front gradient is 25–40°; the elevation is 1, 120–1, 140 m; the thickness of deposit is up to 40 m. In the upper, siltstone is predominant and intercalated with thin coarse sand, pebble layer in the middle. The aquifer is 16–18 m thick. The permeability coefficient is 10–19.6 m/d, and the specific yield is 0.15, strongly watery. The water yield is relatively abundant. The water inflow of single well is 100–150 m^3/d. It is a medium watery aquifer.

(c) **Terrace of the third order**

It is located at the west side of Songma highway, and the face width of the terrace is 80–150, 6 m higher than the terrace of the second order. The elevation of terrace surface is 1, 140–1, 160 m. The deposit is 20 m thick. Exposed by boreholes, in the lower, it is gravel layer, nearly 3 m thick.

The aquifer is 6.05 m thick. The permeability coefficient is 4.3–10 m/d. It is weakly watery.

(d) **Terrace of the fourth order**

It is distributed to the west of the terrace of the third order. The surface is overlaid by eolian sand. The face width of the terrace is 60–150 m. The deposit is 36–40 m thick. The upper section is massive loess, while the lower section consists of a pebble layer of 0.25–1.3 m thick. Loess has developed vertical joints, pores, and voids, and constitutes together with bottom gravel a unified phreatic aquifer. The aquifer is 2–6 m thick. The water inflow of single well is generally smaller than 50 m^3/d. It is weakly watery.

3.2.2 Hydrogeological Characteristics of Major Water Source Sites

3.2.2.1 Division of Water Sources in the Study Area

The reason to divide the major spring fields at the east bank of Ulan Mulun River into water sources is as follows: Topographically, the spring field area is an independent small basin and its periphery is surface watershed composed of weakly water-bearing bedrock or loess, forming the basically consistent water-isolating boundaries of surface and underground watershed, having individual independent recharge, runoff, and discharge conditions, constituting a relatively complete hydrogeological unit. These spring fields have relatively thick loose deposit and are favorable to rainfall recharge and occurrence, forming water-rich section in the area. The area of different spring fields is generally approximately 14–100 km^2. The major aquifers are silty fine sand and medium fine sand of Shalawusu Formation and sand gravel layer of Lower Pleistocene Sanmen Formation, overlaid by eolian sand. Generally, it is difficult for rainfall to form large surface runoff, but favorable to be recharged by rainfall infiltration. Infiltrated groundwater is converged from the periphery of spring fields to the center. Because Shalawusu Formation is well-sorted and structurally loose, groundwater runoff is unimpeded. Therefore, with regard to the area, the major spring fields at the two sides of Ulan Mulun River can be used as ideal water sources for the development of the mining area.

Water supply sources in the study area are mainly distributed in the major spring fields at the east bank of Ulan Mulun River, i.e., Gongnieergaigou, Kaokaolagou, Halagou, and Liugengou.

3.2.2.2 Water Sources in Gongnieergaigou

Gongnieergaigou is the first-order tributary of Ulan Mulun River. The area of the spring field is 69.8 km^2. It is located at the margin of Mu Us Desert, a plateau subject to long-term erosion, and its landform is rolls and swells. Gongniergaigou is originated from Hushigou at the junction of Ejin Horo Banner and Dongshen City, 29.5 km long, and its flow is stable, the measured annual average flow is 0.264 m^3/s at a downstream monitoring station. The recharge source of groundwater of the spring field is mainly rainfall infiltration. Groundwater runs from the periphery of watershed to Gongnieergaigou, downstream hydraulic gradient is 6 ‰ on the average, without exception, and groundwater is discharged in the form of spring and spring group.

3.2.2.3 Water Source in Kaokaolagou

Kaokaolagou spring field is located at the east bank of Ulan Mulun River, the water catchment area is 97.44 km^2, and the average spring flow in many years is 0.185 m^3/s. There are Kaokaolagou spring water discharge zone and Shigetaigou spring water discharge zone. The springs are of type of complete discharge.

The topographic features in the spring field are relatively simple. Around the spring field, there are scattered bedrock hills, occurring in round shape, long beam, forming watershed of spring fields. Inside the field, a large area is eolian desert. Active sand dunes occur in form of crescent, fixed, and semifixed dunes are in elliptical form, form of steamed bread and mount. Because eolian sand invades the depressions of lacustrine deposit, the area of a part of depressions decreases year by year, and some lakes are completely filled with eolian sand, for example, in Zhangjiahaizi lake. Loess landform is seen only in Shigetaigou.

Kaokaolaigou extends in northeast–southwest direction, 8800 m long and 60–100 m wide. The slope gradient of the ravine is 11.8 ‰. The west bank of the north of the ravine is eroded. The ravine wall is relatively steep, mostly between 40 and 70°. The first-order terrace is 0.81–1.0 m higher than the water surface. The slope of the front edge is 60–80°. The upstream terrace face is relatively flat, 30–60 m wide. The trailing edge is mostly overlaid by eolian sand. The middle stream and downstream terrace face is slightly inclined to the ravine. The slope is 2–3°. It is 50–100 m wide. It is mostly reclaimed as farmland, crops grow flourishingly.

Inside the spring field, Mesozoic Jurassic Yan'an Formation and Zhiluo Formation are relatively developed. Cenozoic formation is distributed vastly, varies a lot in thickness, consists mainly of Middle Pleistocene loess derived from rock, Upper Pleistocene Shalawusu Formation, and Holocene lacustrine deposit, alluvial deposit, and eolian deposit.

The aquifers are mainly the fine sand, silty fine sand layers of Upper Pleistocene Shalawusu Formation, phreatic aquifer of Holocene eolian, and alluvial fine sand as well as silty fine sand. The aquifer in Shalawusu Formation varies a lot in thickness, with several low-lying sections as center thinning progressively outward. It aquifer is generally 10–15 m thick with the maximum thickness up to 61.51 m. Lithologically, the aquifers are loose, pores are developed, the permeability is good, the permeability coefficient is 10–19.56 m/d, and the specific yield is 0.15, strongly watery. Secondly, it is the aquifer of Jurassic clastic rocks. Because the joints and fractures are not developed, it is poorly watery. According to the pumping test results of civilian wells, the water inflow of single well is generally less than 50 m^3/d.

The major recharge source of groundwater in the spring field is mainly rainfall infiltration. Because in the spring field the periphery is high, the center is low, the topographic slope is gentle, ravine is not developed, the surface is mostly overlaid by eolian sand layer, and underlying Upper Pleistocene Shalawusu Formation has good permeability and large water storage volume, it is in favor of rainfall infiltration, and even during the concentrated rainfall season (July, August and September) and intense rainfall, runoff rarely occurs on the ground surface. The vertical recharge modulus is 199, 900 $m^3/a\ km^2$.

Groundwater runs and gathers from the north to the south, from the east and west sides to the center. In the intermediate zone of the north of the spring field, the topographic slope is gentle and the hydraulic gradient is small, generally 4.5 ‰. In the south and peripheral section, particularly near the downstream of Kaokaolagou, the hydraulic gradient is big, generally 13.30–15 ‰.

Groundwater is discharged mainly by springs, secondly by vertical evaporation. In some low-lying sections of the center of the spring field, many small lakes and marsh wetlands are formed. Because the burial depth of groundwater level is extremely shallow, evaporation discharge is intense.

The chemical type of groundwater is simple, mainly of heavy calcium carbonate type and locally heavy calcium carbonate magnesium type.

3.2.2.4 Halagou Water Source

Halagou spring field is located at 8 km to the northeast of Daliuta Town at the east bank of Ulan Mulun River. Its boundary is basically consistent with the surface watershed. Its water-gathering area is approximately 36.5 km^2. Its annual average spring flow for many years is 0.07 m^3/s. The springs are of complete discharge type.

The geomorphic features in the field are relatively simple. The periphery is watershed constituted by loess ridges and bedrock monadnock. Inside the field, it is the beach land composed of Upper Pleistocene Shalawusu Formation, overlaid by eolian sand. Extending from the Haojiahao ridge to the beach land of the spring field, the beach land is divided into two parts, the east part and the west part. Its elevation is 1310–1200 m. It is inclined from the northeast toward the southwest. In most beach land, there are fixed and semifixed sand dunes in the form of ridge, wave, and crescent. In the spring field, ravines are not developed. Halagou is the only ravine, approximately 6.5 km long. In the ravine, first-order terrace is developed locally. The spring water in Halagou comes together from springs in east and west tributaries. Halagou is the base level of erosion in the spring field.

In Mesozoic in the spring field, they are only Lower Jurassic Yan'an Formation and Middle Jurassic Zhiluo Formation, occurring scattered. Cenozoic is widely distributed, but varies a lot in thickness. There are mainly Middle Pleistocene loess derived from rock, Upper Pleistocene Shalawusu Formation, and Holocene alluvial layer and eolian deposit.

In the spring field, the aquifers are mainly fine sand and silty fine sand layers of Quaternary Upper Pleistocene Shalawusu Formation, Holocene alluvial fine sand layer, and argillaceous medium fine sand layer with fine gravel, mainly distributed in east and west paleo-grooves of the beach land and Halagou ravine. The aquifer of Shalawusu Formation varies a lot in thickness, is thin at the edge of the paleo-grooves and thick at the center of paleo-grooves, and is generally 10–25 m thick, strongly watery.

Secondly, it is fracture void water aquifer of Quaternary eolian loess and pore fracture water aquifer of clastic rocks, mainly distributed in watershed zone. Because the exposed part is high, the water holding capacity of the aquifer is low and the watery property is poor.

Halgou spring field is an independent hydrogeological unit with vertical infiltration recharge and horizontal runoff discharge. Groundwater is mainly recharged by rainfall infiltration. The majority of the surface of the spring field is overlaid by eolian sand, very easy to accept rainfall infiltration recharge. During abundant water period, there is basically no surface runoff in beach land, only in slope zone of watershed, because of large slope; and when there is heavy rain or intense rain, there is temporary surface runoff and the runoff flows to the beach land, then infiltrates to the underground, recharging groundwater. The groundwater in the spring field runs and gathers from the periphery to the paleo-grooves at the center of the beach land, and is discharged from springs to the ground surface. The groundwater is deeply buried. Vegetation is not developed. Vertical evaporation discharge is very little.

The isotope tritium measurement was conducted on spring water samples and water samples taken from boreholes at the spring field, respectively. The measurement results illustrated that the both are new water recharged by rainfall infiltration.

Because the groundwater is mainly recharged by rainfall infiltration, runoff and discharge conditions are good, so rainfall characteristics influence directly the dynamic change of groundwater. Each year in concentrated rainfall months (July, August, and September), groundwater gets concentrated recharge and the water level rises gradually. The lag phase is generally approximately one month. In dry season, groundwater is discharged and consumed progressively, and the water level drops gradually correspondingly.

In the spring field, groundwater quality is relatively good. The salinity of water is low. It is mainly of heavy calcium carbonate type, locally in small area, heavy calcium carbonate magnesium type, and sodium bicarbonate calcium type.

3.2.2.5 Liugengou Water Source

Liugengou spring field is located to the east of Shigetai Village at the midstream of Ulan Mulun River, and its area is 33.81 km^2. Its annual average flow rate is 0.087 m^3/s. Peripheric bedrock monadnock and loess ridge constitute the watershed of the spring field. The spring field is mostly overlaid by eolian sand. The Upper

Pleistocene Shalawusu Formation constitutes beach land, and inside the beach land, there are depressions of lacustrine deposit of different size. The terrain of the beach land is low and flat. There are perennial water-accumulating ponds in depressions of lacustrine deposit. Liugengou is the only ravine in the spring field, 4.5 km long. Budaihao springs at the ravine head are exposed along the armchair-shaped slope toe. Its geomorphologic morphotype and exposed strata are consistent with Kaokaolagou, so are not repeated here.

Medium fine sand and silty fine sand of Quaternary Shalawusu Formation are major aquifers, and its deposition thickness is controlled by the topography of basement. According to the drilling and geophysical data, there is a paleo-depression in the spring field, maximum 1 km wide, generally 100–400 m wide, and shows the asymmetric form with steep south side and gentle north side, and the sediment layer is up to 55 m in the center of Budaihao beach land and thins gradually toward the periphery, generally 10–40 m thick, strongly watery. Its basement is Jurassic clastic rocks. The fractures are not developed. It may be regarded as relative aquiclude. The fracture, void, and pore water in Quaternary loess, pore, and fracture water-bearing complex in Lower Jurassic clastic rocks are mainly distributed in watershed zone of the spring field and the two sides of the ravine, very poorly watery.

Groundwater is discharged mainly as spring water. Groundwater dynamics are closely related to the recharge, runoff, and discharge. Therefore, the precipitation and the precipitation intensity influence directly the rise and fall of groundwater level and the change of ion concentration in groundwater. Generally, in rainy season, the water level starts to rise; after rainy season, the water level starts to fall, till 4–5 months; and before the rainy season of the next year, the water level drops to its lowest point.

3.2.3 Division and Major Hydrogeological Characteristics of Ground Water System

In order to describe better the characteristics of groundwater flow system in the study area, through the analysis of the formation and the evolution of groundwater, using data on water level at different depth, isotopes, and hydrochemical layering derived from the up-to-date exploration boreholes, the groundwater flow system in the study area is divided into three categories, i.e., local water flow system, intermediate water flow system, and regional water flow system.

The division and the characteristics of groundwater flow system in the study area are shown in Table 3.3.

The boundary type and the nature of groundwater system depend on landform and hydrogeological conditions, and are controlled by the factors such as surface hydrological system and groundwater dynamic system as well as human activities. According to the spatial distribution, the boundary of the groundwater system in the study area can be divided into two categories: lateral boundary and vertical boundary.

Table 3.3 Explanation of the division and the characteristics of groundwater flow system in the study area

First-order system	Subsystem	Alternation degree	Existence area	Aquifer	Recharge source	Water circulation depth	Hydrochemical characteristics
Groundwater Groundwater flow system	Local flow system	Groundwater alternates intensively, renewability is strong	1. Between ridge (platform) and low-lying area (valley depression, pond, marsh wetland)	1. Porous phreatic aquifer of quaternary loose layer	Rainfall	Less than 100 m	pH between 7.52 and 8.32, NO_3^- content 0–30 mg/l, predominant cation Ca^{2+}, 90.5 mg/l on the average, predominant anion HCO_3, 279.8 mg/l on the average, water quality type HCO_3–Ca or HCO_3–Ca·Mg
Groundwater flow system			2. The existence of gob results in the change of recharge, runoff, and discharge conditions of groundwater, forming local flow system in the influencing scope of gob		Mainly sandstone fracture water	About 300 m	Hydrochemical type HCO_3–Ca·Na and $HCO_3 \cdot SO_4$–Ca·Na, with depth, water quality type changed into $SO_4 \cdot Cl$–Na and SO_4–Ca·Mg, water quality type complicated, salinity increases from 290 to 2480 mg/l
			3. Two sides of a part of ravines	3. Burnt rock	Rainfall, phreatic water in Quaternary loose layer	About 100 m	pH 7.7–8.1, salinity 288–474 mg/l, NO_3^- ion 7–24 mg/l, no NO_2 ion. The water quality type of the burnt rock aquifer is mainly HCO_3–Ca

(continued)

Table 3.3 (continued)

First-order system	Subsystem	Alternation degree	Existence area	Aquifer	Recharge source	Water circulation depth	Hydrochemical characteristics
	Intermediate flow system	Relative local flow, active alternating zone, wide influence scope, big depth	Widely distributed in the area	Deeply buried fracture phreatic aquifer of Jurassic Zhiluo Formation	Phreatic water of quaternary loose layer	About 150 m	Water quality of Jurassic aquifer: pH 7.15–8.4, neutral-weak alkaline water, water quality type of a part of water samples is HCO_3–Na, Cl·SO_4 (HCO_3)–Na, Na^+ content in cation is up to 121–459 mg/l
	Regional flow system	Very slow alternation	Widely distributed in the area	Fracture confined aquifer of middle and lower Jurassic Yan’an Formation	Fracture water of Jurassic sandstone and external system	About 300 m	SO_4^{2-} content rises generally is up to 262–1320 mg/l, water quality type SO_4–Ca

3.2.3.1 Lateral Boundary

Lateral boundary refers to the peripheral boundary of the groundwater system in the study area. According to the hydrogeological characteristics and the horizontal hydraulic connection with adjacent groundwater, the lateral boundary may be divided again into water-isolating boundary, lateral discharge boundary, and lateral recharge boundary. The west and the north boundaries are recharge boundaries, and the south and the east boundaries are discharge boundaries.

From the sketch map of the direction of groundwater flow in Ordos Basin (Fig. 3.2), it can be known that in the study area, the groundwater accepts the lateral recharge of groundwater south of Baiyu Mountain surface watershed.

3.2.3.2 Vertical Boundary

Upper boundary: The groundwater in the study area originates in rainfall. Under the influence of natural and artificial activities, various exchanges of water yield, energy, and substance occur in the groundwater, including rainfall infiltration, surface water recharge and discharge, infiltration of return water of agricultural irrigation, spring and mine inflow, and evaporation. It can be regarded as the exchange boundary of substance and energy.

Bottom boundary: The groundwater aquifer in the study area is superimposed on Jurassic coal-forming basin, the underlying Jurassic strata are mainly mudstone and argillaceous limestone, the permeability is poor, and the permeability coefficient is

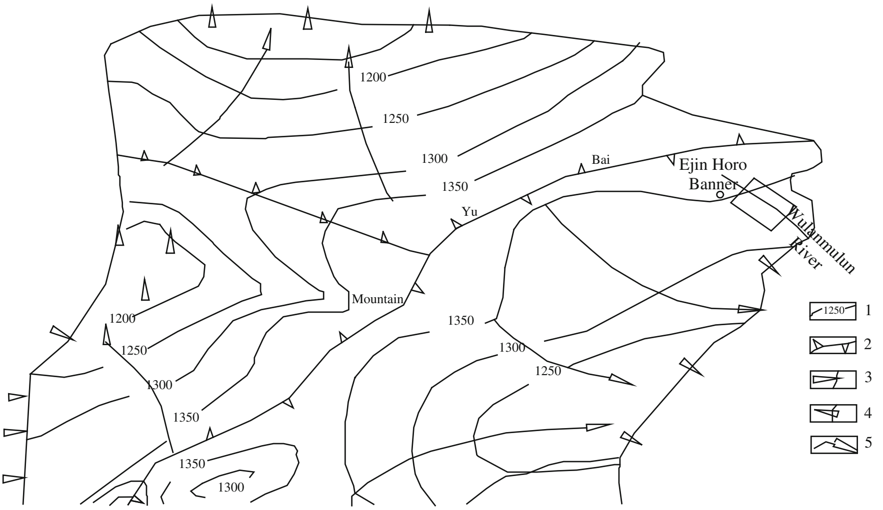

Fig. 3.2 Sketch map of the groundwater system in the north of Ordos Basin. Note: *1* contour of water level; *2* system partition boundary line (surface watershed); *3* water-isolating boundary; *4* lateral recharge boundary; *5* lateral discharge boundary

generally less than 0.05 m/d. In some sections, it is sandstone, because it is well cemented, the sandstone has compact texture and weak permeability, and its permeability coefficient is generally 0.05–0.01 m/d. Compared to Quaternary aquifer, it may be regarded as relative water-isolating boundary.

3.2.3.3 Division of Groundwater System and Subsystem

On the basis of the basic concept of academician Chen Mengxiong on groundwater system, the groundwater of the same system has often the common recharge source and close hydraulic connection as well the same time–space evolution process. Water of different water-bearing systems generally does not have hydraulic connection nor has only weak hydraulic connection. Therefore, the hydraulic connection between water-bearing bodies or the strength of the hydraulic connection must be taken as the basis for groundwater system division.

With regard to the study area of the groundwater system (the influence scope of Ulan Mulun River for the groundwater) in area where the regional area is small, there is no large geological structure, lithology formation is relatively simple, there is big difference in groundwater circulation characteristics, hydrodynamic features and distribution of water-bearing media, and the surface watershed and groundwater watershed are basically consistent, which is regarded as a relative independent and integral groundwater system (first-order system), and its distribution scope is basically consistent with the scope of aquifer.

The groundwater system in the study area is divided by taking the recharge, runoff, and discharge systems (which has the water watershed of Ulan Mulun River drainage basin as boundary) as the key points. The subsystems in the area are divided on the basis of the first-order tributaries of Ulan Mulun River, such as Gongnieergaigou, Huhewusugou, Buliangou, Huojitugou, Zhugaigou, Miaogou, Kaokaolagou, Liugengou, and Halagou which take groundwater watershed as boundary, and have relative independent recharge, runoff and discharge conditions, approximately unified groundwater dynamic field and approximately hydrochemical flow field. But because the specific hydrogeological conditions and the burial and mining conditions of coal resources influence the division of groundwater system in the area, and because of the existence of gob, new discharge points of groundwater have been formed and in the influenced scope, the recharge, runoff, and discharge condition of groundwater have changed.

Inside the system, with the surface water watershed between the first-order tributaries of Ulan Mulun River as boundary, there is obvious relative independence at both sides either in aquifer structure, or in mode of recharge, runoff, discharge of groundwater, and occurrence law, forming 14 groundwater secondary systems (subsystems). The division is shown in Fig. 3.3.

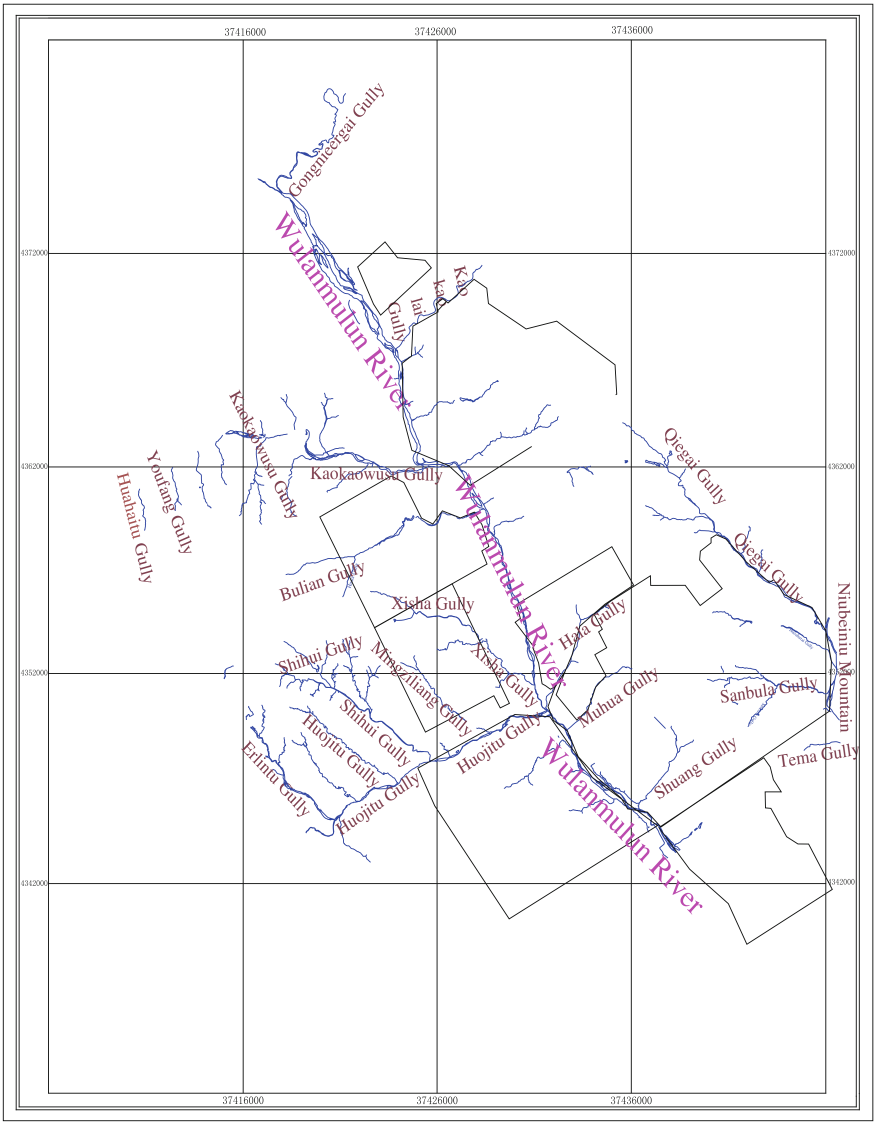

Fig. 3.3 Division of groundwater system in the study area

3.3 Summary

In the study area, the regional area is relatively small, there is no large geological structure, and lithology formation is relatively simple. The difference in groundwater circulation characteristics and features as well as the distribution of water-bearing media is not very big, and the surface water watershed and the groundwater watershed are basically consistent; thus, it is reasonable to take the surface water watershed as the boundary of the subsystems of the study area.

- The scope of the drainage basin of Ulan Mulun River in the study is divided into a first-order groundwater system in the area; the surface water watershed and the groundwater watershed are basically consistent; it is reasonable to take the watershed as boundary; and the groundwater system is divided into 14 subsystems.
- On the basis of the stratigraphic ages of aquifers and their spatial superposition relationship, the groundwater system is divided into two subsystems: subsystem of porous phreatic aquifer of Quaternary loose layer and subsystem of fracture aquifer of Mesozoic clastic rocks. Again on the basis of the combination of lithofacies and paleogeography as well as lithological characteristics of different aquifers, the aquifers are further divided into 6 water-bearing complex systems. Shalawusu Formation and burnt rocks are the major aquifers in the area.
- The groundwater flow system in the study area is divided into three categories, i.e., local flow system, intermediate flow system, and regional flow system.

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Chapter 4
Simulation, Assessment, and Management of the Key Water Source Sites

Aiming at the key water source site—Kaokaolagou spring field, the numeric model of the groundwater flow was set up. The target aquifer is Preatic aquifer of Upper Pleistocene Shalawusu Formation. The target aquifer was the phreatic aquifer of Upper Pleistocene Shalawusu Formation. The influence of mine dewatering on the groundwater system was studied. Secondarily, the water intake mode in the study area is direct water intake from springs. In order to enhance the development and utilization potential of the water source sites of groundwater and to make the full use of the adjustment and storage function of the aquifer, the feasibility and the reliability of conjoint exploitation of wells and springs of the water sources were evaluated.

4.1 Simulation of the Key Water Source Sites of Groundwater System

Kaokalagou spring field is an independent and complete hydrogeological unit, its three sides are watersheds, and only at the boundary bordering Ulan Mulun River, the groundwater is drained as free flow or base flow into the river. It is the largest spring field in the study area. It is located at the east bank of Ulan Mulun River and has a catchment area of 97 km^2, annual average precipitation of 332.1 mm for many years (data of Shigetai Rainfall Station), and annual average spring flow of 185 m^3/s. It is drained into two spring discharge zones, i.e., Kaokalagou and Shigetaigou. The springs are complete discharge springs.

The major aquifer in the area is the phreatic aquifer of Upper Pleistocene Shalawusu Formation. The thickness of the aquifer varies a lot, with several depression sections at the center and thins outside; generally, 10–5 m, and the maximum is up to 61.51 m. The aquifer is lithologically loose, pores developed and

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had good permeability, the permeability coefficient is 10–19.56 m/d, and the specific yield is 0.15.

The major recharge source of groundwater of the spring field is rainfall infiltration. The phreatic water level is strictly controlled by rainfall. Because the periphery of the spring field is high and the center is low, the topographic slope is gentle, and ravine is not developed. The surface is mostly overlaid by eolian sand layer. The underlying Upper Pleistocene Shalawusu Formation has good permeability and large storage volume; thus, it is favorable for rainfall infiltration, even during the concentrated rainfall season (July, August, and September) or heavy rain; there is rarely surface runoff. The vertical recharge modulus is 199,900 $m^3/a\ km^2$.

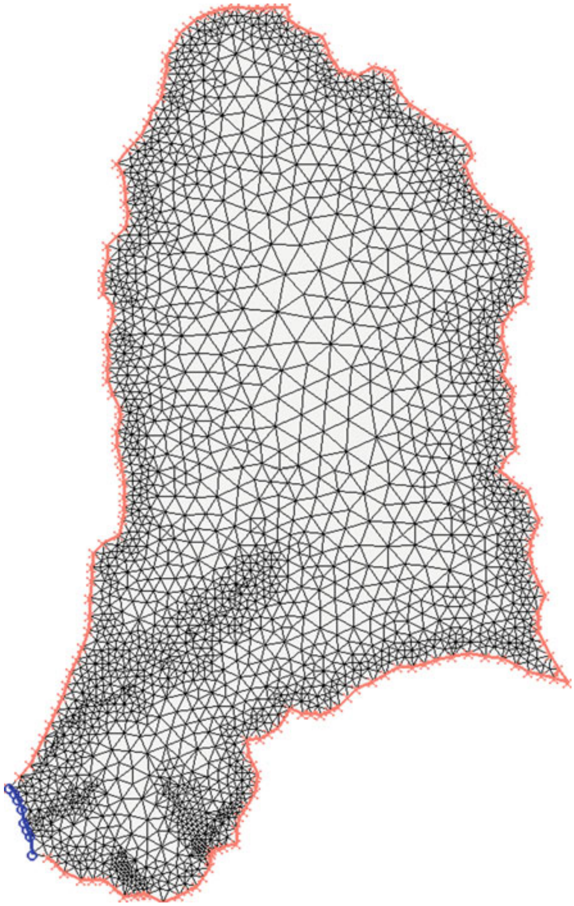
The discharge terms of the study include mainly spring flow, mine inflow, lateral runoff, and evaporation of phreatic water. With the mine development, mine inflow discharge becomes a more and more important drainage way of groundwater. It is necessary to discuss the influence of underground long-term drainage on the regional groundwater system.

4.1.1 Generalization of Hydrogeological Conditions

In the study of the underground flow in the phreatic aquifer of Shalawusu Formation—the key aquifer in Kaokaolagou water source site, horizontally the phreatic aquifer may be approximately regarded as isotropous, and therefore, the groundwater flow system was generalized as heterogeneous isotropous 2D unsteady flow.

The eastern boundary of Kaokaolaigou spring field is the watershed of Ulan Mulun River drainage basin and Beiniuchuan drainage basin, the southern boundary is the watershed of Kaokaolaigou spring field and Liugengou spring field, the northern and the northwestern boundaries are the watershed of Kaokaolaigou spring field and Gongnieergaigou spring field, so the north, east, southeast, and northwest boundaries are all generalized as boundaries with zero flow, and the southwest boundary of Kaokaolaigou spring field is Ulan Mulun River, generalized as flow boundary of second category. The top boundary of the groundwater system is the free water surface of the phreatic aquifer, and through the boundary, vertical water exchange of phreatic water and the groundwater system takes place, e.g., rainfall infiltration recharge and evaporation discharge. Rainfall infiltration is the uppermost recharge way in the area, and therefore, this factor was considered as key point in the model. The base boundary of the groundwater system is weakly permeable bedrock, and in the model, because its permeability coefficient is very small compared to that of Quaternary loose sediment, it can be approximately as water-isolating boundary. The boundary conditions are shown in Fig. 4.1.

Fig. 4.1 Boundary conditions of Kaokaolaigou spring field



4.1.2 Generalization of Mathematic Model

Its mathematic model can be described by the following formula [1]:

$$\begin{cases} \frac{\partial}{\partial x}\left(K(h-B)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K(h-B)\frac{\partial h}{\partial y}\right)+W=\mu\frac{\partial h}{\partial t} & x,y\in\Omega,\ t\geq 0\\ h(x,y,t)|_{t=0}=h_0(x,y) & x,y\in\Omega,\ t\geq 0\\ K\frac{\partial h}{\partial\vec{n}}|_{\Gamma_1}=q(x,y,t) & x,y\in\Gamma_1,\ t\geq 0\\ \frac{\partial h}{\partial\vec{n}}|_{\Gamma_2}=0 & x,y\in\Gamma_2,\ t\geq 0 \end{cases}$$

where

Ω	seepage area
h	water level elevation of aquifer (m)
B	elevation of aquifer floor

K	permeability coefficient (m/d)
W	storage coefficient of aquifer below the free surface (1/m)
μ	gravitational specific yield of aquifer on phreatic water surface
$h_0\ (x, y)$	Initial water level distribution of aquifer (m)
Γ_1	lateral flow boundary of the seepage area
Γ_2	zero flow boundary of lateral watershed of the seepage area
$\vec{n}$	normal direction of the boundary surface
$q\ (x, y, t)$	unit discharge of the lateral boundary (m^2/dm); inflow is positive, outflow is negative, and water-isolating boundary is zero.

The area of the study area is approximately 97.56 km^2, following the subdivision principle corresponding to finite element principle, and the triangular mesh subdivision was conducted for the study area. On this basis, the zero flow boundary and water head boundary of the peripheric watershed, the flow boundary of Kaokaolaigou and Shigetaigou, the discharge zone of water-gushing area were subdivided with dense mesh. The subdivision results are shown in Fig. 4.2. The study area was subdivided into 4992 node points and 4782 triangular units, and there was a node point in approximately 0.019 km^2.

4.1.3 Definite Condition

4.1.3.1 Selection of Simulation Period

In consideration of the fullness and the accuracy of groundwater investigation data as well as the representativeness of rainfall year, July 2006–June 2007 was selected as simulation period.

4.1.3.2 Initial Condition

The distribution of initial water head is the indispensable condition for numeric simulation of unsteady flow of groundwater. Usually, the water level in observation boreholes of certain number is used to get the initial water head value at different node points through interpolation. However, the extent of the study area is relatively large, there were few observation boreholes, the horizon where observation boreholes were located was different, and most boreholes were mixed observation boreholes; it was difficult to get the distribution of water head of aquifer through interpolation, thus causing big problem for model.

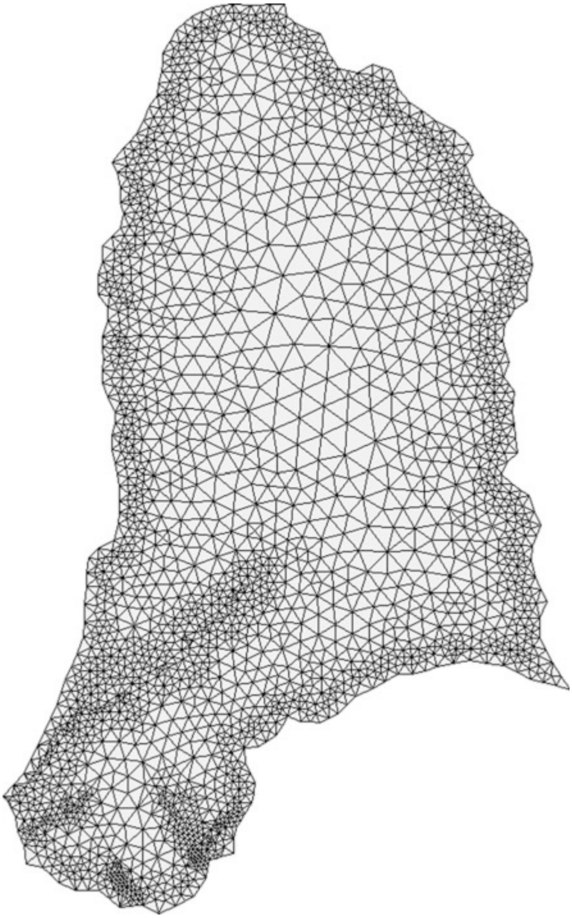
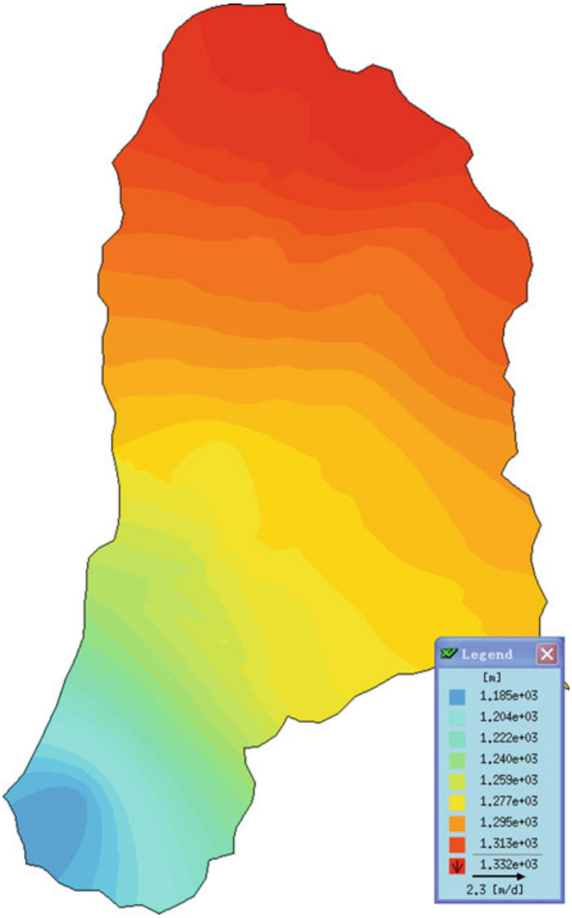


Fig. 4.2 Regional subdivision

Through the analysis of the hydrogeological data of the study area, it can be known that the variation amplitude of water level in the year is not big. So the steady flow was simulated firstly. The annual average of source sink terms was set, mainly including annual average precipitation, exploitation volume, and lateral recharge. Through steady flow simulation, the water level during dynamic balance (i.e., the difference of water balance is zero) was calculated, and then the hydrogeological parameters were preliminarily adjusted, so the calculated water level was overall consistent with the trend of the spatial distribution of phreatic level measured in July 2006 in several observation boreholes in the study area, and this water level was taken as the initial water head of unsteady flow (Fig. 4.3); in this way, the problem that it was difficult to determine the initial water level was relatively reasonably solved.

Fig. 4.3 Initial phreatic water level in the study area



4.1.3.3 Treatment of Source–Sink Terms of Model

The source–sink terms of the model include recharge term and discharge term. The discharge term is mainly rainfall infiltration. The discharge term includes mainly spring flow, mine inflow, and lateral runoff.

Recharge Term

Rainfall infiltration is the major recharge source in the study area. Rainfall infiltration is influenced mainly by surface lithology, burial depth of water level, and other hydrogeological conditions. In the study area, rainfall occurs mainly from June to September, and the rainfall during this period accounts for approximately 80 % of annual total. The rainfall infiltration of different months was calculated on the basis of monthly accumulated rainfall, when the monthly precipitation was less than 10 mm, it was taken as invalid rainfall, and its recharge to groundwater was not considered in calculation. If monthly accumulated rainfall was more than 10 mm, the value obtained from the monthly rainfall multiplied by rainfall infiltration coefficient was taken approximately as the infiltration recharge of the month.

The formula to calculate rainfall infiltration is as follows:

$$Q_{\mathrm{atmospheric}} = \alpha \cdot P \cdot F$$

where

$Q_{\mathrm{atmospheric}}$	rainfall infiltration recharge (m^3/a)
α	rainfall infiltration coefficient; as stated in the above section, the rainfall infiltration coefficient is approximately 0.3
P	rainfall (m) (Table 4.1)
F	area of the calculated area (m^2). According to the statistics, the area of the study area is approximately 97.56 km^2.

Discharge Term

The discharge term of the study area includes mainly spring flow, mine inflow and lateral runoff and evaporation of phreatic water. In most part of the area, the burial depth of groundwater level is more than 10 m, so the evaporation discharge of the phreatic water surface is very small and can be neglected compared to spring discharge and mine inflow.

(a) **Spring flow**

The yearly variation of spring flow in Kaokaolaigou is generally: The spring flow is large during February, latter decreases gradually, reaches the minimum during April, fluctuates during May to September, and increases in October; the second peak occurs and then decreases gradually until to the next spring flood. The characteristics of the spring flow of Shigetaigou are similar to those of Kaokaolagou.

(b) **Lateral runoff**

The calculation of the lateral runoff can be conducted by cutting a section vertical to the groundwater flow direction at the boundary with the lateral runoff and by using Darcy formula:

Table 4.1 Monthly rainfall of Kaokaolaigou during the simulated period (unit mm)

Time	Monthly rainfall	Time	Monthly rainfall
July 2006	85.9	January 2007	7.7
August 2006	53.0	February 2007	3.7
September 2006	24.6	March 2007	3.8
October 2006	9.7	April 2007	4.8
November 2006	8.9	May 2007	17.7
December 2006	2.1	June 2007	30.0

$$Q_{\text{lateral}} = K \cdot I \cdot H \cdot L$$

where

K	average permeability of the aquifer at the section to be calculated; the pumping test results at the cut section are used
I	hydraulic gradient of groundwater at the section to be calculated, taken from the water level contour map
H	average thickness of the aquifer at the section to be calculated
L	length of the section to be calculated.

(c) **Mine inflow**

Mine inflow in the study area occurs mainly at working faces #71101, #71106, transport roadway 71202, and the roadway at the north wing in Shigetai mine. The location and the monthly inflow of different water-gushing zones during the simulated period are shown in Fig. 4.4; Tables 4.2, 4.3, 4.4 and 4.5.

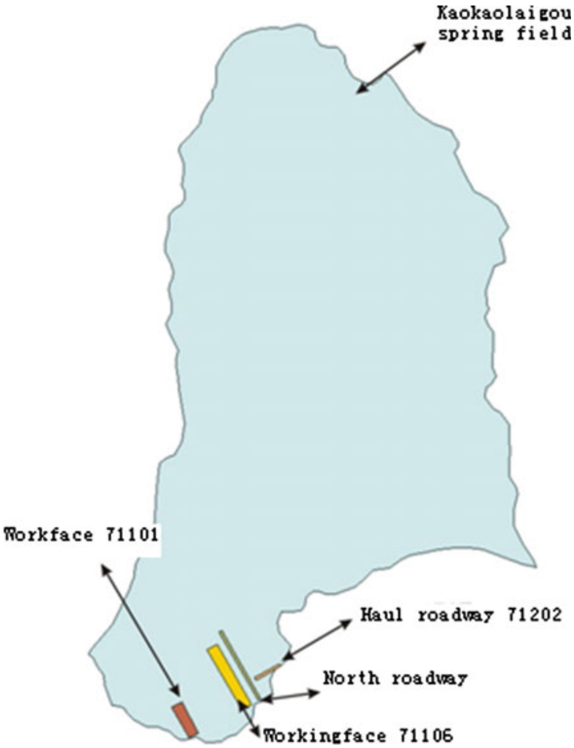


Fig. 4.4 Location of different water-gushing zones in Shigetai mine

Table 4.2 Monthly inflow during the simulated period at the roadway in the north wing of Shigetai mine (unit m^3/h)

Time	Monthly inflow	Time	Monthly inflow
July 2006	10	January 2007	20
August 2006	9	February 2007	30
September 2006	0	March 2007	13.4
October 2006	0	April 2007	13.5
November 2006	27	May 2007	14
December 2006	20	June 2007	10.4

Table 4.3 Monthly inflow at transport roadway 71202 during the simulated period in Shigetai mine (unit m^3/h)

Time	Monthly inflow	Time	Monthly inflow
July 2006	0	January 2007	15
August 2006	3.6	February 2007	15
September 2006	0	March 2007	11.6
October 2006	32.8	April 2007	11.6
November 2006	10	May 2007	10
December 2006	15	June 2007	8.6

Table 4.4 Monthly inflow at the working face 71106 during the simulated period in Shigetai mine (unit m^3/h)

Time	Monthly inflow	Time	Monthly inflow
July 2006	0	January 2007	0
August 2006	10	February 2007	10
September 2006	19.44	March 2007	10
October 2006	21.45	April 2007	15
November 2006	0	May 2007	15
December 2006	0	June 2007	10

Table 4.5 Monthly inflow at the working face #71101 during the simulated period in Shigetai mine (unit m^3/h)

Time	Monthly inflow	Time	Monthly inflow
July 2006	0	January 2007	0
August 2006	20	February 2007	0
September 2006	23.56	March 2007	0
October 2006	0	April 2007	0
November 2006	0	May 2007	0
December 2006	0	June 2007	18

4.1.4 Parameter Inversion

For either saturated flow or unsaturated flow, the corresponding parameters of the groundwater system must be known, so as to predict the movement of subsurface flow or solutes in water by using mathematic model. Determination of parameters of groundwater system is the basis for seepage analysis and critical to whether the analysis is successful and one of the trends of the development of groundwater simulation [2]. But there are few progresses in the research on recognition and estimation of the parameters of groundwater system for long time.

The position of the parameters of groundwater system is decisive for the numeric simulation of groundwater. The uncertainty of parameters in the model will result in the uncertainty of the calculated water head and the flow velocity and influence the reliability of the assessment results of groundwater resources [3]. The major problem for simulation of groundwater flow in saturated zone is still the regional generalization of the heterogeneous parameters. Because the number of exploration boreholes is limited, the obtained parameters of the aquifer are local and cannot be used to generate the parameter distribution of the whole aquifer.

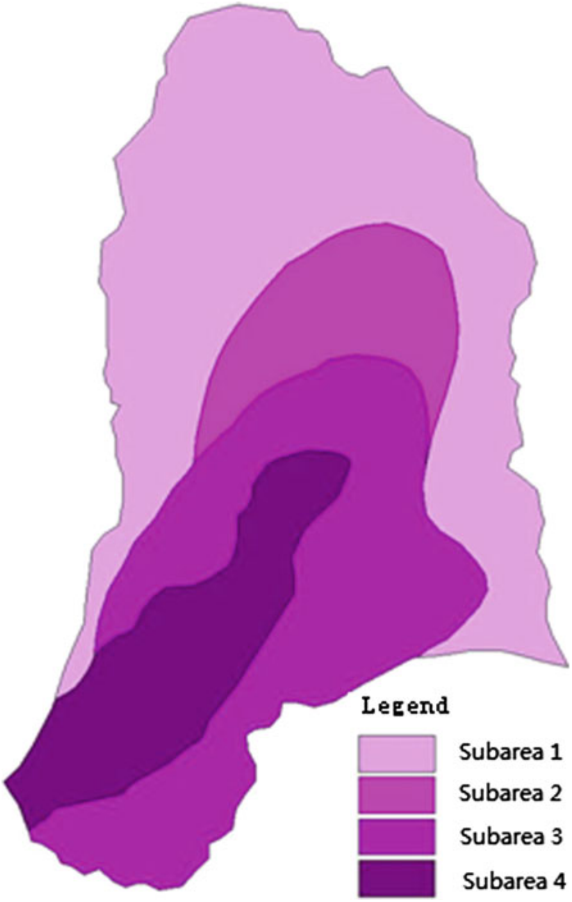
4.1.4.1 Zoning of Hydrogeological Parameters

The hydrogeological parameters are index to characterize the storage capacity, water release capacity of water-bearing media, and the moving capacity of groundwater and are also the basic data for setting up of groundwater simulation model. According to the hydrogeological conditions such as the lithology and zoning of water abundance, through reference to related hydrological reports, Kaokaolagou spring field is divided into 4 subareas of hydrogeological parameters (as shown in Fig. 4.5).

4.1.4.2 Inversion of Hydrogeological Parameters

In order to get the reliable hydrogeological parameters of the aquifers, steady flow pumping test of single well, unsteady flow pumping test of multiple wells, and unsteady flow pumping test of interfering well group were conducted, respectively, in the study area. The hydrogeological parameters of different aquifers where different wells were located, obtained from multiset of pumping tests, may be used as the representative hydrogeological parameters of the aquifers in the subareas where different well were located, and on the basis of this, the groundwater level data measured at the end stage of simulation were used to adjust the hydrogeological parameters. Through the study of the spatial variability of the hydrogeological parameters, the hierarchy structure was used to estimate the influence of the spatial correlative structure of sediments on the permeability and finally to determine the hydrogeological parameters.

Fig. 4.5 Zoning of hydrogeological parameters



The overall correlation of the permeability is expressed by lithofacies percentage, transition probability, and semivariance and covariance function. It can be used to set up the hierarchic spatial random function model with regard to the relation between the permeability and sedimentary structure.

The core of the method is to seek the fitting model of semivariance, covariance, and transition probability of the lower level, to develop the high-level model based on the function of the lower-level model, and to use nested function to fit the lower-level model of semivariance, variance, and transition probability. The least square objective function is used to define the inversion process, and at the same time, some constraining conditions were given. In this way, the model will follow the probability law. Finally, the overall semivariance and covariance model obtained from the estimated parameters can match the field sample model.

The results of the model are also used to check the substitutability assumption related to the lithofacies correlation, particularly the relative importance of autocorrelation and cross-correlation. As regards the overall semivariance model, cross-semivariance cannot be neglected, the cross-covariance is insignificant, and the autocovariance is the most important. Instead of concentric cross-covariance, it is the cross-covariance that reflects the difference of the average between lithofacies.

The overall semivariance or covariance model explains that the permeability structure surpasses the extent of outcrops, and only when the transition probability reflects the percentage, the geometric and parallel mode of lithofacies will surpass the extent of outcrops.

The spatial covariance or semivariance model can be obtained by taking natural logarithm for the permeability, i.e., $Y = \ln(K)$. This model is very important for the development of the macrodiffusion model [4–6]. The method generally used in the research in Boden and Cape Cod military base is through great amount of accurate measurement of the loose sediments (from level 0.01 to level 100) [7, 8]; the acquired data were used to set up a model suitable for the overall autocovariance or auto-semivariance, so as to depict the spatial relation of $[Y(x)\,\text{and}\,Y(x')]$.

If the sedimentary rocks are classified on the basis of the lithofacies types, autocovariance, cross-covariance, and semivariance of samples are made for each lithofacies, respectively, and then all models are combined to form the general model. This kind of model has two advantages:

- It can reveal more deeply how the lithological properties of a lithofacies set influences the overall spatial distribution of the permeability [6, 9–11]. These properties include lithofacies percentage, average and variance of lithofacies extension length at a specific strike, combination form of lithofacies, and spatial correlation between the average variance and $Y(x)$ in a lithofacies.
- Although there are no regional permeability data, on the basis of some known properties of the sediments in the area, the regional spatial correlation can be inferred from this model.

Hierarchical model designed by Ritzi et al. may be applied for the above purpose. The model can be used to connect any amount of units, but the key point herein is at two levels, i.e., lithofacies and lithofacies set, and the autocovariance and the cross-semivariance between N facies may be interrelated to the full semivariance between facies set through the following formula [12–15].

$$\gamma_Y(h) = \sum_{k=1}^{N} \sum_{t=1}^{N} \gamma_{k1}(h) p_k t_{k1}(h) \tag{4.1}$$

The autocovariance and the cross-covariance and the full covariance of the facies set can be expressed by the following formula:

$$C_Y(h) = \sum_{k=1}^{N} \sum_{t=1}^{N} \{C_{k1}(h) + m_k m_1\} p_k t_{k1}(h) - M_\gamma^2 \tag{4.2}$$

In addition, the average, the variance of facies, and the overall average variance of facies set can be expressed by the following formula:

$$M_Y = \sum_{k=1}^{N} p_k m_k \tag{4.3}$$

$$\sigma_Y^2 = \sum_{k=1}^{N} p_k \sigma_k^2 + \sum_{k>1}^{N} \sum_{t>k}^{N} p_k p_t (m_k - m_t)^2 \tag{4.4}$$

where

$\gamma_Y(h)$	is the full covariance between facies
$\gamma_{k1}(h)$	is the autocovariance ($k = i$) or cross-covariance ($k \neq i$)
p_k	is the volume ratio
$t_{k1}(h)$	is the transition probability
$C_Y(h)$	is the full covariance
$C_{k1}(h)$	is the autocovariance ($k = i$) or the cross-covariance ($k \neq i$) m_k and σ_k^2 express, respectively, the average and the variance of $Y(x)$ of facies K m_Y and σ_Y^2 express, respectively, the overall average and the variance.

When characterizing the sediments of sandbar of alternating layer by using these formulae, Ritzi et al. considered the negative correlation between the facies and layer, but neglected the spatial correlative model and did not evaluate the parameters of the model.

In order to solve the fitting functions, measures such as the autocovariance, the cross-covariance, and the transition probability between facies can be taken. For this purpose, it is necessary to use Eqs. (4.1) or (4.2) to conduct estimation through Kriging method used by Rubin in 1995 when analyzing the origin of the macrodiffusion model. The application of Kriging in the fitting function is prone to induce nonnegative matrix in Kriging equation. Some studies have put forward 6 most common and approved models—exponential model, spherical model, Gaussian model, power model, linear model, and cosine function model. The application of some functions may be constrained by analysis dimension, e.g., cosine function. The application condition of Kriging method will not constrain the development of the macrodiffusion model.

It is demonstrated that in the transition probability, the function parameters represent the percentage of lithofacies, geometric features, and lithofacies mode [16, 17]. When the indicative relation can be expressed by summation index function, continuous Markov chain model can be applied. Ritzi [12] indicated that Markov chain model was evolved from the single peak distribution at the combined facies length with the coefficient variable Cv in the binary system. The multimodal distribution of the lithofacies extension length makes probably the transition probability show nested structure, while the function number and types required in this structure are related to the form, the average, and the variance of the lithofacies. The interrelation between the indicative correlation and the facies set length limits the application of the functions. Carle and Fogg [16] pointed out that Gaussian function is not applicable here. And these parameters are constrained by the probability law.

To sum up, geological data (unreliable data and a priori information) may be integrated into the process of setting up the fitting model.

Hoeksema and Kitanidis [18] proposed the estimation of parameters by the maximum likelihood for water space treatment. It is to estimate the spatial covariance structure of the inherent and external random function from the average data of points or space. Samper and Neumann [19] described a cross-verification method. Woodbury and Sudicky [20] adopted the restricted uniline Levenberg–Marquardt method and used exponential function to simulate the experimental semivariance data obtained from the aquifer in Borden military base. Kitanidis [21] discussed the fitting function of the sample variance and covariance model and the evaluation standards probably concerned.

If the application of model function is known, during fitting there should be evaluation standard based on the application. For example, if the model is used in Kriging and point estimation, then the cross-verification may be used, because it has a set of evaluation standards based on the difference of Kriging evaluation and experimental observation. If the model is used in the macrodispersity model obtained from the analysis, the evaluation standards may be based on the difference in the calculated and experimentally observed qualitative spatial moment.

Here, the discussion focuses on the model function and the variability function distinction of variance and transition probability. The least square and Levenberg–Marquardt algorithms are used, and some constraint conditions are added; thus, the transition probability model will follow the probability law.

Nested Structure and Constraint of Transition Probability Model

Firstly, the linear combination function among the semivariance, the variance, and the transition probability is set up:

$$u_{ki}(h) = \sum_{j=1}^{n} w_j u_j(h), \quad (k, i = 1, 2, \ldots, N) \tag{4.5}$$

$$\sum_{j=1}^{n} w_j = 1 \tag{4.6}$$

where w_j is the weight coefficient of jth function $u_j(h)$, when $j = 1$, $u_j(h)$ is an exponential function, when $j = 2$, it is a spherical function, when $j = 3$, it is a linear function, when $j = 4$, it is a cosine function, when $j = 5$, it is power law, and when $j = 6$. It is Gaussian law. N is the number of functions. For the semivariance and variance, $n = 6$. For the transition probability, only the first four functions are definite [12].

To develop the model function through Eq. (4.5) by using the sample data is an inversion problem, and there are many parameters to estimate. For the combination of N facies, it is necessary to apply the nested set of n functions in the semivariance, the variance, and the transition probability of N_2. For each function, there are Np parameters (including the parameters inside the function, such as the structure extent, variance, percentage, or weight). Therefore, $N_2 * n * Np$ parameters are used to estimate the semivariance, the variance, and the transition probability of the functions. In addition, we can apply geological knowledge, reduce n, and Np so as to reduce the number of parameters.

If there is no constraint of other function parameters except for Eq. (4.6), the relationship of linear combination between functions may be set up, and thus, its semivariance, cross-semivariance, and covariance are obtained. With regard to the equation of the transition probability function, there are more constraints. The nested transition probability model must meet the following basic conditions:

$$\sum_{k=1}^{N} p_k = 1, \quad \sum_{k=1}^{N} t_{k1}(h) = 1 \tag{4.7}$$

$$0 \le p_k \le 1, \quad 0 \le t_{k1}(h) \le 1 \tag{4.8}$$

The formula of the basic function of the autotransition probability is different from the formula of the cotransition; for example, the exponential model of the autotransition probability is as follows:

$$t_{kk}(h) = p_k + (1 - p_k)\exp\left(-\frac{3h}{a_k}\right) \tag{4.9}$$

While the model of the cotransition probability is as follows:

$$t_{k1}(h) = p_k - p_k \exp\left(-\frac{3h}{a_k}\right) \tag{4.10}$$

In order to meet the conditions of (4.7) and (4.8), the nested function parameters of the cotransition probability are restricted.

$$\begin{aligned} t_{kk}(h) = \sum_{j=1}^{4} w_j u_j = w_1\left[p_k + (1 - p_k)\exp\left(-\frac{3h}{a_k}\right)\right] + w_2\left\{1 - (1 - p_k)\left[1.5h/a_k - 0.5(h/a_k)^3\right]\right\} \\ + w_3[1 - (1 - p_k)h/a_k] + w_4\left[p_k + (1 - p_k)\cos\left(\frac{\pi h}{b_k}\right)\right] \quad (h < a_k) \end{aligned} \tag{4.11a}$$

$$\begin{aligned} = w_1\left[p_k + (1 - p_k)\exp\left(-\frac{3h}{a_k}\right)\right] + w_2 p_k + w_3 p_k \\ + w_4\left[p_k + (1 - p_k)\cos\left(\frac{\pi h}{b_k}\right)\right] \quad (h \ge a_k) \end{aligned} \tag{4.11b}$$

Here, a_k and b_k are the structural sequence of different functions. Because $\sum_{j=1}^{n} w_j = 1$, Eq. (4.11b) may be simplified as:

$$t_{kk}(h) = p_k + (1 - p_k)\left[w_1 \exp\left(-\frac{3h}{a_k}\right) + w_4 \cos\left(\frac{\pi h}{b_k}\right)\right] \tag{4.12}$$

For any parameter value in Eq. (4.12), $t_{kk}(h) \leq 1$. In order to meet $t_{kk}(h) \geq 0$, it is necessary

$$w_1 \exp\left(-\frac{3h}{a_k}\right) + w_4 \cos\left(\frac{\pi h}{b_k}\right) \geq \frac{-p_k}{1 - p_k} \tag{4.13}$$

Under the condition that $\cos\left(\frac{\pi h}{b_k}\right) \to -1$ is extremely small, or $h = (2m + 1)\, b_k$, $m = 0, 1, 2, 3, \ldots$, the left-hand side of the above formula may be written as:

$$\frac{b_k}{a_k} \leq -\frac{1}{3(2m+1)} \ln \frac{w_4(1 - p_k) - p_k}{w_1(1 - p_k)} \tag{4.14}$$

For Eq. (4.11a), we deduce the same criterion as (4.14) and in the criterion, $m = 0$.

For the nested model of the transition probability, there is similar criterion.

$$\frac{b_k}{a_k} \leq -\frac{1}{3(2m+1)} \ln \frac{(w_4 + 1)p_k - 1}{w_1 p_k} \tag{4.15}$$

Equations (4.7), (4.8), (4.14), and (4.15) are restrictions on the parameters of the nested auto- and mutual transition probability. When fitting the transition probability of samples, more than one function (e.g., nested function) is applied.

Formula of the Inversion Problem

The least square rule is used most commonly in the recognition of the objective function parameters. Assume that $p = (P_1, P_2, P_3, \ldots, P_M)$ is the optimal parameter vector, then the least square rule can be expressed as follows:

$$E(p) = \sum_{m=1}^{Ne} W_m E_m(p) \tag{4.16}$$

where

Ne	is the number of kinds of data
$E_m(p)$	is the minimum quadratic power of each kind of data
W_m	is the weight coefficient of mth data.

The data types can be classified as follows: When data are the semivariance, the covariance, or the transition probability of samples, $m = 1$; when data are the initial value of the parameters, $m = 2$. The weight coefficient W_m is defined by [19, 22–25]:

$$W_m = \frac{W_{0m}}{\frac{E_m(p)}{L_m}} \quad (m = 1, 2, \ldots, Ne) \tag{4.17}$$

where

W_{0m} is user-defined initial weight coefficient of data of different types

L_m is the number of mth types of sample data. Generally, $W_{0m} = 1$. In order to optimize the model, we tend to conduct modeling according to the importance order of W_{0m} value. W_{0m} is a dimensionless number. However, W_m is a dimensional number applicable to $E_m(p)$, and the extent of $E_m(p)$ is usually the square of mth data

$$E_m(p) = \sum_{l=1}^{L_l} w_{lm}^2 (u_{lm}(p) - F_{lm})^2, \quad (m = 1, 2) \tag{4.18}$$

where $u_{lm}(p)$ represents the value of the nested model

F_{lm} represents the semivariance, the covariance, and the transition probability of samples when $m = 1$, and it represents the initial value of parameters when $m = 2$. w_{lm} is the weight coefficient of single sample data; their value depends on the reliability of samples. For simplicity and convenience, k_i (k, $i = 1, 2, \ldots, N$) is omitted, because $u_{lm}(p)$, F_{lm}, w_{lm}, and $E_m(p)$ are defined for the concrete combination of k_i.

Generally speaking, the smaller the lag distance, the bigger the designated weight coefficient (w_{lm}), because the smaller lag distance is based on more data pairs. Thus, w_{lm} can be expressed by the following formula:

$$w_{lm} = \frac{w_{lm0} Np_{lm}}{Ntp} \tag{4.19}$$

where

w_{lm0} is the initial weight coefficient defined by the user for the semivariance, the covariance, and the transition probability of samples of each lag distance and

Np_{lm} is the pair of each lag distance. Ntp is the total pairs. When $m = 2$ and $Np_{lm} = Ntp$, w_{lm0}, is inversely proportional to the parameter representing the initial value.

Optimal Method

Formula (4.16) can be solved through different optimal methods, for example, Newton theorem, Gauss–Newton theorem, modified Newton–Gauss theorem, conjugate gradient, and simplex method.

The study adopted Gauss–Newton theorem and Levenberg–Marquardt algorithm. This mathematic method obtains the unreliability (confidence interval) from the covariance matrix of parameters.

In order to implement the inverse analysis of three different stages, three similar computer codes were developed to estimate the parameters in nested semivariance, variance, and transition probability models. In the nested transition probability model, there are more parameters needed to be estimated. In order to make the obtained parameters meet formulas (4.7), (4.8), (4.14), and (4.15), it is necessary to pair all individual models. Dai et al. adopted the aggregative model consisting of multi-semivariance, covariance and transition probability, and multiple nested functions to demonstrate the accuracy of the estimated parameters. The results of the comprehensive experiment indicated the reliability of the inverse method and code.

The hydrogeological parameters finally obtained are shown in Table 4.6.

4.1.5 Results and Analysis of Running Model

Through the finite element operations of the numeric model, the hydrograph and the groundwater flow field map at the end of the simulation period (July 2006) were obtained, as shown in Figs. 4.6 and 4.7.

Through the analysis of maps resulted from the above models, it can be concluded that groundwater in the study area has the flowing trend from the northeast to the southwest, gathering toward Kaokaolaigou and Shigetaigou, and this is basically consistent with the above-mentioned topographic conditions in the area. When comparing the flow field at the initial stage and the end stage of the simulation period, we found that the water level in the area showed a general downtrend, but the fall amplitude was not evident. The dynamic variation trend of water level during the simulation period in observation hole No. 1 far away from the discharge zone was similar to the month-by-month variation trend (Fig. 4.8), which further

Table 4.6 Major hydrogeological parameters

Subarea	Parameters	
	Permeability K(m/d)	Specific yield μ
Subarea 1	9	0.06
Subarea 2	11	0.09
Subarea 3	14	0.12
Subarea 4	16	0.15

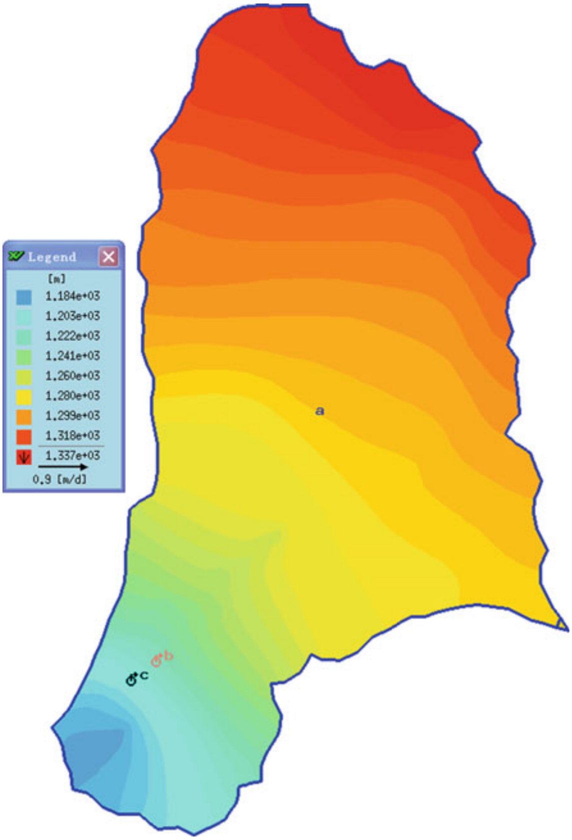


Fig. 4.6 Groundwater level contours

demonstrated that the major recharge source of groundwater in the study area is rainfall. The dynamic variation trend during the simulation period in observation hole No. 2 located near the water-gushing zone in the mine was similar to the month-by-month variation trend of mine inflow (Fig. 4.9), illustrating that the groundwater flow field nearby the water-gushing zone was disturbed by mine inflow. The variation amplitude of water level was approximately 0.5 m.

Through calculation, it is known that:

- The recharge volume of Kaokaolaigou water source site = $P \cdot \alpha \cdot F = 251.9 \times 10^{-3} \times 0.3 \times 97.56 \times 10^{6} = 7.37 \times 10^{6}$ m^3/a.
- The static reserves of Kaokaolaigou water source site = total volume × average specific yield = $9.53 \times 10^{8} \times 0.11 = 1.05 \times 10^{8}$ m^3.

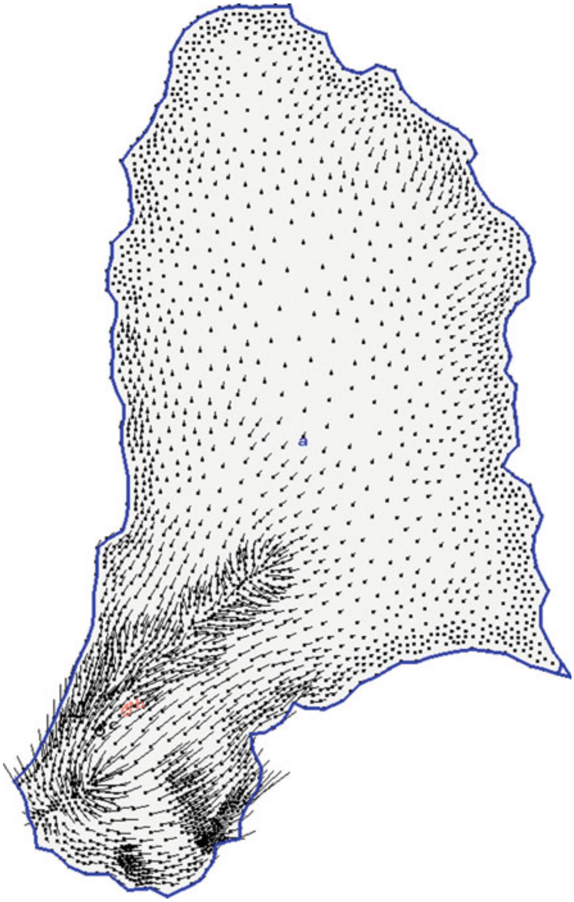


Fig. 4.7 Groundwater flow field

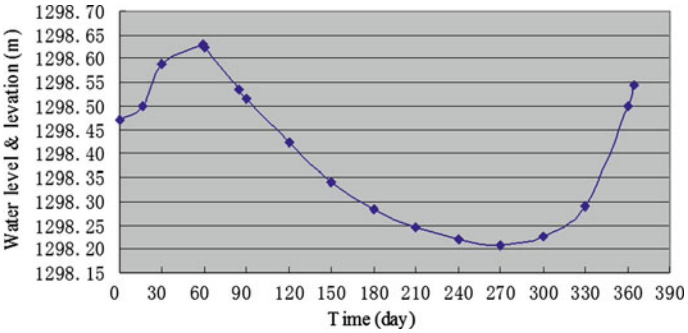


Fig. 4.8 Dynamic curve of water level in observation hole No. 1

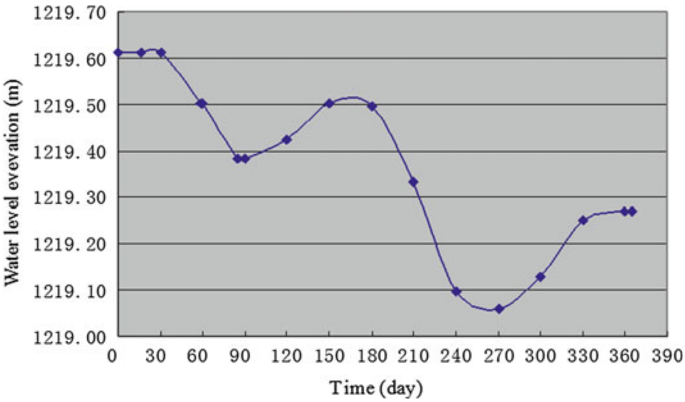


Fig. 4.9 Dynamic curve of water level in observation hole No. 2

4.2 Feasibility Assessment of Joint Extraction of Groundwater from Wells and Springs

The present water resources development in Kaokaolaigou is mainly the utilization of spring water. Kaokaolai water treatment was set up in 1995 with the designed water intake capacity of 32,000 m^3/d. The current maximum water intake capacity is 18,000 m^3/d during dry season, plus two deep water wells with water intake of 14,000 m^3/d. With the implementation of the “Eleventh Five—Year Plan” of Shendong mining area, the demand of water resources is increasing by approximately 10 % yearly. The supply and demand of tap water is for long time in a situation where the ends cannot be met. In order to ease the contradiction of the supply and demand, on one hand, the new constructed water source sites will increases the water reserves. On the other hand, water reserves will be increased by constructing new water source sites, on the other hand and tapping further the latent power of water supply of the existing water sources sites. Therefore, the uppermost water resources site of the mining area—Kaokaolagou spring field was selected as the research target to discuss the feasibility of increasing the extracted water volume of the phreatic aquifer of Shalawusu Formation.

For this purpose, the optimal management model of Kaokaolagou spring field was set up. The objective of management is as follows: Under the existing conditions of water resources in the field, the optimization of water well position and exploitation quantity can develop and utilize maximum groundwater resources on the one hand and on the other hand does not make the groundwater level of the spring field lower too much, avoiding the risk of exhaustion of the spring field.

4.2.1 Groundwater Management Model

Groundwater management model consists of three parts: decision variables, objective functions, and constraint conditions [26]. Its mathematic expression is as follows:

$$\left.\begin{array}{l} V-\min F(\bar{X}) \\ \text{s.t.}\quad G_t(\bar{x})\leq 0,\quad i=1,2,\ldots,m \end{array}\right\} \tag{4.20}$$

where $\bar{x}=(x_1,x_2,\wedge,x_n)^T$; $F(\bar{x})=(f_1(\bar{x}),f_2(\bar{x}),\wedge,f_p(\bar{x}))^T$; $V-\min$ expresses the objective function of the minimized vector, and the objective function of the maximized vector is expressed by $V-\max$; $G_i(\bar{x})(i=1,2,\wedge,m)$ is the constraint function; $F(\bar{x})$ is the vector set of the objective function. For the problem of multiple objectives, $p > 2$, when $p = 1$, it is the problem of the single-objective planning. $\bar{x}=(x_1,x_2,\wedge,x_n)^T$ is the vector of n decision variables.

The groundwater management model is the coupling of the simulation model and optimization model of a groundwater system. The method usually used in coupling of the realistic simulation model and the optimization model is response matrix [27].

The method of response matrix mainly based on the principle of the linear system considers that the drop of groundwater level is the convolution of the exploitation quantity and the response coefficient of the drop of groundwater level.

It expresses the relationship between the input pulse signals (exploitation quantity or water injection rate at unit time) and the response (rise and fall of groundwater level). Of which, the response coefficient is expressed in the form of matrix and takes an equation set as the set of constraint conditions of the management model, so as to realize the coupling of the simulation model and the optimization model of groundwater, so it is called method of response matrix.

4.2.1.1 Theoretical Basis

The theoretical basis of the method of response matrix is the superposition principle. If $\varphi_1=\varphi_1(x,y,t)$ and $\varphi_2=\varphi_2(x,y,t)$ are, respectively, the general solution of non-homogeneous linear partial differential equation $L_1(\varphi)=f_1$ and $L_2(\varphi)=f_2$, its sum $(\varphi_1+\varphi_2)$ or any linear combination $\varphi=C_1\cdot\varphi_1+C_2\cdot\varphi_2$ (where C_1 and C_2 are constants) which is generally φ_1 and φ_2 are also the solution of non-homogeneous linear partial differential equation $L(\varphi)=f_1+f_2$.

Therefore, a problem can be solved by using the superposition principle to divide the problem into several simple subproblems. In the problem of groundwater, the algebraic sum of the action of several dispersed and independent sources or sinks on a point or an area is the result of the conjoint simultaneous action of the sources and the sinks. The sum of the action of some individual boundaries on the groundwater level is equal to the results of the combined action of the total boundary.

4.2.1.2 Response Matrix of Groundwater Level

For the groundwater flow system with homogeneous initial boundary conditions, after the pulse is applied to some sources or sinks, the total response of level induced at a point in the system can be obtained from the algebraic sum of the response induced at the point by the pulse applied alone by different sources or sinks. Here, the pulse refers to the disperse input signals which can stimulate and change the internal status of groundwater system, for example, the pumping rate or water injection rate of groundwater. The response is the output after the pulse had been applied in the system and the status of the system had changed, for example, the change of groundwater level.

The relationship between the response and the pulse of the linear system can be expressed by convolution integration [28]:

$$S(i,j,t) = \int_{0}^{t} \beta(i,j,t-\tau)Q(j,\tau)\mathrm{d}\tau \tag{4.21}$$

where

$S\ (i, j, t)$	response value induced at the moment t and the point i;
$Q\ (j, \tau)$	pulse quantity acting on the point j at the moment τ;
$\beta\ (i, j, t - \tau)$	response coefficient, expressing the response induced at the moment τ and the point i when the pulse is applied to the point j;
i, j	two points inside the area;
t	time.

Equation (4.21) is called as the response of groundwater level and also algebraic technological function. The response coefficient $\beta\ (i, j, t - \tau)$ in the equation is a function, expressing the series of water level responses generated at the place i of the fully penetrating well at the moment $t = \tau$ after the unit pulse starts to be at the point j at the moment $t = 0$.

In order to solve the function of groundwater level response, after the dispersion is conducted for Eq. (4.21), we obtain

$$S(i,j,n) = \sum_{k=1}^{n} \beta(i,j,n-k+1)Q(j,k) \tag{4.22}$$

where

$S\ (i, j, n)$	because of the action at pulse No. j, the water level response at point No. i at the end of time interval No. n;
$\beta\ (i, j, n - k + 1)$	because of the action of the unit pulse at point No. j during the time interval No. k, response in observation well No. i at the end of time interval No. n, i.e., response function of the unit pulse;

Q (j, k)	pulse quantity in well No. j at time interval k; the meaning of other symbols is the same as the above-mentioned one.

Equation (4.22) expresses in form of linear equation the relationship between the pulse and the response in groundwater system. If in a groundwater seepage field pumping and water injection are conducted simultaneously at N source points or sink points, the action on M observation points will form the response coefficient of $M \times N$ unit pulses during a time interval, constituting the response matrix of $M \times N$ orders. If there are L time intervals, it will constitute the response matrix of $M \times N \times L$ orders.

It can be seen that the groundwater level response matrix reflects the characteristics of groundwater system, including the type of aquifer, the internal texture, the nature and the shape of boundary, and the spatial distribution of source points and sink points, and has nothing to do with the input and the output of groundwater system.

4.2.2 Setup of the Optimized Management Model of Conjoint Groundwater Extraction from Wells and Springs

4.2.2.1 Planned Wells and Control Points

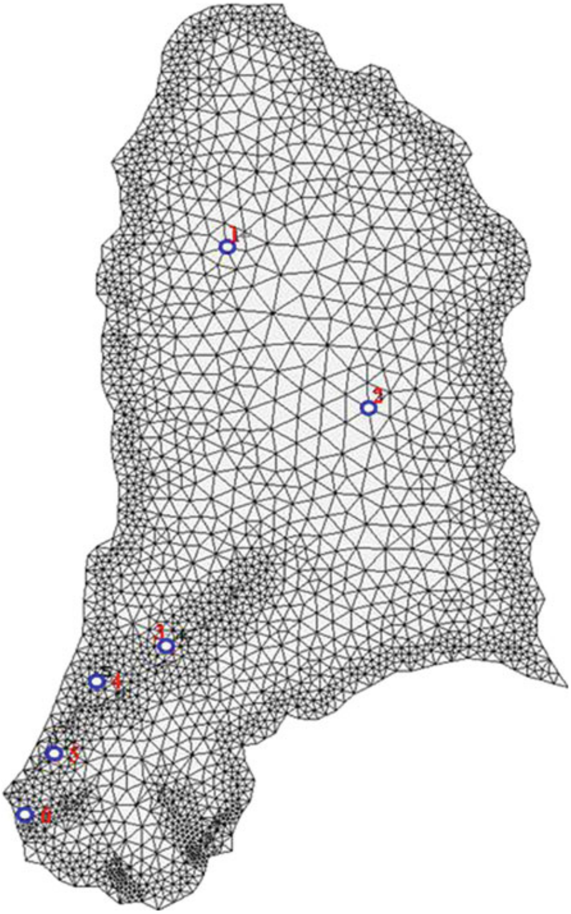
During management of water resources, in order to facilitate management, it is necessary to determine firstly the location of the planned well (well group). Its principle is to take the existing wells as the basis, at the same time to consider the water-rich degree, topographic conditions, and other conditions, and to follow the requirements of suitable dispersion and caring for the whole. Finally, 6 planned wells were determined. The corresponding location was used also as the control points of phreatic water level. The extent and the distribution of the planned wells are shown in Fig. 4.10.

At the same time, in order to control the water level in the whole area, totally 16 control points of water level were set. The distribution of the control points is shown in Fig. 4.11.

4.2.2.2 Determination of the Plan Period and the Time Interval of Management

Because the recharge source of the phreatic aquifer in Kaokaolaigou spring field is mainly rainfall infiltration, the recharge volume is greatly influenced by rainfall and seasons. Therefore, one year was selected as the time interval for calculation. The management period is also one year. The planned management period was from

Fig. 4.10 Layout of the planned wells of groundwater management model



July 2006 to June 2007. The subsequent management will be done only by adjusting the related parameters on the current basis.

4.2.2.3 Objective Function

The total exploitation quantity of different planned wells of the phreatic aquifer of Shalawusu Formation in Kaokaolai spring field is the largest, so it is a linear plan management model of single objective.

$$\max Z = \sum_{j=1}^{m} \sum_{k=1}^{n} Q(j,k) \tag{4.23}$$

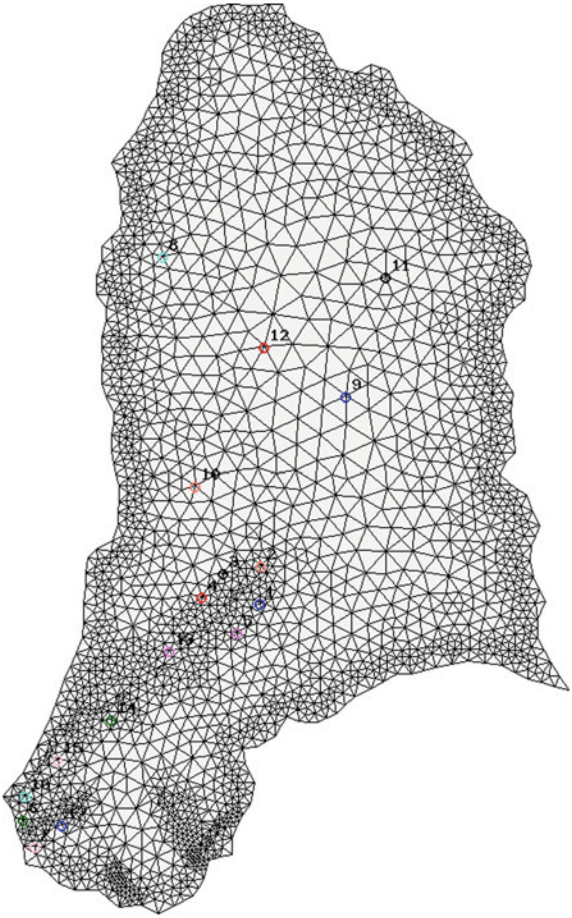


Fig. 4.11 Distribution of the control points of groundwater management model

where

m	total of planned wells, $m = 6$
N	total of time intervals, $n = 1$
$Q\ (j, k)$	exploitation volume of well j during time interval k, $j = 1, \ldots, 6$

4.2.2.4 Constraint Conditions

Among the constraint conditions, the control of water level is critical. For water level, it must be ensured that the water level elevation at different control points is not lower than the elevation of the phreatic aquifer floor at the control points. If it is considered to avoid exhaustion of water resources, the elevation of the phreatic water level at different control points should be higher than the elevation of the phreatic floor. As mentioned above, the minimum thickness of the aquifer is 0.13 m;

therefore, it is required that the elevation of the phreatic water level at different control points is 0.1 m higher than the phreatic water floor. Secondly, the total yield of motor-pumped wells should not be more than the recharge volume of groundwater during the management time interval in the area, that is, the recharge of rainfall. Through calculation, the rainfall recharge is 24, 575, 364 m^3. Finally, it is required that the yield of each well is bigger than zero. Concretely, it is as follows:

- Constraint of water level: The phreatic water level at different control points at the end of time interval n should not be lower than the elevation of the controlled water level; here, it is required that the lowest phreatic water level is 0.1 m higher than the floor elevation at the control points, not making the aquifer become dry. At the same time, it is considered to ensure the existing spring flow, and it is put forward that the water level variation amplitude induced after additional extraction by virtual wells at the end of the management period must be less than 15 % of the aquifer thickness, i.e.,

$$\sum_{j=1}^{m}\sum_{k=1}^{n} Q(j,k)\beta(i,j,n-k+1) \geq (H_d(i,n)+0.1-h(i,n)) \times 15\ \% \tag{4.24}$$

where

$H_d(i,n)$	controlled elevation of water level at point I at the end of time interval *n*;
$h(i,n)$	additional water level at point I at the end of time interval n, generated by the initial conditions, the boundary conditions, and the vertical recharge in case of no pumping in wells;
$\beta(i,j,n-k+1)$	response function of unit pulse.

Constraint of recoverable water resources: The total extraction quantity of groundwater in the spring field cannot be larger than the recharge volume of groundwater in the area.

$$\sum_{j=1}^{m}\sum_{k=1}^{n} Q(j,k) \leq Q_b \tag{4.25}$$

where

Q_b recharge volume of groundwater in the whole spring field during n time intervals.

Nonnegative constraint:

$$Q(j,k) \geq 0 \tag{4.26}$$

4.2.3 Resolving and Analysis of the Optimized Management Model of Conjoint Groundwater Extraction from Wells and Springs

4.2.3.1 Mathematic Model and Its Decomposition

The mathematic model can be described by the following formula [29]:

$$\begin{cases} \frac{\partial}{\partial x}\left(K(h-B)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K(h-B)\frac{\partial h}{\partial y}\right)+\mathrm{W}=\mu\frac{\partial h}{\partial t} & x,y\in\Omega,\ t\geq 0 \\ h(x,y,t)|_{t=0}=h_0(x,y) & x,y\in\Omega,\ t\geq 0 \\ K\frac{\partial h}{\partial\vec{n}}|_{\Gamma_1}=q(x,y,t) & x,y\in\Gamma_1,\ t\geq 0 \\ \frac{\partial h}{\partial\vec{n}}|_{\Gamma_2}=0 & x,y\in\Gamma_2,\ t\geq 0 \end{cases}$$

where

Ω	seepage area
h	water level (m) of aquifer
B	elevation of aquifer floor
K	permeability coefficient (m/d)
μ	gravitational specific yield of phreatic aquifer
$h_0\ (x,\ y)$	initial water level distribution of aquifer (m)
Γ_1	lateral flow boundary of seepage area
Γ_2	zero flow boundary of lateral watershed of the seepage area
$\vec{n}$	-normal direction of boundary face
$q\ (x,\ y,\ t)$	unit discharge of lateral boundary (m^2/dm); inflow is positive, outflow is negative, and water-isolating boundary is 0
W	source and sink terms, including extraction intensity of motor-pumped wells, spring discharge intensity, rainfall recharge intensity, and recharge intensity of stream leakage.

In order to conduct calculation of the management model, according to the superposition principle, the above mathematic model is decomposed into two models, that is, model (I) and model (II) [30, 31].

- Model (I) is groundwater movement induced only by uncontrollable factors such as rainfall recharge, spring discharge, stream leakage, nonzero initial conditions, and boundary conditions in case of no motor pumping and no mine drainage. Its expression is as follows:

$$\begin{cases} \frac{\partial}{\partial x}\left(K(h-B)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K(h-B)\frac{\partial h}{\partial y}\right)+W'=\mu\frac{\partial h}{\partial t} & x,y\in\Omega,\ t\geq 0 \\ h(x,y,t)|_{t=0}=h_0(x,y) & x,y\in\Omega,\ t\geq 0 \\ K\frac{\partial h}{\partial \vec{n}}|_{\Gamma_1}=q(x,y,t) & x,y\in\Gamma_1,\ t\geq 0 \\ \frac{\partial h}{\partial \vec{n}}|_{\Gamma_2}=0 & x,y\in\Gamma_2,\ t\geq 0 \end{cases} \tag{4.27}$$

where W is the source and sink terms without controllable artificial pumping, including the existing rainfall recharge, spring discharge, mine inflow, and pumping of the existing two source water wells. The solution of the model is its water level.

- Model (II) represents the groundwater movement only resulted from the controllable pumping (motor pumping) in the spring field in homogeneous initial conditions and boundary conditions. Its expression is as follows:

$$\begin{cases} \frac{\partial}{\partial x}\left(K(h-B)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K(h-B)\frac{\partial h}{\partial y}\right)+P(x,y,t)=\mu\frac{\partial h}{\partial t} & x,y\in\Omega,\ t\geq 0 \\ h(x,y,t)|_{t=0}=0 & x,y\in\Omega,\ t\geq 0 \\ K\frac{\partial h}{\partial \vec{n}}|_{\Gamma_1}=0 & x,y\in\Gamma_1,\ t\geq 0 \\ \frac{\partial h}{\partial \vec{n}}|_{\Gamma_2}=0 & x,y\in\Gamma_2,\ t\geq 0 \end{cases} \tag{4.28}$$

where $P(x,y,t)$ is the controllable artificial pumping, i.e., motor pumping in the spring field. The solution of the model is $h = s$, and its water level is response water level.

The solution of the mathematic model of the study area is the algebraic sum of models (I) and (II), i.e., $h = H + s$.

4.2.3.2 Calculation of the Response Function and the Additional Water Level

The unit pulse response function can be obtained by using model (II). The method is applicable to the homogeneous initial boundary conditions using the previous finite element numeric model. Pumping is conducted with unit pulse quantity during the first time interval respectively in each planned pumping well. Only one well is allowed to operate at one time. The drop of water level at each control point and at the end of each time interval is then calculated.

The principle for the determination of the unit pulse quantity is when pumping water in different planned wells by applying the unit pulse quantity, the planar response of the majority of planned pumping wells must reach an area two times more than the area that the planned pumping wells represent, while the vertical drawdown must be as less as possible. Through simulation calculation, the unit

Table 4.7 Numeric simulation response matrix of pumping during July 2006–June 2007

Control point	Well no.					
	1	2	3	4	5	6
1	−2.32E−08	5.05E−08	7.66E−02	5.45E−01	3.14E−01	6.84E−02
2	−5.37E−08	−4.73E−08	1.09E−02	2.23E−02	4.30E−02	3.93E−02
3	2.12E−02	1.75E−01	8.04E−05	4.10E−06	2.51E−08	−5.30E−09
4	1.10E−01	9.04E−05	−4.51E−08	−4.66E−08	−4.68E−08	−4.68E−08
5	−4.15E−08	−1.79E−08	4.07E−02	1.48E−01	1.96E−01	7.53E−02
6	5.60E−06	1.39E−03	6.19E−02	6.82E−03	3.89E−04	1.92E−05
7	3.98E−05	4.92E−03	3.36E−02	3.40E−03	1.30E−04	4.66E−06
8	3.62E−05	1.64E−03	8.07E−02	1.22E−02	6.10E−04	2.65E−05
9	1.29E−05	4.34E−04	1.76E−01	3.22E−02	2.20E−03	1.25E−04
10	1.51E−06	3.02E−04	1.39E−01	1.95E−02	1.69E−03	1.17E−04
11	−6.79E−08	−6.79E−08	2.20E−03	3.35E−02	3.20E−01	1.46E+00
12	−6.95E−08	−6.96E−08	1.22E−03	1.96E−02	2.06E−01	1.07E+00
13	3.69E−01	7.92E−04	2.54E−06	3.56E−07	−3.65E−08	−3.91E−08
14	8.11E−03	5.09E−01	2.57E−05	7.43E−07	−2.13E−09	−7.04E−09
15	2.43E−02	3.79E−02	5.32E−09	−2.04E−08	−2.10E−08	−2.10E−08
16	1.09E−01	5.09E−02	2.90E−05	2.44E−06	7.79E−09	−9.78E−09

pulse quantity of the pumping wells in the area is 1000 m^3/d. The calculation results of the numeric simulation response of pumping during July 2006–July 2007 are shown in Table 4.7.

The additional water level can be obtained from model (I) by using the finite element numeric model. The calculation results of the additional water level at different control points and the floor elevation are shown in Table 4.8.

4.2.3.3 Algorithm Implementation and Results

MATLAB's single-objective linear programming function [*x*, fval, exitflag] = linprog (*f*, *A*, *b*, Aeq, beq, *lb*, *ub*) was adopted, where f is the linear objective function; *A*, *b* are inequality constraints, obtained from the response matrix, the additional water level at control points, the floor elevation, and the rainfall recharge; Aeq, beq are equality constraints, and there was not equality constraint in the modeling, i.e., null; *lb*, *ub* are the lower and the upper limits of the decision variable, in the modeling, the lower limit of the decision variable was zero, and the upper limit was not defined, i.e., null; *x* is the calculation result of the decision variable of the model; fval is the calculation result of the objective function; exitflag describes the exit condition of the function calculation: If it is positive, it expresses that the objective function is converged at solution *x*; if it is negative, it expresses that the objective function is not converged; and if it is zero, it expresses that the maximum number of times of function evaluation or iteration is reached.

Table 4.8 Additional water level and floor elevation at control points

Control point no.	Elevation of additional water level (m)	Elevation of aquifer floor (m)
1	1270.702271	1267.7
2	1273.411133	1263.17
3	1268.950195	1255.2
4	1263.834839	1254.76
5	1265.628784	1264.52
6	1187.764893	1186.82
7	1187.666138	1185.72
8	1308.229004	1274.24
9	1295.290649	1241.67
10	1277.717163	1231.87
11	1307.34375	1271.82
12	1298.545776	1279.71
13	1250.28833	1248.96
14	1222.043701	1221.96
15	1189.554688	1189.55
16	1187.106934	1184.64

Through linprog calculation of MATLAB linear programming function, the pumping results of different virtual planned wells are shown in Table 4.9.

The calculation results indicate that on the basis of the existing groundwater utilization, 1–3 more pumping wells can be arranged, the total daily pumpage is 3752.2 m^3, the preferential well location is wells 1#, 3#, and 6#, and the optimized well location is well 3#. The explanation is as follows: well 1# is located in the water-rich area of the thick aquifer at the upstream of the spring field and may be used as an alternative; well 3# is located near the downstream of exposed area of spring group at the middle stream of the spring field as an area of groundwater concentrated discharge of the upstream. The groundwater recharge area is large and the recharge and the lateral recharge at the upstream are big. These are the optimal areas to place wells. The calculation results show that 2409 m^3 water can be pumped every day. In the area where well 6# is located, the aquifer is very thin and it is not suitable to place wells. We believe that the reason why there are more than 1000 m^3 planned recoverable water per day resulted from water level fluctuation

Table 4.9 Calculation results of the optimized management of groundwater

Planned well no.	Planned pumpage (m^3/d)
1#	337.7
2#	0.0000
3#	2409.5
4#	0.0000
5#	0.0000
6#	1005.0
Total	3752.2

nearby the flow boundary during model calculation. It does not have conditions for long-term exploitation, therefore, the area where well 6# is located is excluded. Finally, it is decided that the preferential exploitation area is near well 3#, and during exploitation, 2–3 can be placed. In order to avoid the bad influence on spring flow, the total water yield should be controlled below 4000 m^3/d.

4.3 Summary

The 3D numeric model of the phreatic groundwater flow of the key water source site—Kaokaolaigou spring field—in Shendong mining area was set up. The simulation period is from July 2006 to June 2007. The simulation calculation results indicate the following: Generally, the groundwater level in the spring field shows a descending trend, but the amplitude is not big, the major reason for this is the decrease of rainfall, and mine drainage has only local influence on groundwater flow field near water-gushing area and little influence on the flow field in the whole area.

Through the optimized management model of groundwater, the possibility of groundwater exploitation in Kaokaolaigou spring field was discussed. The feasibility of well–spring conjoint extraction was evaluated. The calculation results of the model indicate that at the end of the control management period (June 2007) under conditions that the variation amplitude of water level is less than 15 % of the aquifer thickness, the preferential groundwater extraction area is near downstream of the exposed area of spring group, and the total increased extraction amount should be less than 4000 m^3/d.

Precipitation is the uppermost recharge source of groundwater in the area. Because of precipitation deficit since recent years, the recharge has been reduced, and the average decreasing amplitude of recharge of Kaokaolaigou water source site is 7.75 % from 1997 to 2004. In case of fragile ecological environments and relatively single recharge in the mining area, we must be prudent for the increase of groundwater extraction volume.

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Chapter 5
Assessment of Coal Mining Impact on Water Resources

Because, in Shendong mining area, the burial depth of the mined seams is relatively shallow, the mining height is big, and the overburden is thin, Quaternary thick loose aquifer overlies in the upper part. In gob, the roof is managed by overall caving; in addition, the hydrogeological conditions are special and the ecological environments are fragile. The development of coal resources in the mining area has caused impact on the water resources system, the ecological environments, and the adjacent peripheral area [1, 2].

5.1 The Impact of Coal Mining on Water Resources Circulation

Rainfall, evaporation, infiltration, and runoff are the major processes of water resources circulation. Before coal mining, water circulation was in natural state, but after mining, because of mine dewatering, surface fissuring, and collapse, water circulation system in the mining area has changed, and it is manifested mainly in the following aspects [3, 4]:

5.1.1 Change of the Transformation Relation Between Surface Water and Groundwater

Analyzed from the angle of water resources and water system, the surface water system is main strong seasonal water flow system constituted by Ulan Mulun River and its tributaries, and groundwater is the main phreatic water of sand gravel layer in paleogully at the bottom of Shalawusu Formation and pore—fracture water of the burnt rock in shallow coal measures. Rainfall is the major recharge source of surface

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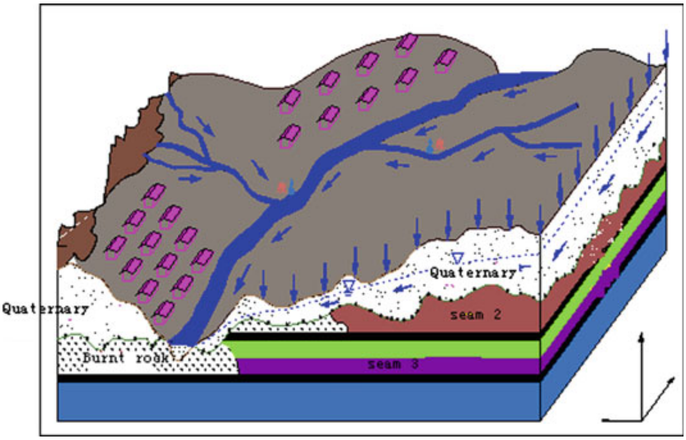


Fig. 5.1 Circulation and conversion relation mode of "three waters" in Shendong mining area under natural conditions

water and groundwater. Under natural conditions, the conversion relation of "three waters" is that the rainfall during rainy season recharges surface water and groundwater, and at the same time, river water recharges groundwater through infiltration, and during dry season, groundwater recharges rivers through depression springs. The circulation and conversion mode of "three waters" are shown in Fig. 5.1. Before coal mining, the conversion and recharge relation of "three waters" were relatively stable.

With the rapid development of coal industry in the study area, mining activities have changed the circulation mode of the water resource system under natural conditions. The gob formed by coal extraction becomes the new discharge area of groundwater; thus, groundwater level form and dynamic variation have changed, so the conversion relation and conversion amount of "three waters" in the study area have changed. Figure 5.2 shows the circulation and conversion mode of "three water" under the influence of coal mining.

After mine drainage, surface water and groundwater accept still the recharge from rainfall, but certain changes occur locally in the discharge form of surface water and groundwater; gob becomes new discharge point in mine. Water flowing into underground mines is involved in water circulation as two parts:

- A part of mine water is drained from underground to the surface sewage treatment plant, a part of the treated mine water is reused, and the rest is all drained to rivers to participate in the overall water circulation. This part of water has basically no impact on water resources circulation.
- Another part of water is accumulated in gob area. The water in the gob area participates in water circulation as two parts: A part of mine water is pumped to the surface through boreholes, and another part of water is stored in gob area. The gob water pumped to the surface has relatively good quality and can be

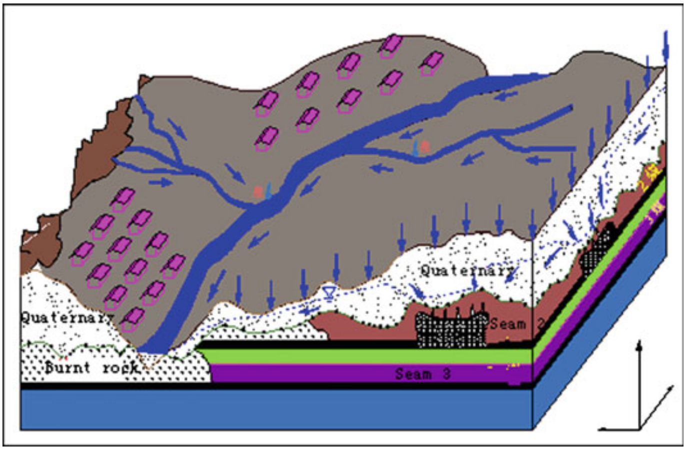


Fig. 5.2 Circulation and conversion mode of "three waters" in Shendong mining area under conditions of coal mining

reused for agriculture and industry after being cleansed, while the water accumulated in gob increases only the water circulation cycle with regard to the conversion of "three waters."

5.1.2 Acceleration of the Infiltration Rate of Rainfall and Surface Water, Reduction of Evaporation

Before mining, adjusted by groundwater reserves, groundwater is shallowly buried and moves horizontally; movement speed is relatively slow, and the time from recharge to discharge is relatively long, so it is favorable to evaporation. After mining, water level drops due to continuous dewatering, the extent of funnel becomes more and more bigger, the gradient of saturation line becomes more and more bigger, the burial depth of groundwater becomes more and more bigger, the movement speed is accelerated, and the movement direction changes mainly from horizontal movement under natural state to vertical movement, particularly under action of surface fissures and collapses; not only the conversion from surface water to groundwater is enhanced, but also rainfall infiltration rate makes a reduced evaporation.

5.1.3 Mine Drainage Makes Water Circulation Complicated

The source of mine water is mainly from the base flow of riverbed and the lateral runoff of groundwater, great amount of mine drainage accelerates the infiltration rate of surface water and the runoff speed of groundwater, and the drained mine water recharges groundwater through seepage, changing the relative percentage of surface runoff and underflow in the watershed, complicating water circulation in the area.

5.2 Impact of Coal Mining on the Structure of Aquifer in Seam Roof

The development of coal resources in the mining area will bring huge income to the national and local economy, but it is undeniable that because of the special hydrogeological conditions and fragile ecological environments, coal mining will also produce big impact on environments in the mining area. The investigated seven mines mine shallow seams at present, coal seams are thick and shallowly buried, the overburden is thin, and there is thick Quaternary loose aquifer; after mining, "two zones" or "three zones" resulted from the destruction, caving, bending, and subsidence of the overlying formation induce certainly the variation of hydrogeological conditions in mine field, making the structure of overlying aquifer change.

In "three zones," the fallen rocks in caving zone and the deformation of formation in fractured zone have resulted in the destruction of the structure of the upper aquifer [5–7]. The destruction and the deformation of roof rocks in gob are mainly related to the thickness, lithology, mechanical properties, and structures of the overlying formation of coal seams, as well as to the weathered fracture development degree. For the destruction and impact of coal mining on the structure of the overlying aquifer, there are basically two following cases:

- Because overall caving is used to manage the roof, after a coal seam has been mined out in large area, gob of large area occurred. After the overlying formation above the gob had been damaged, the formed water-conducting zone would affect the overlying Quaternary sand gravel aquifer or the strongly weathered layer of the bedrock, in area where loess is absent (or the place of "skylight"). Because the bedrock contacts the loose sand layer, the Quaternary loose aquifer would be also affected. In this case, groundwater in the sand gravel layer (Q_{1s}) and water in loose sand layer (Q_{3+4}) would seep rapidly through the water-conducting fractures in fragmentary bedrock, continuously go to underground passages, or because of the change of hydrodynamic conditions and the enhancement of phreatic erosion, the structure of aquifer is damaged (for example, phreatic erosion, compaction, hollowing out, disturbance, formation of new filter layer), further inducing surface subsidence and fracturing, becoming passages for rainfall and surface water to gather and to go to the mine. This is the common problem in the investigated mines. For example, during June–August 1995, in the working face 201, in order to prevent and reduce underground water inrush hazard, artificial water drainage of large flow was conducted, inducing surface fracturing and subsidence in the nearby section, the fissures were 20–100 mm wide, the vertical throw was 50 mm, the cracking zone was 5–55 m wide and 129 m long, and the area was approximately 5742.5 m^2. At present, the cracking zone is filled with and overlaid by eolian sand. Although the above impact and destruction were caused by artificial water drainage rather than by connection of the water-conducting fractured zone in gob, its water-filling mode, nature, impact on the structure of aquifer, and the surface environments were very similar.

- In section where coal seams are thick, the bedrock is thin, while the overlying thick loose aquifer is water-rich, after the seam is mined out, the caving zone of the “three zones” affects the upper sand gravel layer or the loose water-bearing sand layer (the area where the loess layer is absent and weak zone where the thickness of loess layer is less than 5 m) [8]. In this case, interlayer separation, faulting, and falling occur in the overlying formation of coal seams, forming overall collapse destruction of “all thickness—cut fall” type under certain conditions, at last resulting in geological hazards such as fallout and down-movement of Quaternary loose aquifer, water inrush, and sand burst as well as surface collapse. Because of these geological hazards, water level in loose aquifer lowers sharply, wells and springs become dry, and groundwater runoff conditions change.

5.3 Impact of Coal Mining on Surface Water

According to coal mine safety regulations, when coal mining approaches a relatively large river, certain safety coal pillars are reserved, and there exists an aquiclude between the bottom of most riverbed and the underlying seams and formations. When the subsidence induced by coal mining has not affected the surface, there is no hydraulic connection between surface water and mine water, and they do not influence each other.

When coal mining approaches a relatively small river and ravine, the induced water—conducting fractured zone extends to the surface—connects the surface water. The surface water all flows into mine gob through the water-conducting fractures extending to the surface.

5.3.1 Impact of Coal Mining on Surface Water System

From data of many years and the present investigation of water resources, it is found that both all water systems and runoff in the study area have decreased to varying degree.

Ulan Mulun River is the major river in the study area. When coal mining approaches the river, great amount of waterproof pillars are reserved. When the subsidence induced by coal mining affects the surface, under action of waterproof pillars, water-conducting passages do not connect directly the surface water to mine

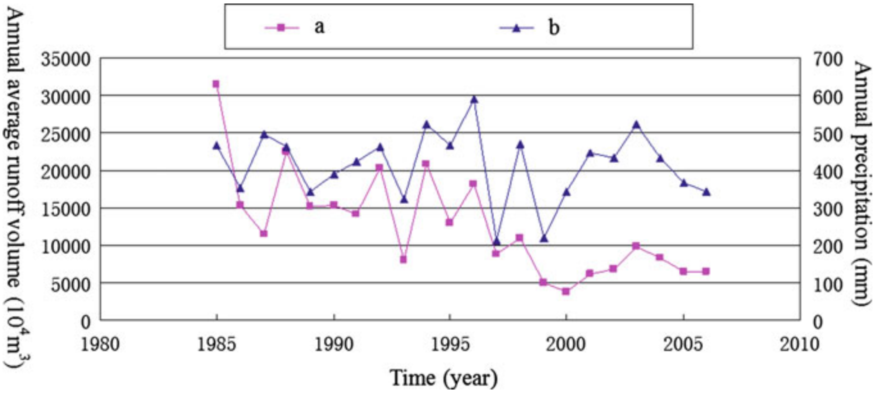


Fig. 5.3 Comparative curve of the annual average runoff of Ulan Mulun River and the annual precipitation in the study area. **a** annual average runoff volume; **b** annual precipitation

gob. Thus, under action of sludge and argillaceous sandstone aquiclude, the surface water does not have direct hydraulic connection with mine gob; only very few surface water recharges groundwater through lateral infiltration.

However, in recent years, the flow of Ulan Mulun River has decreased year by year. Even sometimes there is no water in the river. A lot of people attribute this to coal mining. This understanding is of one-side. From the statistics of rainfall and runoff variation curve of many years, the most direct reason for the decrease of the flow of Ulan Mulun River is the decrease of precipitation in recent years rather than only coal mining activities [9]. Figure 5.3 is the comparative curve of the annual runoff of Ulan Mulun River and the precipitation variation in the study area during 1985–2006. From the figure, it can be known that with the increase of precipitation in wet year, the flow of Ulan Mulun River increased correspondingly. When the precipitation decreased, the flow of Ulan Mulun River decreased too. From the variation trend of the whole curve, the annual runoff of Ulan Mulun River is proportional to precipitation, demonstrating that the flow variation of Ulan Mulun River mainly depends on the precipitation. From this, it is known that the flow of Ulan Mulun River mainly depends on the precipitation.

Of course, the decrease of the water yield of Ulan Mulun River is related to a lot of newly constructed factories and mines as well as the sharp increase of population along the banks. Water is used for production in factories and mining enterprises, and domestic water used by residents is taken from Ulan Mulun River. According to the statistics, the total water amount used by industry, agriculture, and residents is up to several hundred thousand cubic meters per day. During dry period, such large water demand has certainly caused significant impact on Ulan Mulun River basin.

Therefore, the decrease in the flow of Ulan Mulun River and even cutoff of water in the river in recent years resulted from the joint action of the decrease of precipitation and the sharp increase of water amount used in industry and agriculture, in which the precipitation played its predominant role.

5.3.2 Impact of Coal Mining on Surface Water Quality

Various kinds of wastewater are produced during the development of the coal mining area, mainly the mine wastewater, industrial wastewater, wastewater of coal preparation, domestic sewage, and sewage of hospitals, of which mine wastewater and industrial wastewater are the most important sources [10].

At present, the surface water in the study area has been polluted to varying degree, and the pollution sources are mainly the arbitrary discharge of mine water of the peripheric small coal mines and the industrial wastewater of private coking plants. State-own large mines have special sewage treatment plants that strictly treat and clean all mine water, industrial wastewater, and domestic sewage. After the assay is approved, the treated wastewater which reaches the standards for discharge of industrial sewage is drained to the rivers and participates in the transformation of natural “three water,” so as to keep the ecological balance in the whole study area [11]. However, the dense smoke discharged from the private coking plants which appear as bamboo root after a spring rain not only pollutes seriously the air, but also destroys tremendously the nearby surface water bodies, resulting in the increase of polluting elements in Ulan Mulun River basin. Therefore, it is ensured that the pollution of water quality in the whole Ulan Mulun River basin no longer increases. Environmental protection department and the related departments must jointly enforce the law, reorganize strictly the enterprises of high-energy consumption, and high pollution at the two banks of Ulan Mulun River and its tributaries, to strengthen the supervision of wastewater discharge.

5.4 Impact of Coal Mining on Groundwater

The coal seams mined in Shendong mining area are shallowly buried, the bedrock is thin, and generally the water-conducting fractured zone induced by mining extends to the surface, resulting in phenomena such as great amount of leakage and reduction in even dry out of surface water, thus leading to the reduction of the recharge in Quaternary loose aquifer which relies the recharge from the surface water and to drawdown of Quaternary aquifer [12]. At the same time, the water from different aquifers above coal seams leak completely to mine gob, further decreasing groundwater level.

The groundwater leaked to gob increases the mine water discharge, and mine drainage breaks the natural balance state of the existing water system; long-term water drainage during coal mining forms the cone of depression with the mine as center, making the surface water and the groundwater above the coal seams converge toward mine. Within its influencing radius, the flow velocity is accelerated, water level falls, water storage capacity is reduced, locally the confined fracture water is transformed into free water, simultaneously the groundwater flow field changes, and the runoff and discharge conditions also change.

5.4.1 Relationship Between the Drop of Groundwater Level and Destruction of Overburden Rocks

Underground mining destroys the original mechanical equilibrium and results in movement, deformation, and fracturing in overlying formations. When water-conducting fractured zone affects the overlying aquifer, the water in the aquifer will flow to gob along fractures. From this, it can be seen that the drop of groundwater level is closely related to the fracturing of the overburden rocks. With the advance of working face, the height of the fractured zone increases. When the area of gob reaches the extent of sufficient mining disturbance, the height of the fractured zone will be maintained at a certain value, and the height of the destruction zone at the boundary of gob is bigger than the height of destruction zone at the center of gob [13, 14].

According to the height of the destruction zone in the overburden rocks and its distribution pattern, the variation of water level in general mining case can be inferred. For the overburden layer non-sufficiently disturbed by mining, the maximum height of the destruction zone is located at the center of the gob, resulting in the maximum drawdown of aquifer there (Fig. 5.4).

If the area of a gob is relatively large, the fractures above the center of the gob are compacted and closed. The drawdown of aquifer induced by this reaches the maximum at the boundary of the gob (Fig. 5.5).

For aquifer affected by the caving zone of the overburden formation in the case of big mining height and small mining depth, the water of the aquifer flows directly to the gob, forming a diffusion cone of depression with the mining boundary as boundary (Fig. 5.6).

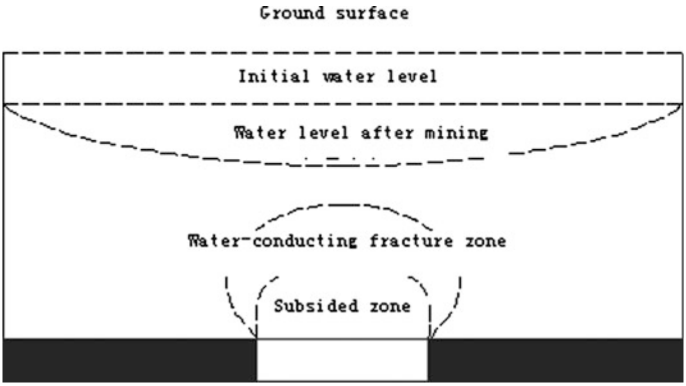


Fig. 5.4 Water level variation induced by non-sufficient mining disturbance

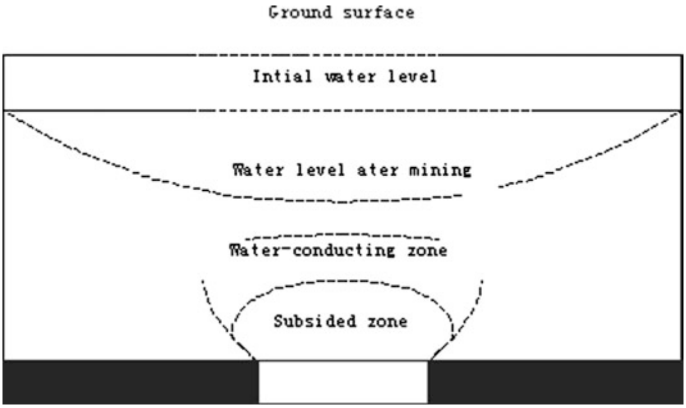


Fig. 5.5 Water level variation induced by sufficient mining disturbance

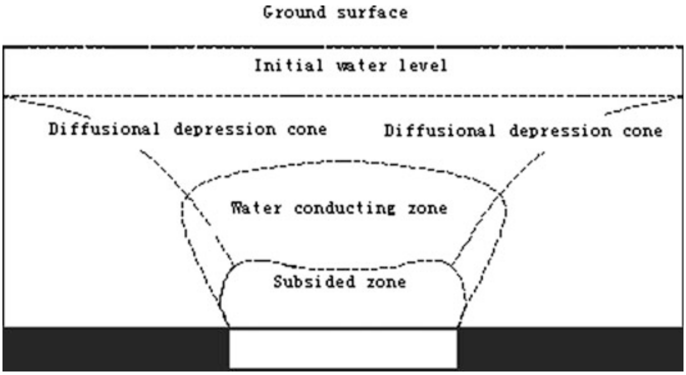


Fig. 5.6 Variation of water level induced by large depth—thickness ratio and sufficient mining disturbance

5.4.2 Impact of Coal Mining on Water Level of the Major Aquifer

Quaternary loose phreatic aquifer is the major aquifer in Shendong mining area, composed of porous phreatic water of alluvial layer (Q_4) and porous phreatic water of eolian, alluvial, and lacustrine deposits (Q_{3s} + Q_4), of which Shalawusu Formation is the most important aquifer for phreatic water of Quaternary loose aquifer. The exploitation of coal resources has big influence on the shallow groundwater of Shalawusu Formation.

In the area where the coal seams are shallowly buried, the consequence of the extension of the water-conducting fractured zone to the floor of Quaternary aquifer is that on the one hand, the groundwater and fine sand in the aquifer of Quaternary Shalawusu Formation flood enormously into mines, resulting in accident of water inrush and sand burst in underground mine and on the other hand, the drainage of great amount of groundwater not only wastes the precious water resources, but also destroys the water environments in the mining area.

According to the hydrogeological conditions and the occurrence characteristics of coal seams as well as great amount of ground fissures distributed in the subsidence area, it is indicated that the water-conducting fractured zone formed after mining at a part of the area has extended to the upper part of Quaternary System, resulting in the change of phreatic runoff and discharge conditions in Quaternary loose aquifer, and the original predominant horizontal runoff and discharge was transformed into the predominant vertical leakage, increased the mine inflow, and induced groundwater drawdown of large amplitude. In area where the water-conducting fractured zone is developed and the loose layer is strongly water-rich, groundwater level descended continuously, forming the cone of depression. Within the influence area of the cone of depression, the water level in civic wells dropped continuously, and the flow of springs was reduced gradually. In area where the water-conducting fractured zone is developed but the loose layer is poorly water-rich, the aquifer is dried out or the water level descended to the floor of the bedrock, resulting in dry out of civic wells and disappearance of the exposed point of springwater.

Great amount of mine dewatering and drainage have resulted in drawdown of large amplitude in the aquifer of Shalawusu Formation, and the maximum drawdown was up to more than 15 m. The time of the pilot production in Huojitu mine was not long, but ground fractures and collapse appeared at the top, resulting in the drop of water level in the aquifer. At Wangjiahao, the burial depth of the groundwater level decreased from approximately 1 m before mining to approximately 6 m. At Budaihao, before coal mining, the burial depth of the groundwater level was only 1–2 m, and lakes were formed by perennially accumulated water in low zones. With the coal mining in recent years, the groundwater level decreased to 4 m. Most lakes became dry. The water level in civic water wells tends to decrease obviously.

Daliuta mine is a mine starting coal mining the earliest and also one of the typical mines where the groundwater is influenced by coal mining. Muhegou spring field is located in the mine. The spring field is a complete water-bearing basin of Quaternary groundwater flow. Shalawusu Formation is the unique aquifer of the spring field. The original water-collecting area was 14.25 km^2, mainly recharged by rainfall, and infiltrates naturally. Except that a few of seepage recharges the lower weak aquifer, all springwater is gathered at the mouth of Muhegou. Muhegou eroded and undercut the aquifer, resulting in overflow of groundwater and recharge of surface water, i.e., discharge in the form of depression spring. According to the long-term observation, the monthly average flow of Muhegou spring was 59,613 m^3/d and the maximum monthly average flow was 106,273 m^3/d. During the initial stage of the development in Shenfu mining area, the groundwater in Muhegou spring field had been the water supply source in the mining area. The spring flow observed in April 2002 was only 16,803 m^3/d, and the largest spring was dry. The spring flow has been attenuated by 72 %.

The drop of the groundwater level of the major aquifer may be reflected from the civic wells in villages. The villages located in Huojitu mine are Wangjiahao, Lijiaban, Tulowan, Shanzi, Wuchenggong and Zhujiagou. As many as 60 water wells are involved, 14 wells were used for key-point investigation and water sampling. According to the investigation, the shallowest burial depth of the investigated water level was 1.0 m below the ground surface and the deepest was 11.2 m. The lowest elevation of the burial depth of water level was 1115 m and the highest was 1256 m. During the investigation, the villagers indicated that the extraction of coal resources caused the water level drops in all water wells and some wells even became dry. This phenomenon was more common within the extent of gobs. A well in Daliushuanggou village took water from the burnt rock, intaking 4800 m^3 water per day, is dry at present.

Great amount of above-mentioned cases demonstrated that the water level of the major aquifer has dropped to varying degree due to coal mining in the study area.

5.4.3 Impact of Coal Mining on Groundwater Flow Field

Many mines were investigated and studied. Here, we take the first fully mechanized mining face in Shenfu mining area as a typical example to state emphatically the impact of coal mining on groundwater flow field.

The working face 20601 is the first fully mechanized mining face in Shenfu mining area, located in Muhegou spring field. The landform is desert bottomland. The strata from the old to the young are Yan'an Formation (J_{2y}), Zhiluo Formation (J_{2z}), Shalawusu Formation (Q_3), and Holocene eolian sand. Yan'an Formation is the unique coal-bearing strata. The uppermost minable seam is seam 2^{-2} and 4.47 m thick, the roof is alternating layer of sandstone and mudstone and 38.84–51.95 m thick, overlaid by water-rich sand layer of Shalawusu Formation, which is the unique water-bearing formation in the area. The thickness of Shalawusu Formation is 26.43–41.92 m, the burial depth of water level is 13–20 m, and the average thickness of the aquifer is 13 m.

Muhegou spring field is a complete water-bearing basin of Quaternary groundwater flow. Shalawusu Formation is the unique aquifer of the spring field. The original water-collecting area was 14.25 km^2, mainly recharged by rainfall, and infiltrates naturally. Except that a few of seepage recharges the lower weak aquifer, and all springwater is gathered at the mouth of Muhegou. Muhegou eroded and undercut the aquifer, resulting in overflow of groundwater and recharge of surface water, i.e., discharge in form of depression spring. According to the long-term observation, the average flow of Muhegou spring was 7430 m^3/d and the exploitable quantity of groundwater is 1600 m^3/d. During the initial stage of the development in Shenfu mining area, the groundwater in Muhegou spring field had been the water supply source in the mining area. The hydrogeological cross section of Muhegou spring field is shown in Fig. 5.7.

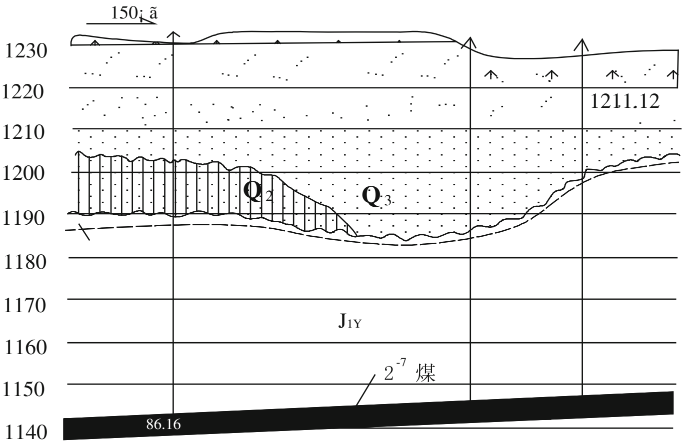


Fig. 5.7 Hydogeological cross section of Muhegou spring field

No. 20601 is the first highly productive and efficient full-mechanized mining face in Shenfu mining area of 228 m wide and 2700 m long, started mining on July 31, 1995 and ended mining in 1996. The mining height was 4.20 m. Through the observation of groundwater level before and after mining, the variation law of groundwater level is summarized as follows:

5.4.3.1 The Original Groundwater Flow Field

Before mining, the original groundwater flow field was an artesian basin around the discharge point—Muhegou spring. Because of the influence of the paleotopography of the bedrock surface, relative water-rich zone was formed in the initial mining district and paleogully area. Groundwater migrated from the east, the west, and the north to the paleogully, the recharge intensity from the east was relatively big. The thickness of the aquifer is 20 m at the center and thin toward the margin. The runoff of groundwater is evidently controlled by paleotopography. The elevation of groundwater level is 1200–1212 m. The lowest elevation of groundwater level is 1195.12 m at the mouth of Muhegou spring. The groundwater in Muhegou spring field is discharged through Muhegou spring (Fig. 5.8).

5.4.3.2 Variation of Groundwater Flow Field During Mining

The cutting point of the first mining district of working face 20601 was justly at the heartland of Muhegou spring field. Before mining, the work for prevention and control of geological hazards such as water inrush and sand burst was done, and in advance dewatering was conducted. Through continuous dewatering of 74 d,

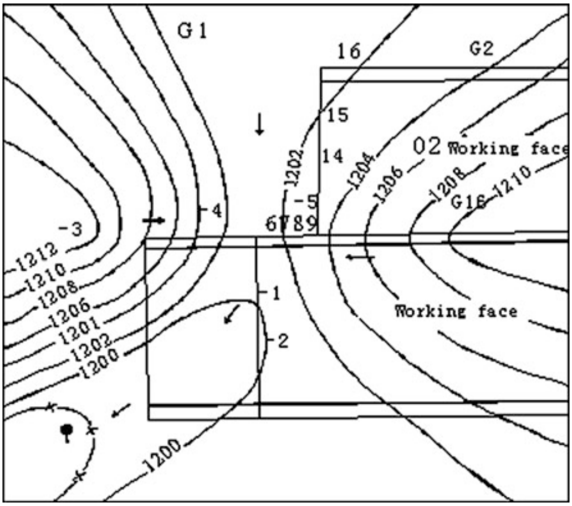


Fig. 5.8 Distribution of observation points and the original groundwater flow field before mining

groundwater level dropped 8–9.46 m. The natural flow field of groundwater changed, and the original discharge way which had Muhegou spring as the discharge point was transformed into the discharge way which had dewatering wells as center, forming the cone of depression with the borehole (observation point) as center (Fig. 5.9).

The radius of the cone was approximately 100–210 m, the hydraulic gradient was approximately 0.029–0.06, and at the same time, the flow of Muhegou spring was reduced, but a part of discharge was remained; after depressurizing and dewatering, except that the thickness of the aquifer was remained at approximately 15 m in paleotopographic low zone, the aquifer was generally less than 5 m thick in other sections.

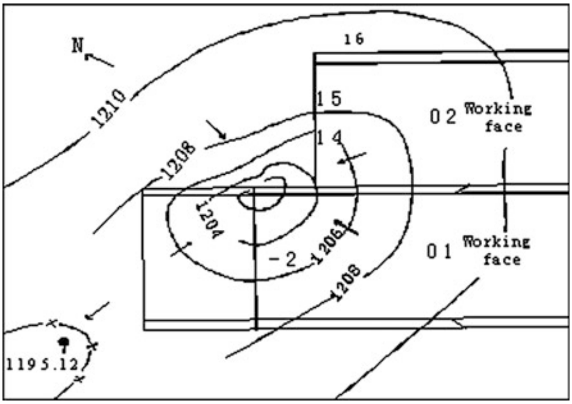
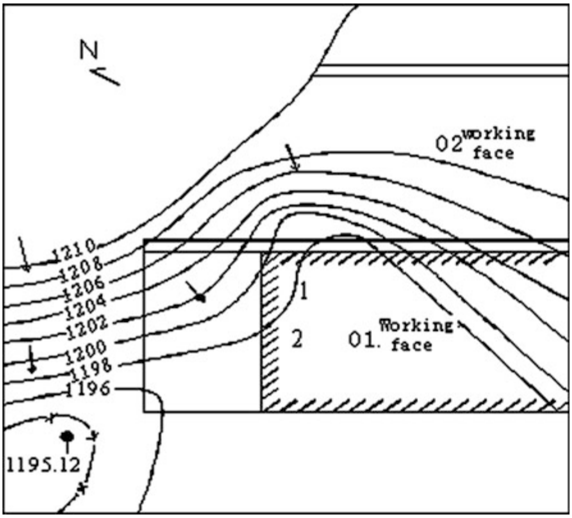


Fig. 5.9 Groundwater flow field at the end of depressurizing and dewatering engineering

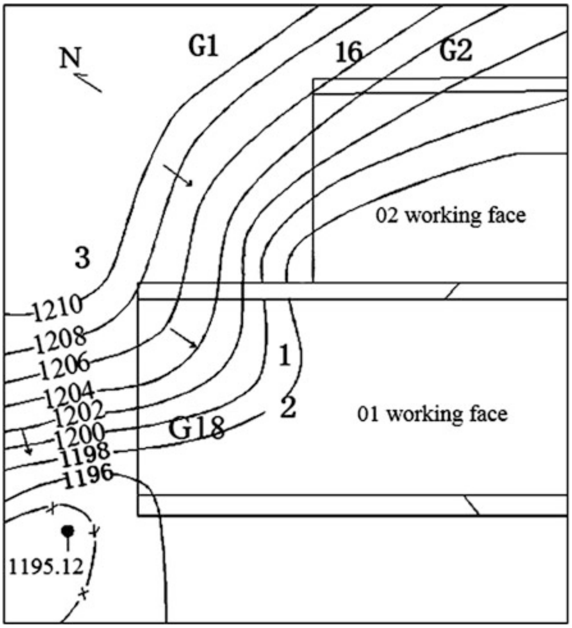
Fig. 5.10 Characteristics of groundwater flow field during coal mining



During coal mining, groundwater flow field changed continuously with the increase of mining intensity, and the discharge area with gob as center was gradually formed, and the contour lines of groundwater level were also inclined toward the side of gob (Fig. 5.10), forming the hydraulic gradient with the gob as center. The hydraulic slope was approximately 0.07. The thickness of aquifer was also reduced. The residual thickness of a part of aquifer was only 0.55 m. Compared to that at the end of depressurizing and dewater engineering, the thickness of the aquifer was reduced by approximately 2 m. From Fig. 5.10, it is shown that the common discharge center was formed at Muhegou and the subsidence area.

At the end of extraction, the groundwater flow field did not change much and basically kept the characteristics of the flow field maintained after the initial caving (Fig. 5.11) when the recharge source of groundwater was mainly underground runoff in the northeastern part, except that a part of groundwater continued to recharge Muhegou spring along the original flow field and was discharged through the spring. The majority of groundwater entered into the gob along the caving (fractured), forming mine water. But because there existed borehole for depressurizing and dewatering in the working face, majority of groundwater entered into the concentrated water drainage system and then was drained from mine. After extraction, groundwater level tended to be relatively stable, the residual thickness of the aquifer was only 0.09–5.60 m; at the observation points far away from the gob, groundwater level was remained at decreasing status, and in the main runoff belt, the hydraulic slope was 0.097. The influential width surpassed 300 m, but the peripheral water level dropped relatively slowly; as time went on, the roof of the gob in subsidence area was rebuilt and compacted gradually; groundwater level tended to be at the stable state, but basically remained near the interface of the bedrock.

Fig. 5.11 Characteristics of groundwater flow field after mining



5.4.4 Impact of Coal Mining on Groundwater Quality

After the development of coal field, not only the surface water quality is influenced, but also the groundwater quality is influenced [15].

The collapsed gob induced by mining resulted in the destruction of aquifer and aquifuge, changed the quality type of groundwater leaked into the gob. From the analysis of hydrochemical data from 1985 to 2006, coal mining had significant impact on the quality type of groundwater. The seams mined in the presently investigated 7 mines are all of coal with extremely low-sulfur content. The total ion was less than 0.5 g/l. In June 1988, the hydrochemical type of groundwater in Muhegou mine was HCO_3–Ca·Na; the hydrochemical type measured in May and September 1994 in Daliuta mine was Cl–Ca·Na and $HCO_3 \cdot SO_4$–Ca, and the hydrochemical type measured in April 1996 was $HCO_3 \cdot SO_4$–Na·Ca; the water quality type measured in November was relatively complex; it was $SO_4 \cdot Cl$ (HCO_3)–Na, $HCO_3 \cdot Cl$–Na, $SO_4 \cdot HCO_3$–Na in Huojitu mine, water sump of the west second panel of seam 1^{-2} in Shangwan mine, water sump of the main haulage roadway in Halagou mine and Bulianta sewage pool (188). The salinity was relatively high, 790–1915 mg/l, whereas the stream of Halagou mouth, Zhangjiagou mine drainage, drainage of Shigetai mine sewage treatment plant, drainage of the annex haulage roadway of seam 2^{-2} of Daliuta mine had relatively low salinity. The water quality type was HCO_3 (SO_4)–Ca·Na, $HCO_3 \cdot SO_4$–Na·Ca and HCO_3–Ca (Mg).

Coal mining resulted in the change of the quality type of groundwater; at the same time, it made other component content exceed standard. The mine water in the study was basically with high suspended solid. Organic matter exceeded slightly standard. Fluorine ion of Shanwan mine water and Ulan Mulun mine water exceeded standard. Mercury ion and volatile phenol of different mine water exceeded standard.

Shendong mining area is located in desert and is very short of water resources. Quaternary water and surface water are the major water source. In the area, surface water is mostly intermittent stream, the flow during dry season and flood reason is quite different, and dilution capacity of perennial flow is low. If drained directly to valley without treatment, mine water will result in pollution of water resources in the area. Great amount of mine water discharge threatens undoubtedly seriously people's life, at the same time, resulting in the huge waste of water resources. As a result, the target of cycle economy cannot be realized.

Therefore, aiming the problem that some component content of mine water exceeds standard, multilevel treatment has been conducted for mine water discharge to the surface. After reaching the industrial discharge standard, mine water is allowed to be drained to surface rivers and participates in natural water circulation.

5.5 Impact of Coal Mining on Water Resources Quantity

The so-called water resources quantity refers to the freshwater quantity which can be recovered or renewed year by year. Because coal mining has changed the water circulation system, the corresponding change has occurred in the recharge and available amount of the regional water resources. Rom the present research degree, it is still difficult to evaluate quantitatively the impact of coal mining on water resources quantity, and here, we carry out only its qualitative trend prediction and analysis.

5.5.1 Impact of Coal Mining on the Total Water Resources

Collapse induced by coal mining has reduced the evaporation of surface water

Surface water bodies are all exposed to the air. In Maowusu Desert belt, the evaporation is very intense. Here, Majiata open pit is taken as example. The open pit is located at Ulan Mulun River bank. After water is stored in its remained huge pit, its annual evaporation is as much as 500,000 m^3. From this, it is inferred and known that how huge the water resources lost due to evaporation of surface water bodies in such large extent of the study area. Coal mining has resulted in surface subsidence and made surface water bodies leak into the gobs. Superficially, it reduces surface water quantity, essentially it transforms the storage space of surface water, and surface water is converted into groundwater and stored. From the angle of the total water resources, the total water resources in the whole study area were kept the same. Compared to the previous total water resources, because the evaporation is deducted, it is equivalent to increase the total regional water resources in other way.

5.5.1.1 Groundwater Drawdown Induced by Coal Mining Has Reduced the Evaporation of the Shallow Groundwater

Because Shendong mining area is located in Maowusu Desert, the evaporation in the area is 4–5 times more than the precipitation. The groundwater level is too shallowly buried. The water seeped to the underground during rainy season and stored as groundwater is evaporated to the atmosphere, reducing greatly the total regional water resources.

The related research data indicate that under the specific geological conditions of the study area, the maximum evaporation depth is generally 0.8 m. When the burial depth of groundwater level is more than 0.8 m, the evaporation is limited. Because the loose sand layer is very permeable, rainfall seeps to the depth of more than 0.8 m. The evaporation is greatly limited. Therefore, when groundwater drawdown induced by coal mining is more than 0.8 m, water amount evaporated to the atmosphere is greatly reduced, compared to the previous total water resources in the whole study area. The deduction of evaporation is equivalent to increase the total water resources in other way.

5.5.2 Groundwater Drawdown Induced by Coal Mining Reduced the Output of Springs

As a discharge way of groundwater, springs formed spring field after being exposed on the surface, resulted in direct exposure of groundwater to the atmosphere and made the groundwater which was originally not evaporated greatly, reducing to varying degree the total groundwater resources. After groundwater drawdown, a lot of springs disappeared; the evaporation of groundwater to the atmosphere was reduced, which is equivalent to increase the total water resources in the whole study area.

5.5.2.1 Groundwater Drawdown Induced by Coal Mining Increased the Capture of Water Resources from the Exterior Drainage Basin

The surface fractures and the subsidence generated after coal mining accelerated the conversion of surface water to underground water and the infiltration speed of rainfall, so the infiltration capacity of both surface water and rainfall increased, particularly during wet season, reducing the discharge of surface runoff toward the outside of the area; in addition, mine drainage lowered groundwater level and increased the capture of water from the exterior drainage basin, reduced the undercurrent flowing toward the outside of the drainage basin and the evaporation of groundwater, resulting in certain increase of the recharge of the regional water resources, thus increasing the total water resources in the whole study area.

To summarize, coal mining resulted in certain increase of the total water resources in the study area.

5.5.3 Impact of Coal Mining on the Available Water Resources

5.5.3.1 Impact of Coal Mining on the Available Surface Water Resources

Because of great amount of dewatering and drainage in mines, the natural flow field of the groundwater equilibrium system has changed; in addition, after coal was mined out the rocks above the gob were bended, separated even fallen under action of gravity to form subsidence, fractured to make the existing fractures in the rocks extend further and affect the surface, decreasing surface runoff through leakage along the fractures and resulting in the decrease of water flow even interruption of water current in many rivers. Eventually, the available surface water resources are reduced.

Muhegou spring field is a tributary of Ulan Mulun River at the upstream of Kuye River. The ravine is a complete water-bearing basin of Quaternary groundwater flow. Shalawusu Formation is the unique water-bearing formation in the spring field. The water-collecting area of the spring field is 14.25 km^2, recharged by precipitation and infiltration. Infiltrates occur naturally except a few of leakage recharge to the lower weak aquifer. Groundwater is gathered at the mouth of Muhegou. Muhegou eroded and undercut the aquifer, resulting in the discharge of groundwater on the surface in form of springs. The average flow of the springs was 5961 m^3/d. During the initial stage of the development of the mining area, the groundwater in Muhegou spring field had been the water supply source in the mining area. After 1996, the groundwater level of the aquifer in the spring field has been lowered continuously, and the groundwater detected in 1997 had been lowered near the bedrock surface, demonstrating that the groundwater in Shalawusu Formation was basically drained. The flow of Muhegou springs decreased continuously; there was no flow in the main spring port. The water flow measured in April 2002 was only 1680 m^3/d, attenuation was up to more than 70 % and the spring became dry in 2004.

5.5.3.2 Impact of Coal Mining on the Available Groundwater Resources

Groundwater resources quantity refers mainly to the dynamic groundwater quantity which has recharge and discharge directly related to precipitation and surface water bodies, that is, the groundwater quantity which participates in the modern water circulation and is renewed continuously. The groundwater resources in the study area are water in Quaternary Shalawusu Formation and the burnt rocks, secondarily fracture water in Jurassic sandstone.

1. **Coal mining has different impact on groundwater of different types**.

    - Surface subsidence made the water in the aquifers of Shalawusu Formation and burnt rocks infiltrate into the gob through water-conducting fractures and converted to mine water, resulting in unwatering in the two aquifers and big difficulty in direct exploitation and utilization of groundwater in civic water wells. Although these two aquifers are unwatering, the total water resources remain unchanged, only changed the storage space, water is all accumulated and stored in gobs. A part of mine water resides in short time in the gobs can be pumped through the enhanced drainage boreholes and utilized directly. However, the majority of mine water is remained in the gobs, cannot be reused, and must go through relatively long circulation period to be utilized, thus reducing the use level of the regional water resources.
    - In addition, the water used for cooling equipment and the water gushed from working face have been polluted to varying degree, cannot be directly used, and can only be used after being drained and treated on the surface.

To summarize, the storage space of water in aquifers of Quaternary Shalawusu Formation and burnt rock has changed; the available quantity of water has decreased to varying degree, but the total water quantity remained unchanged.

2. **Sandstone fracture water occurs in Jurassic coal measures**.

    - Because mine drainage has broken the original equilibrium state, water drainage for coal mining in many years has formed the depression cone with mine as center, made fracture water converge toward mine pit; within its influence radius, groundwater flow velocity has been accelerated, water level has dropped, water storage has decreased, locally confined water has been converted into pressure-free water, resulting large amplitude decrease of water level in aquifer, and locally confined water has been converted into pressure-free water, resulting large amplitude decrease of water level in aquifer. Water level has decreased even to the aquifer floor. Except that a part of roof water flowing to the gob is pumped to the surface through enhanced drainage borehole for direct use, the rest of water became all water accumulated in the gob. The accumulated water in the gob has been polluted in the gob and working face, and the available direct usage of the accumulated water in the gob has decreased greatly.

- The quality water accumulated in the gob has changed and cannot be used directly, but can be utilized after being treated and converted into resources. The accumulated water in mine gob is the groundwater resources which are not sufficiently understood and exploited as well as utilized so far. In case where the groundwater level drops continuously, the industrial and agricultural water usage becomes more and more, and the drinking water is short gradually; hence, it has good prospect of development and utilization.

5.6 Summary

Through the present study, the impact of coal mining on the water resources system in the study area is relatively clearly understood. The major conclusions are as follows:

1. Coal mining has changed the conversion relation of the surface water and the groundwater and had certain impact on the surface water resources and the groundwater resources. The key for protection of the water resources is to control the development height of the water-conducting fractured zone, to protect the aquifer structure from damage. Since the full caving is adopted to manage the roof in the majority of the study area, the roof management method must be improved to protect the aquifer.
2. In recent years, the reduction of steam flow of the largest water system in Shendong mining area—Ulan Mulun River basin is the conjoint action of the large decrease of precipitation, the sharp increase of industrial and agricultural as well as residents' water usage at the two banks of the river. The precipitation has played the predominant role, and mining has had relatively small impact.
3. Coal mining has induced the vertical fractures, made the surface water transferred and stored in mine gob, increased groundwater quantity, at the same time, increased the vertical infiltration of the surface water and rainfall, and resulted in certain decrease of groundwater level. In overall, the total water resources in Shendong mining area have not been reduced.
4. Coal mining has resulted in some increase of the water resources in the whole study area, but the direct available amount has been reduced. As the reduced part, the accumulated water in mine gob can be exploited and utilized as backup resources through treatment.

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Chapter 6
Study on MultiObjective Optional Allocation of Complex Water Resources System

From chapter three, it can be seen that the water resources system in Shendong mining area has complexity, i.e., multilevel (surface water, groundwater, and mine water). Multiuser and distributive characters, at the same time, are impacted by coal mining activities. The water resources system is characterized by multiinput, difficult restoration because of the fragility due to being easy to be influenced by human activities. As regards the coexisting decision problem of the multiobjectives such as economic objective, environmental ecological objective, and overall objective of the system, it is of decisive role to apply the optimal allocation theory of the multiobjective to realize the efficient operation of the complex water resources system in Shendong mining area for maintaining the stability and sustainable development of the coal chemical base.

6.1 Generalities of the MultiObjective Optimal Allocation Model of Water Resources

The multiobjective optimal allocation model consists of the model, the decision variables, the objective function, and the constraint conditions.

6.1.1 Mathematical Model

The expression of the multiobjective optimal allocation model is [1–6]:

$$\left.\begin{array}{l} V-\min F(\overline{X}) \\ s.t.\ Gi \leq 0, \quad i=1,2\cdots m \end{array}\right\}$$

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where

$\bar{x} = (x_1, x_2, \wedge, x_n)^T$	vector of n decision variables;
$F(\bar{x}) = (f_1(\bar{x}), f_2(\bar{x}), \wedge, f_p(\bar{x}))^T$	vector set of the objective function; for the multiobjective, $p > 2$; when $p = 1$ it is the planning of the single objective;
$V - \min$	objective function of the minimized vector; for the objective function of the maximized vector, it is expressed by $V - \max$;
$G_i(\bar{x})(i = 1, 2, \wedge, m)$	constraint function.

6.1.2 Decision Variables

The decision variables are control and operation conducted on the system to reach the objective of the system, belong to the controllable variables. On the basis of the characteristics of the optimal allocation of water resources, the major decision variables of the optimal allocation model of water resources can be summarized as the following four types:

1. **Decision variables of the regional economic and social development**

Water resources development and utilization are closely related to the regional economy. Therefore, when building the optimal allocation model of water resources, it often comes down to some decision variables concerning the economic development according to the nature or problem to solve, such as GDP growth rate, industrial development percentage, percentage of investment and allocation, percentage of agriculture, forestry and animal husbandry, irrigation area, percentage of cultivated crops, and employment rate.

2. **Running of decision variables**

The decision variables are run to determine the concrete program of water resources development and utilization, for example, the optimal extracted amount of groundwater and surface water, cross-basin called in and called out water amount, water amount from springs, water transfer capacity of reservoirs, surface water and groundwater development percentage corresponding to the regional development strategy, percentage of local water and water from the outside, and the percentage of broadening the source and water saving.

3. **Decision variables of engineering facilities**

This is to determine whether where and when an engineering facility related to water resources development and utilization will be constructed; for example, whether an underground reservoir, an underground water source, a facility of returned groundwater should be constructed. In the optimal water allocation model, these decision variables are usually integral variables. The optimal allocation model of this type of variables is commonly solved with programming of integral number or mixed integral number.

4. **Ecological environmental decision variables**

Ecological environmental decision variables include usually sewage discharge, treated amount of sewage, ecologically used water amount, and oasis area.

6.1.3 Objective Function

The objective function is the mathematical expression that the management personnel or the decision maker uses to seek the objective of the system. The objective is expressed with linear or nonlinear function of the decision variables. The objective is different; the expression of the objective function is different too. According to the optimal allocation problem to solve, it may be to seek the maximum value, also the minimum value. On the basis of the characteristics and the requirement, the objective of economic benefit is to realize the regional sustainable economic growth, to improve people's living standard, to invest the least, and to get the maximum benefit, for example, the maximum net profit of water supply system, the lowest unit water cost, the maximum production value of industrial and agricultural departments related to water resources development, the minimum investment in water resources development, the maximum total net income of irrigation in drainage basin, the minimum sum of deviation between grain production, industrial and agricultural production value, and objective of different planning years.

6.1.3.1 Objective of Environmental Quality

High-speed economic development and improvement of environmental quality are the most concerned problems of the decision makers. For this purpose, it is usually necessary to consider the objective of environmental quality, for example, the minimum drop or the maximum rise of groundwater level through artificial backfilling of water during the optimization period, the maximum discharge of wastewater after treatment and self-cleaning of strata, and the optimal distribution of solute in groundwater by taking solute in groundwater as objective.

6.1.3.2 Objective of System Operation

If certain constraint conditions are met, the maximum extraction or backfilling of groundwater, the least well number, the maximum utilization of surface water and groundwater, and seeking the optimal operation rules and optimal water allocation with consideration to joint use of surface water and groundwater are all the objective functions of this type.

6.1.4 Constraint Conditions

In the optimal allocation of water resources, the solution of each problem is constrained by some conditions. They are laws, rules, and regulations that the system relies on when operating the parameters and the variables, including resources constraint, demand constraint, and dynamics constraint of the migration law of water resources, engineering investment constraint, and ecological environmental constraint.

6.1.4.1 Resources Constraint

Resources constraint means that the resources needed during each period must be not more than the maximum resources during the period, including land resources constraint and total available water resources constraint.

6.1.4.2 Demand Constraint

It means that the optimal decision should meet the basic water resources demand of different users (departments).

Dynamics constraint of water resources migration law
The continuity equation or the equilibrium equation based on masse and energy conservation is taken as constraint conditions, embodying the relationship between the decision variables and the state of the system. Calculation of simulation model can provide the surface water inflow in the typical year, the inflow process of the long series, and the inflow of the continuous dry year. Groundwater movement is influenced by many factors such as geology, hydrogeology, hydrology, weather, and environment; its complexity is much more than that of the surface water. Therefore, we must shift the groundwater simulation model to the optimization model through the response matrix or insertion on the basis of the definite solution of groundwater movement and combine the optimization technique with the simulation model, so as to embody that the optimization calculation is restricted by groundwater movement law. The quantitative variation and transition of different terms during the development and utilization of groundwater resources can be reacted in the optimal model.

Environmental constraint
Considering the angle of the development and utilization of water resources as well as the coordinate development with environment, it is necessary to ensure certain environmental benefit and environmental capacity; for example, the definite restraints of groundwater level rise and drop for prevention, control, and improvement of occurrence and development of various geological problems in the

management area; certain chemical component and physical properties of intake (or backfilled) water cannot surpass the corresponding water quality requirements.

Engineering investment constraint
It is to ensure that the development investment and the operation cost of water resources in an area do not surpass the budget standard. In practice, the optimal allocation models of different types can be set up according to the requirements of the objective such as hydraulic requirement, water quality requirement, and environmental requirement and are solved with the corresponding methods.

Other constraints
According to the concrete conditions, other necessary constraint conditions can also be set.

6.2 Setup of the Optimal Allocation Model of Complex Water Resources System in the Study Area

The extractable water resources may be considered as extractable groundwater resources composed of the flow from water sources of different springfields and mine inflow. Precipitation is the upmost recharge source of the local groundwater. Since recent years, the precipitation shows the decreasing trend year by year, and the recharge has decreased also year by year. But the water demand has increased by 10 % annually, and the supply and demand situation of water has been tense year by year, particularly the water sources used as domestic water. In this case, it is necessary to utilize the most reasonably water resources and get the maximum benefit under natural recharge, runoff, and discharge conditions. Therefore, aiming at the supply and demand conditions of water resources in Shendong mining area, conducting the multiobjective optimal management of water resources is to carry out the related organization, coordination, supervision, dispatch for the development, utilization, and protection of water resources, to deal with the contradiction of water usage in different mines, supervise, and limit various unreasonable development and utilization of water resources, to realize the internal optimal allocation under the current status and conditions of water resources, to improve the utilization efficiency of water resources, and to formulate the optimal allocation program of water resources.

The supply of water resources in the study area consists mainly of the following parts: (1) groundwater provided by water sources in springfields; (2) surface water extracted from seeping ditch; (3) mine water; and (4) reused water provided by the treatment plant of domestic sewage. Among them, the first three are included in the regional extractable water resources; the fourth is the reusage of water resources. According to the present mode of water utilization in the mining area, by water quality, water sources are classified as water source for tap water supply, water source for industrial reused water, and water source for reused water of afforestation, and the present work adopted also methods classified by water quality of water sources to divide the water supply quantity into groups.

6.2.1 Principle for Model Setup

In order to utilize sufficiently the water resources in the mining area, to realize the minimum cost on the basis of ensuring water supply to meet the demand, the principle for setting up the present model is as follows:

1. Users are put in order according to the priority, that is, to meet the demand of production firstly and then to meet the demand of livelihood, industry, and afforestation.
2. According to different water quality of various water sources, the water supply plan for different users is as follows:
    - Water used for afforestation: The poorest water quality only meets the demand of afforestation and therefore only supply water for afforestation rather than for other users.
    - Industrial reused water: Water quality is better than that for afforestation, but it cannot meet the domestic requirement; therefore, the industrial reused water must meet firstly the demand of production and industry, and the surplus can meet the demand of afforestation.
    - Independent water sources for livelihood in different mines and network tap water: Water quality is the best; therefore, it must meet firstly the demand of livelihood, and the water shortage of other users can be supplemented by tap water.

(3) According to different requirements on water quality of different users, the following water allocation plan will be adopted at the aspect of water source allocation:

- Production: Industrial reused water can meet the water quality requirement of production; therefore, when allocating water resources, industrial reused water is utilized in priority, and if the industrial reused water is no sufficient, it is supplemented by tap water of better water quality.
- Livelihood: Livelihood has the highest requirement on water quality, and only the independent water sources for livelihood in different mines and networking tap water can meet the requirement; therefore, water demand of livelihood must be supplied firstly by the independent water sources for livelihood, and the shortage will be supplemented by networking tap water.
- Industry: The water quality of industrial reused water can meet the requirement of industry, and its water supply plan can be divided into two cases: firstly, if the industrial reused water has some surplus after meeting the demand of production, the surplus should be utilized in priority, and the

shortage will be supplemented by networking tap water with better water quality, and secondly, if the industrial reused water does not have surplus, all water will be supplied by networking tap water.

- Afforestation: Afforestation has the lowest requirement on water quality; therefore, different water sources can meet its requirement. In order to realize the objective of the lowest cost, its water allocation plan is also divided into two cases: Firstly, if the independent reused water for afforestation meets the demand of afforestation, the reused water for afforestation is utilized in overall rather than other water sources. Secondly, if the independent reused water for afforestation cannot meet the demand, and the industrial reused water does not have surplus after meeting the demand of production and industry, the shortage will be supplemented by networking tap water. Thirdly, if the independent reused water for afforestation in amine cannot meet the demand, and the industrial reused water has some surplus after meeting the demand of production and industry, the shortage will be supplemented by the networking tap water.

6.2.2 Selection of Decision Variables

According to the objectives of the model (i.e., to realize the maximum assurance rate of water resources supply and the lowest water supply cost through comprehensive consideration to the basic information such as the location, water yield, water quality of water sources, location, and water demand of the major water users), $X_{ijk,}$ i.e., the water supply of the water source number i to the user number ji in the subarea number k, is taken as the decision variable.

- The study area was divided into 8 subareas; their number and areas are shown in Table 6.1.
- The users were divided into 4 categories, i.e., production, livelihood, industry, and afforestation. Their mark number is shown in Table 6.2.
- According to water quality of water sources, water sources were divided into 3 categories shown in Table 6.3.

Therefore, the decision variables of the study area are 8 × 4 × 3 = 96.

Table 6.1 Subareas of the study area

Subarea number (k)	Area (mine)
1	Daliuta
2	Bulianta
3	Shangwan
4	Feed system of coal liquification
5	Halagou
6	Ulan Mulun
7	Shigetai
8	Huojitu

Table 6.2 Division of users in the study area

User category number (j)	Area (mine)
1	Production
2	Livelihood
3	Industry
4	Afforestation

Table 6.3 Division of water sources in the study area

Water source category number (i)	Area (mine)
1	Networking tap water
2	Industrial reused water
3	Reused water for afforestation

6.2.3 Setup of Objective Function and Objective Constraint

The objective function is expressed by the linear or nonlinear function of the decision variables. For different objectives, the expression of the objective function is different; according to the management problem to solve, it may be to seek the maximum, also the minimum. The major aim of the multiobjective programming model of water resources in the mining area is to realize the maximum assurance rate of the water resources supply and the minimum water supply cost; therefore, the model has two objective functions.

Objective 1: The output of supplying water in the whole area meets maximumly the water demand of different users in different subareas.

$$\max f_1(x) = \sum_{k=1}^{K} \sum_{j=1}^{J(k)} \sum_{i=1}^{I(k)} x_{ijk}$$

where

i	user category number, $i = 1, 2, 3, 4$;
j	water source category number, $j = 1, 2, 3$;
k	subarea number, $k = 1, 2, 3, 4, 5, 6, 7, 8$;
x_{ijk}	output of supplying water of water source number i to the user j in subarea number k;
$f_1(x)$	Output of supplying water in the whole area.

Objective 2: the minimum water supplying cost

$$\min f_2(x) = \sum_{k=1}^{K} \sum_{j=1}^{J(k)} \sum_{i=1}^{I(k)} x_{ijk} \alpha_j$$

where

i user category number, $i = 1, 2, 3, 4$;
j water source category number, $j = 1, 2, 3$;
k subarea number, $k = 1, 2, 3, 4, 5, 6, 7, 8$;
x_{ijk} output of supplying water of water source i to the user j in the subarea k;
α_j cost coefficient of supplying unit water volume of the water source j;
$f_2(x)$ cost of the output of supplying water in the whole area.

Based on the principle for setting up the model, water supply by different quality was adopted. The objective constraints are as follow:

1. **Constraint for the objective of water usage**
   (a) If the supply capacity of the industrial reused water is smaller than the water demand of production, the industrial reused water should be utilized in priority, and its usage rate is 70–100 %. The shortage is supplemented by networking tap water, and the assurance rate of water supply is 100–120 %.
   (b) If the supply capacity of the industrial reused water is bigger than the water demand of production, all will use the industrial reused water. The assurance rate of water supply is 100–120 %.
   (c) Constraint for the objective of domestic water.
   (d) If the water supply of the independent water source is smaller than the domestic water demand, the independent water source is used preferentially, and the shortage is supplemented by the networking tap water. The assurance rate of water supply is 100–120 %.
   (e) If the water supply capacity of the independent water source is bigger than the domestic water demand, all will use the independent water source, and it is not supplemented by the networking tap water.
2. **Constraint for the industrial water**
   (a) If all the industrial reused water is supplied to production, when it does not have the surplus, the industrial reused water is not supplied to the industrial and afforestation users. The priority is given to production. The assurance rate of water supply is 100–120 %.
   (b) If the industrial reused water has some surplus after meeting the water demand of production.

When the surplus of the industrial reused water is smaller than the industrial water demand, all the surplus will be supplied to the industrial water demand, its use ration is 70–100 %, the shortage will be supplemented by the networking tap water to meet the demand, and the assurance rate of water supply is 100–120 %.

When the surplus of the industrial reused water is bigger than the industrial water demand, all the surplus will be used to meet the industrial water demand.

3. **Constraint for the objective of afforestation water**
   (a) If the water supply capacity of the reused water for afforestation is bigger than the water demand of afforestation, all the reused water for afforestation will be used to meet the water demand of afforestation, and the assurance rate of water supply is 100–120 %.
   (b) If the water supply capacity of the reused water for affectation is smaller than the water demand of afforestation.

When the industrial reused water does not have surplus after meeting the water demand of production and industry, the shortage will be supplemented by the networking tap water, and the assurance rate of water supply is 100–120 %.

When the industrial reused water has surplus after meeting the water demand of production and industry, and the surplus is more than the deficit of the water demand of afforestation, the shortage will be supplemented by the surplus of the industrial reused water, and the assurance rate of water supply is 100–120 %.

When the surplus of the industrial reused water is less than the deficit of the water demand of afforestation water, the shortage after the surplus of the industrial reused water is all used will be supplemented by the networking tap water, and the assurance rate of water supply is 100–120 %.

6.2.4 Determination of the Constraint Conditions

Constraint conditions are the law, rules, and regulations the model relies on when seeking the solution; only under the definite constraint conditions, the calculation results are effective. The present model has the following four categories of constraints:

1. **Constraint of water demand**
   The constraint of water demand is that on the basis of meeting the different users' water demand on different water sources, the maximum water supply is not more than 120 % of the water demand, so as to save water and decrease water cost. The constraint of water demand is divided into the constraint of production water demand and the constraint of domestic water demand, and the constraint of industrial water demand and the constraint of afforestation water demand.

   (a) Constraint of production water demand in different subareas:

$$Q_{\text{production water demand}} \leq x_{11k} + x_{21k} \leq 1.2 * Q_{\text{production water demand}}$$

   where k—subarea number, k = 1, 2, …, 8;

(b) Constraint of domestic water demand in different subareas:

$$Q_{k\,\text{Domestic water demand}} \leq x_{12k} \leq 1.2 * Q_{k\,\text{Domestic water demand}}$$

where k—subarea number, $k = 1, 2, \ldots, 8$;

(c) Constraint of afforestation water demand in different subareas:

$$Q_{k\,\text{afforestation water demand}} \leq x_{14k} + x_{24k} + x_{34k} \leq 1.2 * Q_{k\,\text{afforestation water demand}}$$

where k—subarea number, $k = 1, 2, \ldots, 8$;

2. **Constraint of the water supply capacity of different subareas**

(a) Constraint of tap water supply capacity:

$$\sum_{k=1}^{8} \sum_{j=1}^{4} x_{1jk} \leq Q_{\text{networking tap water}} + Q_{\text{independent tap water}}$$

That is, the sum of tap water supplied to different users in different subareas is not bigger than the total water supply of the networking tap water and the self-owned independent water sources in different mines.

(b) Constraint of the supply capacity of the industrial reused water in different subareas:

$$x_{21k} + x_{23k} + x_{24k} \leq Q_{k\,\text{industrial water supply}}$$

where k—subarea number, $k = 1, 2, \ldots, 8$;
The sum of water supplied to different users in different subareas is not more than the supply capacity of the industrial reused water in the subareas.

(c) Constraint of the supply capacity of the reused water for afforestation in different sub areas:

$$x_{34k} \leq Q_{k\,\text{afforestation water supply}}$$

where k—subarea number, $k = 1, 2, \ldots, 8$;
That is, the sum of the reused water supplied to afforestation is not more than the total supply capacity of the reused water for afforestation.

3. **Nonnegative constraint of decision variables**

$$x_{ijk} \geq 0$$

The decision variables involved in the optimization calculation; i.e., the water supply to different users in different subareas must be bigger or equal to zero.

4. **Zero constraint of decision variables**

$$x_{31k} = x_{32k} = x_{33k} = 0 \tag{1}$$

$$x_{22k} = 0 \tag{2}$$

According to the criteria of modeling and the principle of water supply by quality, formula (1) expresses that the reused water for afforestation is not used in production, livelihood, and industry; its corresponding variable is zero and not involved in the optimization calculation, and formula (2) expresses that the industrial reused water is not used in livelihood; its corresponding variable is zero and not involved in the optimization calculation.

6.3 Solution Method of Model

MATLAB means Matrix Laboratory. Apart from the excellent numeric computation ability, it provides also symbolic computation of professional level, word processing, visualized modeling and simulation, real-time control, and other functions. The basic data unit of MATLAB is matrix, and its instruction expression is very similar to the form commonly used in mathematics and engineering; therefore, resolving the problem by using MATLAB is much more simple and direct than the languages such as C and FORTRAN. Current popular MATLAB 7.0 includes a main package with several hundred internal functions and more than 30 kinds of toolboxes. The toolboxes can be divided into the functional toolboxes and the disciplinary toolboxes. The functional toolboxes are used to expand the functions such as the symbolic computation, visualized modeling and simulation, word processing, and real-time control. The disciplinary toolboxes are professional toolboxes. The control toolbox, signal processing toolbox, and communication toolbox are of this kind of toolbox.

Realizing the multiobjective optimal allocation of the water resources in the mining area by using MATLAB not only greatly reduces the programming difficulties and makes the staff put more energy to the setup of the multiobjective optimal allocation model of the water resources in the mining area, but also increases greatly the accuracy and the running speed of the model.

Using the optimization toolbox of MATLAB, we can solve the problems of linear programming, nonlinear programming, and multiobjective programming. In this regard, it includes linear and nonlinear minimization, maximum minimization, quadratic programming, semi-infinite problem, solution of linear and nonlinear equation (set), and linear and nonlinear least square problem. In addition, the toolbox provides also the solution method of the problems in large- and medium-scale task, such as linear and nonlinear minimization, solution of equation, curve fitting, and quadratic programming, providing a more convenient and more rapid approach for the actual application of the optimization method in engineering. According to the objective of the current project, the dissertation has chosen the tool fgoalattain in MATLAB to solve multiobjective problem.

In order to be convenient to realize the definite algorithm in MATLAB program, 96 decision variables x_{ijk} are translated into the numbering form Xm which can be recognized by MATLAB, and totally 64 variables are set (Table 6.4).

Table 6.4 Corresponding relation of the decision variables and the variable Xm in the program

k	*i j*	1 (production)	2 (livelihood)	3 (industry)	4 (afforestation)
k = 1 (Daliuta)	1 (tap water)	X111	X121	X131	X141
	Corresponding variable in MATLAB	X1	X2	X3	X4
	2 (industrial reused water)	X211	X221	X231	X241
	Corresponding variable in MATLAB	X5		X6	X7
	3 (afforestation reused water)	X311	X321	X331	X341
k = 2 (Bulianta)	1 (tap water)	X112	X122	X132	X142
	Corresponding variable in MATLAB	X9	X10	X11	X12
	2 (industrial reused water)	X212	X222	X232	X242
	Corresponding variable in MATLAB	X13		X14	X15
	3 (afforestation reused water)	X312	X322	X332	X342
	Corresponding variable in MATLAB				X16
k = 3 (Shangwan mine)	1 (tap water)	X113	X123	X133	X143
	Corresponding variable in MATLAB	X17	X18	X19	X20
	2 (industrial reused water)	X213	X223	X233	X243
	Corresponding variable in MATLAB	X21		X22	X23
	3 (afforestation reused water)	X313	X323	X333	X343
	Corresponding variable in MATLAB				X24

(continued)

Table 6.4 (continued)

k	*i j*	1 (production)	2 (livelihood)	3 (industry)	4 (afforestation)
k = 4 (Coal feeding system of liquification)	1 (tap water)	X114	X124	X134	X144
	Corresponding variable in MATLAB	X25	X26	X27	X28
	2 (industrial reused water)	X214	X224	X234	X244
	Corresponding variable in MATLAB	X29		X30	X31
	3 (afforestation reused water)	X314	X324	X334	X344
	Corresponding variable in MATLAB				X32
k = 5 (Halagou)	1 (tap water)	X115	X125	X135	X145
	Corresponding variable in MATLAB	X33	X34	X35	X36
	2 (industrial reused water)	X215	X225	X235	X245
	Corresponding variable in MATLAB	X37		X38	X39
	3 (afforestation reused water)	X315	X325	X335	X345
	Corresponding variable in MATLAB				X40
k = 6 (Ulan Mulun)	1 (tap water)	X116	X126	X136	X146
	Corresponding variable in MATLAB	X41	X42	X43	X44
	2 (industrial reused water)	X216	X226	X236	X246
	Corresponding variable in MATLAB	X45		X46	X47
	3 (afforestation reused water)	X316	X326	X336	X346
	Corresponding variable in MATLAB				X48
k = 7 (Shigetai)	1 (tap water)	X117	X127	X137	X147
	Corresponding variable in MATLAB	X49	X50	X51	X52
	2 (industrial reused water)	X217	X227	X237	X247
	Corresponding variable in MATLAB	X53		X54	X55
	3 (afforestation reused water)	X317	X327	X337	X347
	Corresponding variable in MATLAB				X56

(continued)

Table 6.4 (continued)

k	*i j*	1 (production)	2 (livelihood)	3 (industry)	4 (afforestation)
k = 8 (Huojitu)	1 (tap water)	X118	X128	X138	X148
	Corresponding variable in MATLAB	X57	X58	X59	X60
	2 (industrial reused water)	X218	X228	X238	X248
	Corresponding variable in MATLAB 中对应变量	X61		X62	X63
	3 (afforestation reused water)	X318	X328	X338	X348
	Corresponding variable in MATLAB				X64

In Table 6.4, according to modeling criteria and objective constraint, a part of decision variables x_{ijk} are not involved in the optimization calculation; therefore, a part of decision variables x_{ijk} were not assigned the corresponding variable Xm.

6.4 Results and Analysis of Running Model

In the optimal allocation of the water resources, 2005 was taken as the reference year. According to the arrangement of project content and “The 11th Five-Year Plan and the prospective plan to 2020 of Shendong mining area,” the optimal allocation of the water sources was conducted for the comprehensive utilization of water resources in 3 years, 5 years, 10 years, and 15 years after the reference year; i.e., 2008, 2010, 2015, and 2020 were chosen as planning level years.

On the basis of the existing water consumption data during 2000–2005, model GM (1, 1) was used to predict the water demand of different users in 2008, 2010, 2015, and 2020, the obtained data were taken as users’ water demand used in the optimal allocation, and the results are shown in Table 6.5.

The data of water supply capacity of different water sources in the planning level years, used in the optimal allocation, are derived from “The 11th Five-Year Plan and The Prospective Plan to 2020 of Shendong Mining Area,” and the results are shown in Table 6.6.

In the above table, the water yield of the water sources of Majiata infiltration ditch, Majiata mine pit, and Rear Buliangou mine pit is mainly to serve the coal feeding base of liquification and therefore mainly used in Shangwan, Bulianta, and the coal feeding system of liquification.

Table 6.5 Predicted water demand of different users of different subareas in different planning level years and analysis results (*unit* m^3/d)

Year	Subarea	Production water	Industrial water	Domestic water	Afforestation water
2008	Daliuta mine district	2972	892	2378	1.209
	Huojitu mine district	2675	802	2140	1.089
	Bulianta mining area	5944	1783	4755	2.419
	Coal feeding system of liquification	1486	446	1189	605
	Halagou ming area	2972	892	2378	1.209
	Ulan Mulun mining area	1486	446	1189	605
	Shigetai mining area	2378	713	1902	968
2010	Daliuta mine district	3306	6992	2644	1.392
	Huojitu mine district	2975	892	2380	1.253
	Bulianta mining area	6611	1983	5289	2.784
	Shangwan mining area	3306	6992	2644	1.392
	Coal feeding system of liquification	1653	496	1322	696
	Halagou ming area	3306	992	2644	1.392
	Ulan Mulun mining area	1653	496	1322	696
	Shigetai mining area	2644	793	2116	1.114
2015	Daliuta mine district	3283	6985	2626	1.430
	Huojitu mine district	2955	886	2364	1.287
	Bulianta mining area	6566	1970	5253	2.861
	Shangwan mining area	3283	6985	2626	1.430
	Coal feeding system of liquification	8864	2659	7091	3.862
	Halagou ming area	3283	985	2626	1.430
	Ulan Mulun mining area	1641	492	1313	715
	Shigetai mining area	3283	985	2626	1.430
2020	Daliuta mine district	4102	7231	3282	1.764
	Huojitu mine district	3692	1108	2954	1.587
	Bulianta mining area	8205	2461	6564	3.527
	Shangwan mining area	4102	7231	3282	1.764
	Coal feeding system of liquification	11,077	3323	8861	4.762
	Halagou ming area	4102	1231	3282	1.764
	Ulan Mulun mining area	2051	615	1641	882
	Shigetai mining area	4102	1231	3282	1.764

Table 6.6 The predicted available water supply of different water sources in different planning level years (*unit* m^3/d)

Category	Water source		Water source number	2008	2010	2015	2020
Tap water source	Networking water source	Kaokaolaigou water source	q_1	16,000	15,000	13,000	10,000
		Daliuta underground water treatment plant	q_5	10,000	10,000	10,000	10,000
		Clear water in Ulan Mulun mine	q_4	3000	3000	3000	3000
		Bulianta underground water treatment plant	q_{20}	6000	10,000	10,000	10,000
		Halagou water source	q_3	3000	0	0	0
		Gongnieergaigou reservoir	q_2	9000	9000	9000	9000
		Subtotal	Q_k	47,000	47,000	45,000	42,000
	Independent water source	Shigetai water source	Q_7	1500	1500	1500	1500
		Xiaoliuta water source (used in Ulan Mulun)	Q_6	2000	2000	2000	2000
		Huojitu seepage well	Q_8	1000	1000	1000	1000
		Buliangou infiltration ditch	Q_2	1400	1400	1400	1400
		Subtotal	Q	5900	5900	5900	5900
	Total of tap water sources		Q	52,900	52,900	50,900	47,900
Industrial reused water sources	Daliuta well (underground reused water)		q_8	1920	1920	1920	1920
	Daliuta underground water treatment plant (Industrial reused water)		q_9	3000	3000	3000	3000
	Subtotal in Daliuta		Q_1	4920	4920	4920	4920
	Huojitu underground water treatment plant (underground reused water)		Q_8	2300	2300	2300	2300
	Halagou mine (underground reused water)		Q_5	1400	2400	2400	2400
	Shangwan mine (underground reused water)		Q_3	1070	1070	1070	1070

(continued)

Table 6.6 (continued)

Category	Water source	Water source number	2008	2010	2015	2020
	Bulianta mine (underground reused water)	Q_2	3100	3100	3100	3100
	Ulan Mulun mine (underground reused water)	Q_6	1400	1400	1400	1400
	Shigetai mine (underground reused water)	Q_7	1200	1200	1200	1200
	Majiagou infiltration ditch and water source of mine pit (used for coal supply base)	q_{21}	10,000	10,000	10,000	10,000
	Rear Bulian mine pit (used for coal supply base)	q_{25}	0	10,000	10,000	10,000
	Total of industrial reused water sources	Q	25,390	36,390	36,390	36,390
Afforestation reused water source	Daliuta mine domestic sewage treatment plant (afforestation reused water)	q_{15}	4000	4000	4000	4000
	Daliuta underground water treatment plant (afforestation reused water)	q_{16}	2000	2000	2000	2000
	Huojitu underground water treatment plant (afforestation reused water)	Q_8	1500	2000	2000	2000
	Shangwan mine (afforestation reused water)	q_{18}	2200	2200	3000	3000
	Heitangou domestic sewage treatment plant (used in Shangwan)	q_{26}	2000	2000	2000	2000
	Oxidation pond of Bulianta mine (afforestation reused water)	Q_2	1500	1500	2000	2000
	Subtotal of afforestation reused water sources	$Q_{\text{Tota lafforestation water}}$	13,200	13,700	15,000	15,000
Total of water yield of all water sources year by year		Q_{total}	91,490	102,990	102,990	99,290

The multiobjective optimal solution of the water resources is mainly to set constraint conditions on the basis of users' water demand and the water supply capacity of water sources, to combine all the constraint conditions, to form the matrix of constraint conditions, and to conduct calculation by taking the obtained constraint condition matrix as parameter and substituting the obtained constraint condition matrix into the multiobjective programming function *fgoalattain* of MATLAB toolbox. According to the steps of the optimizing calculation, the data of the water demand of different users and the data of the water supply capacity of different water sources in different subareas in 2008, 2010, 2015, and 2020 are brought in the constraint conditions of water demand and water supply capacity, solved through the multiobjective programming function *fgoalattain* of MATLAB; finally, the results of the multiobjective optimal allocation of water resources for different users in different subareas in 2008, 2010, 2015, and 2020 are obtained. The optimal development program of water resources in different subareas is analyzed and studied, respectively, in the following section.

6.4.1 Analysis of Water Resources Optimization Results in Daliuta Shaft District

Daliuta shaft district belongs to Daliuta mine and is located in the northwest of Shenmu County, Shaanxi Province, 53 km to the eastern bank of Ulan Mulun River, in administrative division, it belongs to Daliuta town, the west of Daliuta mine has Ulan Mulun River as boundary, across the river from the mine lies Huojitu shaft, the east of the mine has Beiniuchuan as boundary, the south of the mine is bordered to Dahaize minefield, and the north of the mine is adjacent to Qianshiban minefield.

6.4.1.1 Analysis of Water Supply Sources and Output of Supplying Water in Different Level Years

Seen from different water sources in Daliuta shaft district, the tap water comes from the networking water source. The planned water supply is 47,000 m^3/d in 2008 and 2010, 45,000 m^3/d in 2015, and 42,000 m^3/d in 2020. The industrial reused water comes from the underground direct reused of Daliuta mine and Daliuta underground water treatment plant, and the output of supplying water is 4920 m^3/d in 2008, 2010, 2015, and 2020. Afforestation reused water comes from Daliuta domestic sewage treatment plant and Daliuta underground water treatment plant, and the output of supplying water is 6000 m^3/d in 2008, 2010, 2015, and 2020.

6.4.1.2 Analysis of the Balance Between Supply and Demand of Water Resources in Different Level Years

From the above setup of optimal allocation model, we can obtain the results of the optimal allocation of water resources for different water users in Daliuta shaft district in 2008, 2010, 2015, and 2020 (see Table 6.7). From the table, it can be seen that:

The output of supplying tap water in the above table refers to the output of supplying water in the whole district.

The domestic water in 2008, 2010, 2015, and 2020 is supplied by the networking tap water in the study area.

As regards production water, the industrial reused water can completely meet the demand and has some surplus in 2008, 2010, 2015, and 2020. The surplus is supplied to the industry.

As regards the industrially used water, in 2008, the surplus of the industrial reused water can completely meet the demand, and in 2010, 2015, and 2020 after all the surplus of the industrial reused water is used in the industry, there are 5374.5, 5348, and 6413 m^3/d shortages in the shaft district.

In 2008, 2010, 2015, and 2020, the shaft district-owned afforestation reused water source is used for afforestation and can meet the demand.

6.4.1.3 Analysis of Water Supply Potential

On the basis of the existing and planned water supply engineering as well as the output of supplying water in different level years, the water supply potential in different years can be analyzed and obtained.

As regards the tap water, because the water yield of the water supply springfield shows the decreasing trend, general speaking, the networking tap water has small water supply potential.

As regards the industrial reused water, in 2008, 2010, 2015 and 2020, the water supply potential is 3234 m^3/d, with increase of the future mine inflow, and the water supply potential will increase correspondingly.

As regards the afforestation water, in 2008, 2010, 2015, and 2020, the water supply potential is 4200 m^3/d, with the increase of the future water consumption, and the afforestation reused water supply potential will increase correspondingly.

6.4.1.4 Suggestions for Water Resources Development and Utilization

From the analysis of the supply and demand balance of water resources as well as the water supply potential, it can be seen that as regards industrially used water, the surplus of the industrial reused water alone cannot meet the demand. The problem can be solved through the following approach: (1) to increase a part of water supply potential through increasing the capacity of water supply network of the industrial

Table 6.7 The results of the optimal allocation of water resources in different level years in Daliuta shaft district (*unit* m^3/d)

Planned level year	User source	Output of supplying water	Water supply potential	Water demand				Surplus and shortage 余缺量
				Production	Livelihood	Industry	Afforestation	
2008	Tap water	47,000	–	0	2378	0	0	–
	Industrial reused water	4920	3234	2972		892	0	1056
	Afforestation reused water	6000	4200				1209	4791
2010	Tap water	47,000	–		2644		0	–
	Industrial reused water	4920	3234	3306		6992	0	−5375
	Afforestation reused water	6000	4200				1430	4570
2015	Tap water	45,000	–	0	2626		0	–
	Industrial reused water	4920	3234	3283		1637	0	−5348
	Afforestation reused water	6000	4200				1430	4570
2020	Tap water	42,000	–	0	3282		0	–
	Industrial reused water	4920	3234	4102		818	0	−6413
	Afforestation reused water	6000	4200				1764	4236

Note 1 Tap water comes from the networking tap water source

Note 2 Industrial reused water comes from underground direct reused of Daliuta mine and Daliuta underground water treatment plant

Note 3 Afforestation reused water comes from Daliuta domestic sewage treatment plant and Daliuta underground water treatment plant reused water, (2) to improve water treatment technology, and to increase water quality standard so as to meet the demand of the users who have higher requirement on water quality. As regards afforestation water, with the increase of the future water consumption, the domestic sewage will increase correspondingly. Therefore, to increase the capacity of domestic sewage treatment will provide powerful guarantee for afforestation water during the planning period.

6.4.2 Analysis of the Optimization Results of Water Resources in Bulianta Mine

The coal feeding base of liquification consists of Bulianta mining area, Shangwan mining area, and coal feeding system of coal liquification. Bulianta mine is at approximately 5 km to Ulan Mulun town located in the southeast of Ejin Horo Banner, Ordos City, Inner Mongolia.

6.4.2.1 Analysis of Water Supply Source and the Output of Supplying Water in Different Level Years

Seen from the sources of different water in Bulianta mining area, the tap water comes from the networking water source in the study area and the independent water source of Buliangou infiltration ditch (supplied to Bulianta mine). In 2008 and 2010, the output of supplying water is 48,400 m^3/d, of which the output of supplying water of networking water source is 47,000 m^3/d, and the output of supplying water of the independent water source of Buliangou infiltration ditch is 1400 m^3/d; the output of supplying water in 2015 is 46,400 m^3/d, of which the output of supplying water of networking water source is 45,000 m^3/d, and the output of supplying water of the independent water source of Buliangou infiltration ditch is 1400 m^3/d; the output of supplying water in 2020 is 42,000 m^3/d, of which the output of supplying water of networking water source is 42,000 m^3/d, and the output of supplying water of the independent water source of Buliangou infiltration ditch is 1400 m^3/d; the industrial reused water comes from the underground direct reused of Bulianta mine, water source of Majiagta mine pit. In 2008, the output of supplying water is 13,100 m^3/d, and in 2010, 2015, and 2020, the output of supplying water is 23,100 m^3/d. Afforestation reused water comes from the afforestation reused water of the oxidation pond in Bulianta mine, and the output of supplying water is 1500 m^3/d in 2008 and 2010, and 2000 m^3/d in 2015 and 2020.

6.4.2.2 Analysis of the Balance Between Supply and Demand of Water Resources in Different Level Years

From the above setup of optimal allocation model, we can obtain the results of the optimal allocation of water resources for different water users in Daliuta shaft district in 2008, 2010, 2015, and 2020 (see Table 6.8). From the table, it can be seen that:

- The domestic water in 2008, 2010, 2015, and 2020 is supplied by the networking tap water in the study area and the independent water source of Buliangou infiltration ditch.
- As regards production water, the industrial reused water can completely meet the demand and has some surplus in 2008, 2010, 2015, and 2020. The surplus is supplied to the industry.
- As regards the industrially used water, in 2008, 2010, 2015, and 2020, the surplus of the industrial reused water can completely meet the demand.
- As regards afforestation water, in 2008, 2010, 2015, and 2020, the mining area-owned afforestation reused water source cannot meet the water demand, and there are 919, 1284, 861, and 1527 m^3/d shortages, respectively.

6.4.2.3 Analysis of Water Supply Potential

On the basis of the existing and planned water supply engineering as well as the output of supplying water in different level years, the water supply potential in different years can be analyzed and obtained.

- As regards the industrial reused water, in 2008, 2010, 2015, and 2020, the water supply potential is 13,338 m^3/d, with increase of the future mine inflow; the water supply potential will increase correspondingly.
- As regards the afforestation water, in 2008, 2010, 2015, and 2020, the water supply potential is 7100 m^3/d, with the increase of the future water consumption. The afforestation reused water supply potential will increase correspondingly.

6.4.2.4 Suggestions for the Development and Utilization of Water Resources

From the analysis of the supply and demand balance of water resources as well as the water supply potential, it can be seen that the industrial reused water has big water supply potential and comes mainly from Bulianta mine water. The water supply potential can be enhanced through increasing the capacity of industrial reused water network and improving water treatment technology. Thus, water supply to Bulianta from the reused water source of Majiata mine pit and the reused

Table 6.8 The results of the optimal allocation of water resources in different level years in Bulianta mining area (*unit* m^3/d)

Planned level year	User source	Output of supplying water	Water supply potential	Water demand				Surplus and shortage
				Production	Livelihood	Industry	Afforestation	
2008	Tap water	48,400	–	0	4755		0	–
	Industrial reused water	13,100	13,388	5944		1783	0	5373
	Afforestation reused water	1500	7100				2419	−919
2010	Tap water	48,400	–	22.5	5289.0		0	–
	Industrial reused water	23,100	13,388	6588.5		1983	0	14,535
	Afforestation reused water	1500	7100				2784	−1284
2015	Tap water	46,400	–	0	5253		0	–
	Industrial reused water	23,100	13,388	6566		1970	0	14,564
	Afforestation reused water	2000	7100				2861	−861
2020	Tap water	43,400	–	0	6564			–
	Industrial reused water	23,100	13,388	8205		2461	0	12,434
	Afforestation reused water	2000	7100				3527	−1527

Note 1 Tap water comes from the networking tap water source and the independent water source of Buliangou infiltration ditch
Note 2 Industrial reused water comes from underground direct reused of Majiata mine, the water sources of Majiata and Rear Bulian mine pits
Note 3 Afforestation reused water comes from Heitangou domestic sewage treatment plant and Bulianta oxidation pond

water in Rear Bulian mine pit can be reduced, and the reduced part of water can be used as water supplied to Shangwan and the coal feeding system of liquification. As regards afforestation water, the shortage problem can be solved through the following approach: Because its water supply potential is 7100 m^3/d, the water supply potential can be excavated through improving and enhancing the treatment technology of the afforestation reused water. In addition, with the increase of future water consumption, the domestic sewage will increase correspondingly, to increase the intensity of sewage treatment will provide powerful guarantee for afforestation water during the planning period.

6.4.3 Analysis of the Optimization Results of Water Resources in Shangwan Mining Area

The coal feeding base of liquification consists of Bulianta mining area, Shangwan mining area, and the coal feeding system of liquification. Shangwan mine is located in the west bank of Ulan Mulun River, the north of the mine is bordered to Bulianta mine, and the south of the mine is adjacent to Huojitu mine.

6.4.3.1 Analysis of Water Sources and Output of Supplying Water in Different Level Years

Seen from the sources of different water, the tap water comes from the networking water source in the study area. The output of supplying water is 47,000 m^3/d in 2008 and 2010, 45,000 m^3/d in 2015, and 42,000 m^3/d in 2020. The industrial reused water comes from the underground direct reused of Shangwan mine water, the water source of Majiata mine pit, and the water source of Rear Bulian mine pit. The output of supplying water is 11,070 m^3/d in 2008 and 21,070 m^3/d in 2010, 2015, and 2020. Afforestation reused water comes from the underground reused water of Shangwan mine. The output of supplying water is 2200 m^3/d in 2008 and 2010 and 3000 m^3/d in 2015 and 2020.

6.4.3.2 Analysis of the Balance Between Supply and Demand of Water Resources in Different Level Years

From the above setup of optimal allocation model, we can obtain the results of the optimal allocation of water resources for different water users in Daliuta shaft district in 2008, 2010, 2015, and 2020 (see Table 6.9). From the table, it can be seen that:

- The domestic water in 2008, 2010, 2015, and 2020 is supplied by the networking tap water in the study area.

Table 6.9 The results of the optimal allocation of water resources in different level years in Shangwan mining area (*unit* m^3/d)

Planned level year	User source	Output of supplying water	Water supply potential	Water demand				Surplus and shortage
				Production	Livelihood	Industry	Afforestation	
2008	Tap water	47,000 (whole area)	–	0	2378		0	–
	Industrial reused water	11,070	1168	2972		6892	0	1206
	Afforestation reused water	2200	0				1209	991
2010	Tap water	47,000 (whole area)	–		2644		0	–
	Industrial reused water	21,070	1168	3306		6992	0	10,772
	Afforestation reused water	2200	0				1430	770
2015	Tap water	45,000 (whole area)	–	0	2626		0	–
	Industrial reused water	21,070	1168	3283		6985	0	10,802
	Afforestation reused water	3000	0				1430	1570
2020	Tap water	42,000 (whole area)	–	0	3282		0	–
	Industrial reused water	21,070	1168	4102		7231	0	9737
	Afforestation reused water	3000	0				1764	1236

Note 1 Tap water comes from the networking water source in the study area

Note 2 Industrial reused water comes from Shangwan mine water, water source of Majiata mine pit, and water source of Rear Bulian mine pit

Note 3 Afforestation reused water comes from Shangwan mine reused water

- As regards production water, the industrial reused water can completely meet the demand and has some surplus in 2008, 2010, 2015 and 2020. The surplus is supplied to the industry.
- As regards the industrially used water, in 2008, 2010, 2015, and 2020, the surplus of the industrial reused water can completely meet the demand.
- As regards afforestation water, in 2008, 2010, 2015, and 2020, the mining area-owned afforestation reused water source can meet the water demand.

6.4.3.3 Analysis of Water Supply Potential

On the basis of the existing and planned water supply engineering as well as the output of supplying water in different level years, the water supply potential in different years can be analyzed and obtained.

As regards the industrial reused water, in 2008, 2010, 2015, and 2020, the water supply potential is 1168 m^3/d, with increase of the future mine inflow, and the water supply potential will increase correspondingly.

6.4.3.4 Suggestions for the Development and Utilization of Water Resources

From the analysis of the supply and demand balance of water resources as well as the water supply potential, it can be seen that as regards industrial reused water. Part of water sully potential can be increased through increasing the capacity of industrial reused water network and improving water treatment technology. Thus, water supply to Bulianta from the reused water source of Majiata mine pit and the reused water in Rear Bulian mine pit can be reduced, and the reduced part of water can be used as water supplied to Shangwan and the coal feeding system of liquification. As regards afforestation water, with the increase of future water consumption, the domestic sewage will increase correspondingly, to increase the intensity of sewage treatment will provide powerful guarantee for afforestation water during the planning period.

6.4.4 Analysis of the Optimization Results of Water Resources of the Coal Feeding System for Coal Liquification

In the coal feeding system of liquification, the main inclined shaft is used. Coal is transported through the underground main connection roadway in Shangwan and Bulianta mines from underground coal bunker to the raw coal bunker of the coal liquification base to realize coal feeding for liquification.

6.4.4.1 Analysis of Water Supply Sources and the Output of Supplying Water in Different Level Years

Seen from the sources of different water of the coal feeding system of liquification, the tap water comes from the networking water sources in the study area, and the output of supplying water is 47,000 m^3/d in 2008 and 2010 and 45,000 m^3/d in 2015, and 42,000 m^3/d in 2020. The industrial reused water comes from the water sources of Majiata mine pit and Rear Bulian mine pit, and the output of supplying water is 10,000 m^3/d in 2008 and 20,000 m^3/d in 2010, 2015, and 2020.

6.4.4.2 Analysis of the Balance Between Supply and Demand of Water Resources in Different Level Years

From the above setup of optimal allocation model, we can obtain the results of the optimal allocation of water resources for different water users in Bulianta mining area in 2008, 2010, 2015, and 2020 (Table 6.10). From the table, it can be seen that:

- The domestic water in 2008, 2010, 2015, and 2020 is supplied by the networking tap water in the study area.
- As regards production water, the industrial reused water can completely meet the demand and has some surplus in 2008, 2010, 2015, and 2020. The surplus is supplied to the industry.
- As regards the industrially used water, in 2008, 2010, 2015, and 2020, the surplus of the industrial reused water can meet also completely the demand.
- As regards afforestation water, the coal feeding system of liquification does not have special water source for afforestation; therefore, there are 605, 835.2, 3862, and 4762 m^3/d shortages, respectively, in 2008, 2010, 2015, and 2020.

6.4.4.3 Analysis of Water Supply Potential

According to the water supply project planning and the output of supplying water in different level years, the water potential in different years can be analyzed and obtained. As regards the industrial reused water, the water supply capacity of projects reaches the maximum.

6.4.4.4 Suggestions for the Development and Utilization of Water Resources

From the analysis of the balance between the water supply and the water demand as well as the water supply potential, it can be seen that as regards the afforestation water, with the increase of the future water consumption, the domestic sewage will increase correspondingly, and it is suggested to set up special domestic sewage

Table 6.10 The results of the optimal allocation of water resources in different level years in coal feeding system of liquification (*unit* m^3/d)

Planned level year	User source	Output of supplying water	Water supply potential	Water demand				Surplus and shortage
				Production	Livelihood	Industry	Afforestation	
2008	Tap water	47,000	–	0	1189			–
	Industrial reused water	10,000	0	1486		446	0	8068
	Afforestation reused water		0				605	−605
2010	Tap water	47,000	–		1322			–
	Industrial reused water	20,000	0	1653		496	0	17,851
	Afforestation reused water		0				696	−696
2015	Tap water	45,000	–	0	7091			–
	Industrial reused water	20,000	0	8864		2659	0	8477
	Afforestation reused water		0				3862	−3862
2020	Tap water	42,000	–	0	8861			–
	Industrial reused water	20,000	0	11,077		3323	0	5600
	Afforestation reused water		0				4762	−4762

Note 1 Tap water comes from the networking water source in the study area

Note 2 Industrial reused water comes from the water sources of Majiata mine pit and Rear Bulian mine pit treatment project to meet the demand of afforestation in different level years. In addition, the surplus of the industrial reused water can be suitably supplied to afforestation.

6.4.5 Analysis of the Optimization Results of the Water Resources in Halagou Mining Area

Halagou mine is located in the eastern side of Ulan Mulun River at the northwest 55 km away from Shenmu County, Shaanxi Province, administrated by Daliuta town. The present Halagou mine consists of Chiyaowan mine, Qianshiban mine, and former Halagou mine, and its extent is irregularly rectangular in shape, 10 km long and 8 km wide.

6.4.5.1 Analysis of Water Sources and the Output of Supplying Water in Different Level Years

Seen from the sources of different water in Halagou mining area, the tap water comes from the networking water source in the study area. The output of supplying water is 47,000 m^3/d in 2008 and 2010, 45,000 m^3/d in 2015, and 42,000 m^3/d in 2020. The industrial reused water comes from the underground direct reused of Halagou mine water, and the output of supplying water is 1400 m^3/d in 2008 and 2400 m^3/d in 2010, 2015, and 2020.

6.4.5.2 Analysis of the Balance Between Supply and Demand of Water Resources in Different Level Years

From the above setup of optimal allocation model, we can obtain the results of the optimal allocation of water resources for different water users in Halagou mining in 2008, 2010, 2015, and 2020 (see Table 6.11). From the table, it can be seen that:

- The domestic water in 2008, 2010, 2015, and 2020 is supplied by the networking tap water in the study area.
- As regards production water, the output of the industrial reused water is 1400 m^3/d in 2008, meeting partly the water demand of production, 2400 m^3/d in 2010, 2015, and 2020, meeting partly the water demand of production; there are 906, 883, and 1702 m^3/d shortages, respectively.
- As regards the industrially used water, because the industrial reused water is used in production, there is no surplus.
- As regards afforestation water, there is no special water source for afforestation; therefore, in 2008, 2010, 2015, and 2020, the shortage of afforestation is 1209, 1392, 1430, and 1764 m^3/d.

Table 6.11 The results of the optimal allocation of water resources in different level years in Halagou mining area (*unit* m^3/d)

Planning level year	User source	Output of supplying water	Water supply potential	Water demand	Surplus and shortage			
				Production	Livelihood	Industry	Afforestation	
2008	Tap water	47,000	–		2378			–
	Industrial reused water	1400	1796	2972		892	0	−2464
	Afforestation reused water						1209	−1209
2010	Tap water	47,000	–		2644			–
	Industrial reused water	2400	1796	3306		0	0	−1898
	Afforestation reused water						1392	−1392
2015	Tap water	45,000	–		2626			–
	Industrial reused water	2400	1796	3283		985	0	−868
	Afforestation reused water		4200				1430	−1430
2020	Tap water	42,000	–		3282			–
	Industrial reused water	2400	1796	4102		1231	0	−2933
	Afforestation reused water						1764	−1764

Note 1 Tap water comes from the networking water source in the study area
Note 2 Industrial reused water comes from the direct use of Halagou mine water

6.4.5.3 Analysis of Water Supply Potential

On the basis of the existing and planned water supply engineering as well as the output of supplying water in different level years, the water supply potential in different years can be analyzed and obtained.

As regards the industrial reused water, in 2008, 2010, 2015, and 2020, the water supply potential is 1796 m^3/d, with increase of the future mine inflow and the water supply potential will increase correspondingly.

6.4.5.4 Suggestions for the Development and Utilization of Water Resources

From the analysis of the balance between the water supply and the water demand as well as the water supply potential, it can be seen that as regards production water and industrial water, the industrial reused water alone cannot meet the water demand. The problem can be solved through the following approach: through increasing the capacity of the water supply network of the industrial reused water and improving water treatment technology, to increase the water supply potential to meet the demand. As regards afforestation water, with the increase of the future water consumption, the domestic sewage will increase correspondingly, and it is suggested to set up special domestic sewage treatment project to meet the demand of afforestation in different level years.

6.4.6 Analysis of the Optimization Results of the Water Resources in Ulan Mulun Mining Area

Ulan Mulun mine is located at the eastern bank of Ulan Mulun River in Ejin Horo Banner in the south of Ordos City, Inner Mongolia, 41 km away from Ordos City, and its administration division belongs to Booltai Township of Ejin Horo Banner.

6.4.6.1 Analysis of Water Sources and Output of Supplying Water in Different Level Years

Seen from the sources of different water in Ulan Mulun mining area, the tap water comes from the networking water source in the study area and the independent water source of Xiaoliuta. The industrial reused water comes from the direct reused of Ulan Mulun mine water.

Seen from the sources of different water in Ulan Mulun mining area, the tap water comes from the networking water source in the study area and the independent water source of Shigetai. The output of supplying water is 47,000 and

2000 m^3/d in 2008 and 2010, 45,000 and 2000 m^3/d in 2015, respectively, and 42,000 and 2000 m^3/d in 2020. The industrial reused water comes from the underground direct reused of Ulan Mulun mine water, and the output of supplying water is 1400 m^3/d in different level year.

6.4.6.2 Analysis of the Balance Between Supply and Demand of Water Resources in Different Level Years

From the above setup of optimal allocation model, we can obtain the results of the optimal allocation of water resources for different water users in Ulan Mulun mining area in 2008, 2010, 2015, and 2020 (see Table 6.12). From the table, it can be seen that:

- As regards production water, the output of the industrial reused water is 1400 m^3/d in 2008, 2010, 2015, and 2020 and cannot meet the water demand of production; there are 86, 253, 241 and 651 m^3/d, shortages, respectively.
- As regards the industrially used water, there is no surplus after all is used in production; the shortage is 446, 496, 492, and 615 m^3/d in 2008, 2010, 2015, and 2020.
- As regards afforestation water, if the special water treatment engineering is constructed from afforestation water, tap water or industrial reused water used for afforestation will be saved.
- As regards the industrial water, the industrial reused water does not have surplus after all is used in production.
- As regards afforestation, there is no special treatment engineering for afforestation water in the mining, while the water consumption of afforestation is 605, 696, 715, and 882 m^3/d in 2008, 2010, 2015, and 2020, respectively.

6.4.6.3 Analysis of Water Supply Potential

On the basis of the existing and planned water supply engineering as well as the output of supplying water in different level years, the water supply potential in different years can be analyzed and obtained.

As regards the industrial reused water, with the increase of future mine inflow and the enhancement of water treatment capacity, the water supply potential will also increase correspondingly.

As regards afforestation water, if the special water treatment engineering is constructed from afforestation water, tap water or industrial reused water used for afforestation will be saved.

Table 6.12 The results of the optimal allocation of water resources in different level years in Ulan Mulun mining area (*unit* m^3/d)

Planned level year	User source	Output of supplying water	Water supply potential	Water demand				Surplus and shortage
				Production	Livelihood	Industry	Afforestation	
2008	Tap water	49,000 (whole area 47,000, Xiaoliyta water source 2000)	–		1189			–
	Industrial reused water	1400	5896	1486		446	0	−532
	Afforestation reused water						605	−605
2010	Tap water	49,000 (whole area 47,000, Xiaoliuta water source 2000)	–		1322			–
	Industrial reused water	1400	5896	1653		496	0	−749
	Afforestation reused water						696	−696
2015	Tap water	47,000 (whole area 45,000, Xiaoliuta water source 2000)	–		1313			–
	Industrial reused water	1400	5896	1400		492	0	−733
	Afforestation reused water						715	−715
2020	Tap water	44,000 (whole area 42,000, Xiaoliuta water source 2000)	–		1641			–
	Industrial reused water	1400	5,96	1400		615	0	−3933
	Afforestation reused water						882	−882

Note 1 Tap water comes from the networking water source in the study area and Xiaoliuta independent water source
Note 2 Industrial reused water comes from the direct reused of Ulan Mulun mine water

6.4.6.4 Suggestions for the Development and Utilization of Water Resources

From the analysis of the balance between the water supply and the water demand as well as the water supply potential, it can be seen that as regards industrial water, the shortage problem of industrial water and afforestation water in 2008, 2010, 2015, and 2020 in Ulan Mulun mining area can be resolved through the following approaches: (a) to increase a part of water supply potential through enhancing the capacity of the water supply network of the industrial reused water, (b) to increase water quality, to improve water treatment technology so as to the high requirement of the industrial users on water quality, and (c) to construct special treatment project for afforestation water.

6.4.7 Analysis of the Optimization Results of the Water Resources in Shigetai Mining Area

Shigetai mine is located in the north of Shenmu County, Shaanxi Province, at the eastern bank of Ulan Mulun River, administrated by Daliuta Township of Shenmu County. The west of the mine is Ulan Mulun River, the south of the mine is adjacent to Qianshiban minefield, and the north is bordered to Batuta minefield.

6.4.7.1 Analysis of Water Sources and Output of Supplying Water in Different Level Years

Seen from the sources of different water in Shigetai mining area, the tap water comes from the networking water source in the study area and Shigetai independent water source. The industrial reused water comes from the direct reused of Shigetai mine water.

Seen from the sources of different water in Shigetai mining area, the tap water comes from the networking water source in the study area and Shigetai independent water source. The output of supplying water is 47,000 and 1500 m^3/d in 2008 and 2010, 45,000 and 1500 m^3/d in 2015, and 42,000 and 1500 m^3/d in 2020, respectively. The industrial reused water comes from the underground direct reused of Shigetai mine water. The output of supplying water is 1200 m^3/d in different level year.

6.4.7.2 Analysis of the Balance Between Supply and Demand of Water Resources in Different Level Years

From the above setup of optimal allocation model, we can obtain the results of the optimal allocation of water resources for different water users in Shigetai mining area in 2008, 2010, 2015, and 2020 (see Table 6.13). From the table, it can be seen that:

- As regards production water, only the output of the industrial reused water is 1200 m^3/d in 2008, 2010, 2015, and 2020 and cannot meet the water demand of production.
- As regards afforestation water, if the special water treatment engineering is constructed from afforestation water, tap water or industrial reused water used for afforestation will be saved.
- As regards afforestation water, there is no special treatment engineering for afforestation water, while the water consumption of afforestation in 2008, 2010, 2015, and 2020 is, respectively, 968, 1114, 1430, and 1764 m^3/d.

6.4.7.3 Analysis of Water Supply Potential

On the basis of the existing and planned water supply engineering as well as the output of supplying water in different level years, the water supply potential in different years can be analyzed and obtained.

As regards the industrial reused water, with the increase of future mine inflow and the enhancement of water treatment capacity, the water supply potential will also increase correspondingly.

As regards afforestation water, if the special water treatment engineering is constructed from afforestation water, tap water or industrial reused water used for afforestation will be saved.

6.4.7.4 Suggestions for the Development and Utilization of Water Resources

From the analysis of the balance between the water supply and the water demand as well as the water supply potential, it can be seen that as regards industrial water, the shortage problem of industrial water and afforestation water in 2008, 2010, 2015, and 2020 in Shigetai mining area can be resolved through the following approaches: (a) to increase a part of water supply potential through enhancing the capacity of the water supply network of the industrial reused water, (b) to increase water quality, to improve water treatment technology so as to meet the high requirement of the industrial users on water quality, and (c) to construct special treatment project for afforestation water.

Table 6.13 The results of the optimal allocation of water resources in different level years in Shigetai mining area (*unit* m^3/d)

Planned level year	User source	Output of supplying water	Water supply potential	Water demand				Surplus and shortage
				Production	Livelihood	Industry	Afforestation	
2008	Tap water	48,500 (whole area 47,000, Shigetai independent water source 1500)	–		1902			–
	Industrial reused water	1200	1968	2378		713	0	−1891
	Afforestation reused water						968	−968
2010	Tap water	48,500 (whole area 47,000, Shigetai independent water source 1500)	–		2116			–
	Industrial reused water	1200	1968	2644		793	0	−2237
	Afforestation reused water						1114	−1114
2015	Tap water	46,500 (whole area 45,000, Shigetai independent water source 1500)	–		2626			–
	Industrial reused water	1200	1968	3283		985	0	−3068
	Afforestation reused water						1430	−1430
2020	Tap water	43,500 (whole area 42,000, Shigetai independent water source 1500)	–		3282			–
	Industrial reused water	1200	1968	2902		1231	0	−2933
	Afforestation reused water						1764	−1764

Note 1 Tap water comes from the networking water source in the study area and Shigetai independent water source
Note 2 Industrial reused water comes from the direct reused of Shigetai mine water

6.4.8 Analysis of the Optimization Results of the Water Resources in Huojitu Shaft District

Huojitu shaft belongs to Daliuta mine and is located in the side of Shaanxi of the junction of Shaanxi and Inner Mongolia and administrated by Zhongji Township of Shenmu County. The northwest boundary of the minefield is the main channel of Huojitugou, the southwest boundary is the connecting line of boreholes No. 274, 5, and 46, the southeast boundary is the connecting line of borehole No. 57 and Shujihe triangle point, bordered to Zhugaita minefield, and the northeast boundary is the main channel of Ulan Mulun River, and across the river lies Daliuta minefield.

6.4.8.1 Analysis of Water Sources and Output of Supplying Water in Different Level Years

The tap water comes from the networking water source in the study area and the independent water source of Huojitu infiltration ditch. The industrial and afforestation reused water comes from Huojitu underground water treatment plant.

Seen from the sources of different water in Ulan Mulun mining area, the tap water comes from the networking water source in the study area and Huojitu infiltration ditch in 2008 and 2010. The output of supplying water is 47,000 and 1500 m^3/d in 2008 and 2010, 45,000 and 1500 m^3/d in 2015, respectively, and 42,000 and 1500 m^3/d in 2020. The industrial reused water comes from Huojitu underground water treatment plant, and the output of supplying water is 2300 m^3/d in different level year. Afforestation reused water comes also from Huojitu underground water treatment plant, and the output of supplying water is 1500 m^3/d in 2008 and 2010 and 2000 m^3/d in 2015 and 2020.

6.4.8.2 Analysis of the Balance Between Supply and Demand of Water Resources in Different Level Years

From the above setup of optimal allocation model, we can obtain the results of the optimal allocation of water resources for different water users in Huojitu shaft district in 2008, 2010, 2015, and 2020 (see Table 6.14). From the table, it can be seen that:

- As regards domestic water, the tap water is supplied by the networking tap water in the study area and Huojitu infiltration ditch in 2008, 2010, 2015, and 2020.
- As regards production water, the industrial reused water cannot meet the water demand of production in 2008, 2010, 2015, and 2020. The shortage is 375, 675, 655, and 1108 m^3/d, respectively.

Table 6.14 The results of the optimal allocation of water resources in different level years in Huojitu shaft district (*unit* m^3/d)

Planned level year	User source	Output of supplying water	Water supply potential	Water demand				Surplus and shortage
				Production	Livelihood	Industry	Afforestation	
2008	Tap water	48,000 (whole district 47,000, infiltration ditch 1000)	–		2140		0	–
	Industrial reused water	2300	2940	2675		802		−1177
	Afforestation reused water	1500	–				1089	411
2010	Tap water	48,000 (whole district 47,000, infiltration ditch 1000)	–		2380		0	
	Industrial reused water	2300	2940	2975		892	0	−1567
	Afforestation reused water	1500	–				1287	213
2015	Tap water	46,000 (whole district 45,000, infiltration ditch 1000)	–		2364		0	–
	Industrial reused water	2300	2940	2955		886	0	−1541
	Afforestation reused water	2000	–				1287	713
2020	Tap water	43,000 (whole district 2000, infiltration ditch 1000)	–		2954		0	–
	Industrial reused water	2300	2940	3692		1108	0	−2500
	Afforestation reused water	2000	–				1587	413

Note 1 Tap water comes from the networking tap water source and the independent water source of Huojitu infiltration ditch

Note 2 Industrial reused water comes from Huojitu underground water treatment plant

Note 3 Afforestation reused water comes from Huojitu underground water treatment plant

- As regards industrial water, the industrial reused water cannot meet the water demand of industry in 2008, 2010, 2015, and 2020, and the shortage is 802, 892, 866, and 1392 m^3/d, respectively.
- As regards afforestation water, all afforestation water uses the self-owned afforestation reused water source in the shaft district in 2008, 2010, 2015, and 2020, and the water demand can be met.

6.4.8.3 Analysis of Water Supply Potential

On the basis of the existing and planned water supply engineering as well as the output of supplying water in different level years, the water supply potential in different years can be analyzed and obtained.

As regards the industrial reused water, with the increase of future mine inflow and the enhancement of water treatment capacity, the water supply potential will also increase correspondingly.

As regards afforestation water, the water supply potential is 411, 213, 713, and 413 m^3/d in 2008, 2010, 2015, and 2020. With the increase of future water consumption, afforestation reused water potential will increase correspondingly.

6.4.8.4 Suggestions for the Development and Utilization of Water Resources

From the analysis of the balance between the water supply and the water demand as well as the water supply potential, it can be seen that as regards industrial water, the shortage problem of industrial water and afforestation water in 2008, 2010, 2015, and 2020 in Huojitu shaft district can be resolved through the following approaches: (a) to increase a part of water supply potential through enhancing the capacity of the water supply network of the industrial reused water, (b) to increase water quality, to improve water treatment technology so as to meet the high requirement of the industrial users on water quality, and (c) to use directly the networking tap water to meet the water demand of industrial users. As regards afforestation water, with the increase of water consumption, domestic sewage will increase correspondingly, and the enhancement of domestic sewage treatment intensity will provide powerful guarantee for afforestation water.

6.4.9 Comprehensive Analysis on the Water Resources Optimization Results in the Study Area

On the basis of optimal calculation, the comprehensive analysis on the optimization results of different planned level years 2008, 2010, 2015, and 2020 in the study area is conducted as a whole in the following section.

6.4.9.1 Comprehensive Analysis of the Optimization Results in 2008

- In 2008, the total water supply capacity in the whole area is 91,490 m^3/d, which meets the water demand of 63,373 m^3/d in the whole area. The surplus is 28,117 m^3/d, demonstrating that the total output of supplying water can meet the demand.
- Statistics of the optimal calculation results were conducted based on the water source. For example, if to meet the water demand in 2008, 34,032 m^3/d of tap water, 24,334 m^3/d of industrial reused water, and 5007 m^3/d of afforestation water are needed; in 2008, the tap water supply capacity in the whole area is 52,900 m^3/d, the industrial reused water supply capacity is 25,390 m^3/d, and the afforestation reused water supply capacity is 13,200 m^3/d, illustrating that the tap water capacity has surplus of 18,868 m^3/d, the surplus of industrial reused water is 1056 m^3/d, and the surplus of afforestation reused water is very large, up to 8139 m^3/d.
- Industrial water demand is 12,866 m^3/d totally, including 4660 m^3/d of industrial reused water. In 2008, the tap water has surplus of 18,868 m^3/d. If industrial water demand has higher requirement on water quality, tap water is completely capable to substitute industrial reused water to meet the water demand of industry.
- In order to reflect more vividly the water supply of different water sources to different water users in different mines, the water supply network diagram of 2008 was specially drawn (see Fig. 6.1). In the figure, the arrow expresses the water supply direction. The number on the arrow is water yield. If it is zero, it means no water supply.

6.4.9.2 Comprehensive Analysis of the Optimization Results of 2010

- The total water supply capacity is 102,990 m^3/d and the water demand is 76,171 m^3/d in 2010 in the whole study area. According to the optimal calculation, the total output of supplying water of the optimal allocation is 78,080.6 m^3/d. The assurance rate of water supply is 102.5 %; the surplus is 24,909.4 m^3/d, illustrating that the total output of supplying water can meet the demand.
- Statistics of the optimal calculation were conducted based on water source. If to meet the water demand in 2010, 37, tap water 966.3 m^3/d, industrial reused water 34,467.3 m^3/d, and afforestation reused water 5647 m^3/d are needed in 2010. In 2010, in the whole area, the tap water supply capacity is 52,900 m^3/d, the industrial reused water supply capacity is 36,390 m^3/d, and the afforestation reused water supply capacity is 13,700 m^3/d, demonstrating that there is some

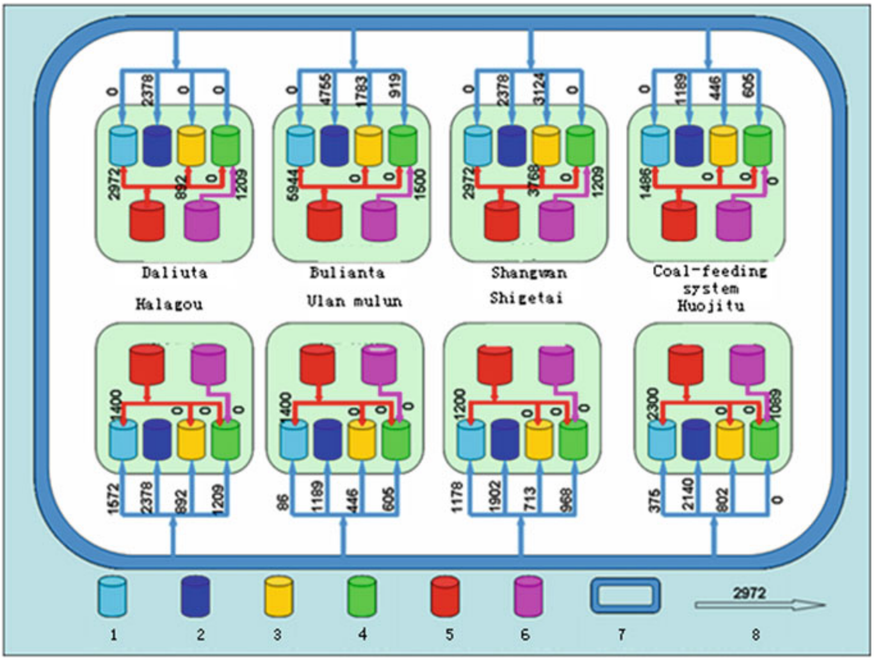

Fig. 6.1 Water supply network of 2008. *Note 1* production water demand; *2* domestic water demand; *3* industrial water demand; *4* afforestation water demand; *5* industrial reused water; *6* afforestation reused water; *7* networking tap water; *8* water supply direction and water yield

surplus in the tap water supply capacity, the surplus is 14,933.7 m^3/d, the surplus of the industrial reused water is 1922.7 m^3/d, and the surplus of the afforestation reused water is very big, up to 8053 m^3/d.

- The total industrial water demand is 19,893.8 m^3/d, including industrial reused water 11,046.6 m^3/d; in 2010, tap water has surplus of 14,933.7 m^3/d. If the industrial water demand has higher requirement on water quality, tap water is completely capable to substitute industrial reused water to meet the water demand of industry.
- In order to reflect more vividly the water supply of different water sources to different water users in different mines, the water supply network diagram of 2008 was specially drawn (see Fig. 6.2). In the figure, the arrow expresses the water supply direction. The number on the arrow is water yield. If it is zero, it means no water supply.

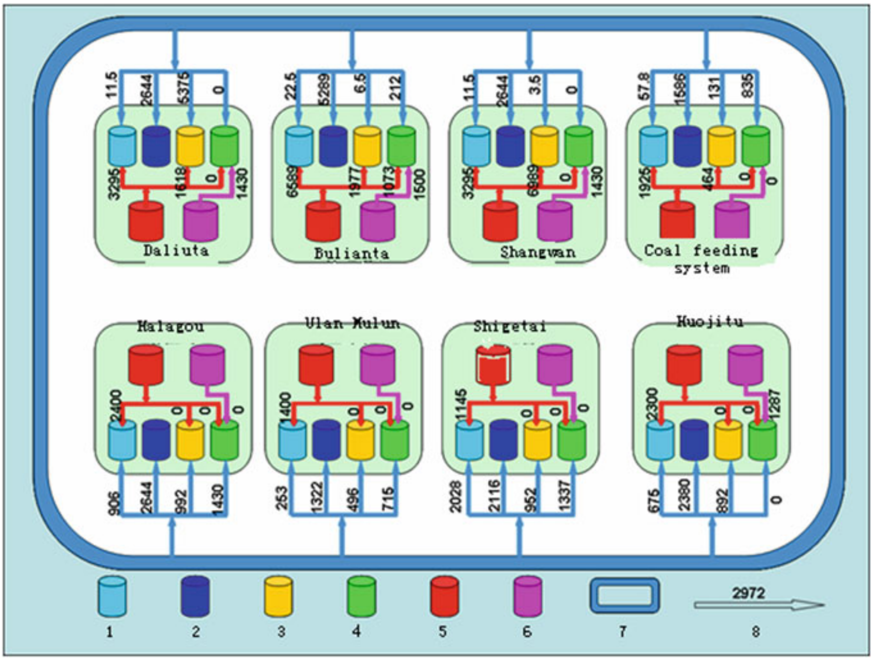

Fig. 6.2 Water supply network of 2008. *Note 1* production water demand; *2* domestic water demand; *3* industrial water demand; *4* afforestation water demand; *5* industrial reused water; *6* afforestation reused water; *7* networking tap water; *8* water supply direction and water yield

6.4.9.3 Comprehensive Analysis of the Optimization Results of 2015

- The total water supply capacity is 102,290 m^3/d and the water demand is 96,075 m^3/d in 2015 in the whole study area. According to the optimal calculation, the total output of supplying water of the optimal allocation is 96,075 m^3/d. The total water supply has surplus of 6215 m^3/d, illustrating that the total output of supplying water can meet the demand.
- Statistics of the optimal calculation were conducted based on water source. If to meet the water demand in 2015, 53,538 m^3/d tap water 53,538 m^3/d, industrial reused water 36,390 m^3/d, and afforestation reused water 15,000 m^3/d are needed in 2015. It is illustrated that in 2015 even all the industrial reused water is used up, tap water supply capacity is still insufficient. The shortage is 2638 m^3/d. The surplus of afforestation reused water is very big, up to 8853 m^3/d. There are two plans to resolve the shortage problem of tap water: firstly, to treat the surplus of afforestation reused water to improve water quality, so that the treated water can meet industrial demand and a part of tap water can be saved from industrial water consumption, finally complementing the shortage of tap water and

secondly, to increase the usage rate of industrial reused water, so as to save a part of tap water.

- The total industrial water demand is 21,947 m^3/d, including industrial reused water 7094 m^3/d and tap water 14,853 m^3/d. The tap water supply accounts for 67.7 % of the total water demand and can meet completely the requirement of industrial water demand on water quality.
- In order to reflect more vividly the water supply of different water sources to different water users in different mines, the water supply network diagram of 2008 was specially drawn (see Fig. 6.3). In the Figure, the arrow expresses the water supply direction. The number on the arrow is water yield. If it is zero, it means no water supply.

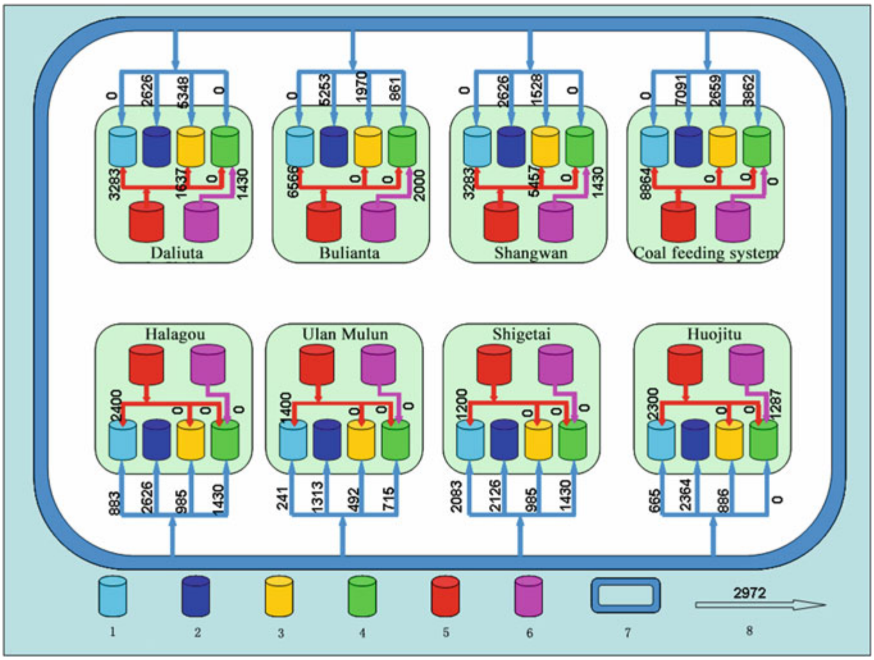

Fig. 6.3 Water supply network of 2015. *Note 1* production water demand; *2* domestic water demand; *3* industrial water demand; *4* afforestation water demand; *5* industrial reused water; *6* afforestation reused water; *7* networking tap water; *8* water supply direction and water yield

6.4.9.4 Comprehensive Analysis of the Optimization Results of 2020

- The total water supply capacity is 99,290 m^3/d and the water demand is 116,826 m^3/d in 2020 in the whole study area. The total water supply cannot meet the demand. The shortage is 17,536 m^3/d.
- Statistics of the optimal calculation were conducted based on water source. If to meet the water demand in 2015, tap water 73,320 m^3/d, industrial reused water 36,390 m^3/d, and afforestation reused water 7115 m^3/d are needed in 2020. In 2020, in the whole study area, the tap water supply capacity is 47,900 m^3/d, the industrial reused water supply capacity is 36,390 m^3/d, and the afforestation reused water supply capacity is 15,000 m^3/d, illustrating that in 2020 even all the industrial reused water is used up. The tap water supply capacity is still insufficient and the shortage is 25,420 m^3/d. The surplus of afforestation reused water is very big, up to 7885 m^3/d. There are two plans to resolve the shortage problem of tap water: firstly, to treat the surplus of afforestation reused water to improve water quality, so that the treated water can meet industrial demand and a part of tap water can be saved from industrial water consumption, finally complementing the shortage of tap water and secondly, to increase the usage rate of industrial reused water, so as to save a part of tap water.
- The total industrial water demand is 24,431 m^3/d, including industrial reused water 1607 m^3/d and tap water 22,824 m^3/d. Tap water supply accounts for 93.4 % of the total water demand and can meet completely the requirement of industrial water demand on water quality. At the same time, it is illustrated that with the great amplitude increase of industrial water demand, in case where the total amount of industrial reused water keeps the same, industrial reused water meets in priority demand of production, resulting in the great amplitude decrease of the available amount of industrial reused water in industrial water demand and sharp increase of tap water usage.
- In order to reflect more vividly the water supply of different water sources to different water users in different mines, the water supply network diagram of 2020 was specially drawn (see Fig. 6.4). In the figure, the arrow expresses the water supply direction. The number on the arrow is water yield. If it is zero, it means no water supply.

6.5 Summary

- The chapter stated firstly the theoretic basis of the multiobjective programming model of the water resources in the mining area, then aiming at the programming objective and tasks, formulated the criteria for modeling and established the objective function, the decision variables, objective constraint, and constraint conditions of the programming model of multiobjectives, multiwater sources, multiusers, and different water quality. Year 2005 was taken as the

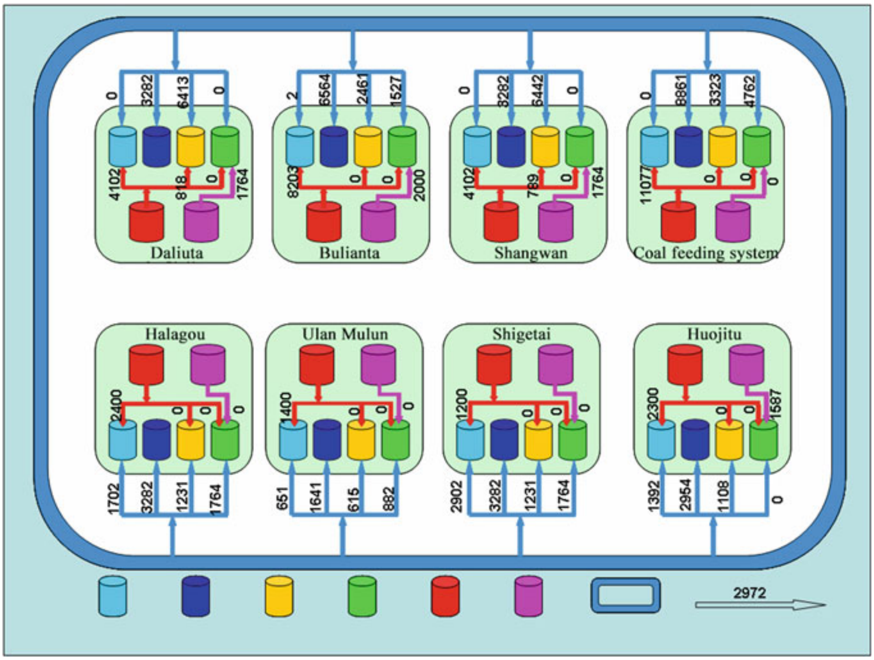

Fig. 6.4 Water supply network of 2020. *Note 1* production water demand; *2* domestic water demand; *3* industrial water demand; *4* afforestation water demand; *5* industrial reused water; *6* afforestation reused water; *7* networking tap water; *8* water supply direction and water yield

reference year. The water resources were optimally allocated, respectively, for level years 2008, 2010, 2015, and 2020. Through analysis of the calculation results of the model, the objective of the maximum assurance rate of water resources supply and the minimum water cost was reached. The optional technical plan of comprehensive utilization and allocation of water resources for different water sources and different users was put forward.

- The dissertation realized the optimization algorithm of the model by utilizing the multiobjective optimization function fgoalattain in the powerful optimization toolbox of MATLAB. The excellent characteristics of being rapid, stable, and highly efficient of MATLAB in large matrix calculation were reflected. The program operation was converged; the results were valid. The calculation results embodied completely the objective constraint of the optimal allocation.
- Through the analysis of the optimal calculation results of the years 2008, 2010, 2015, and 2020, we can conclude that the total water supply can meet the total water demand in 2008, 2010, and 2015, and the total water supply cannot meet the water demand in 2020. Water shortage occurs in 2015 and 2020 and shows the increasing trend.

  - In 2008, the water sources of different categories can meet the demand of different users on water quality and quantity and have surplus.
  - In 2010, the water sources of different categories can meet the demand of different users on water quality and quantity and have surplus.
  - In 2015, although the total water supply can meet the total water demand, in case where all the industrial reused water is used up, afforestation reused water has surplus of 8853 m^3/d, but tap water has shortage of 2638 m^3/d.
  - In 2020, the total water supply cannot meet the total water demand, and the total shortage is 17,536 m^3/d. In case where all the industrial reused water is used up, afforestation reused water has surplus of 7885 m^3/d, the shortage of tap water is 25 m^3/d, and tap water is seriously shortage. Because afforestation reused water is of mine-owned water source, cross-area allocation of afforestation reused water was not considered in the optimal allocation; therefore, in the mining area with abundant afforestation reused water, there is surplus of afforestation reused water, and the mining area without afforestation reused water source can use only tap water or the surplus of the industrial reused water, aggravating the shortage of tap water.

- According to the optimal allocation plan, the water supply plan by water quality, by user and by level must be adopted to utilize the most economically and the most efficiently the existing water sources. In case of the greatest possible utilization of the existing industrial reused water and afforestation reused water, the major problem is the shortage of tap water.

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Chapter 7

Patterns of Rational Development and Utilization of Water Resources in the Study Area

Through the above analysis, in the case of the continuous increase of regional water resources demand in Shendong mining area, with the decrease of the water recharge, different water source sites show the decreasing trend of water level, and water resources are faced with shortage. In recent years, with the direct utilization of water source sites in different spring fields, groundwater extraction in infiltration ditch, motor-pumped wells, and mine drainage has become the important factor influencing groundwater dynamical variation.

The current status of the development and utilization of water resources in the area is that by the end of 2005, the water supply in the study area can meet the total water demand and has some surplus. But in dry period, in 2003, tap water supply is not sufficient, there is 1961 m^3/d short, and in 2004 and 2005 the output of supplying water is also not very abundant.

Through the analysis of the optimization calculation results of years 2008, 2010, 2015, and 2020, we arrive at the following: in 2008, 2010, and 2015, the total water supply can meet the total water demand, and in 2020, the total water supply cannot meet the total water demand. In 2015 and 2020, tap water shortage occurs and shows the increasing trend.

- In 2008, different water sources can meet the demand of different users on quality and quantity of water and has some surplus.
- In 2010, different water sources can meet the demand of different users on quality and quantity of water and has some surplus.
- In 2015, although the total water supply can meet the total water demand, in case where all the industrial reused water is used up, there is surplus of 8853 m^3/d of afforestation reused water, but tap water has 2638 m^3/d short.
- In 2020, the total water supply cannot meet the total water demand, and the total shortage is 17,536 m^3/d. In case where all the industrial reused water is used up, afforestation reused water has surplus of 7885 m^3/d, and the shortage of tap water is 25,240 m^3/d. The tap water is seriously short.

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In order to be faced with the tense situation of water resources in the future, we should begin the work mainly from throttling, potential tapping, and open source. It is suggested to take the following measures.

- To realize the internal optimal allocation results and to increase the utilization efficiency of water resources. To carry out actively the comprehensive utilization of water resources, to utilize sufficiently the industrial reused water and the afforestation reused water, and to reduce to the greatest extent the consumption of tap water.
- To increase the reused rate of mine water is the important way to increase the development and utilization potential of water resources in the study area.
- To dig into actively the development and utilization potential of water resources in the study area and peripheral available new water sources.
- To formulate the patterns, the plan and safeguards of the scientific and rational development and utilization of water resources.

7.1 Problems of Mine Water as Usable Resources and Study of Countermeasure

In the study area, the average water inflow in many years in Daliuta mine, Huojitu mine, Shangwan mine, Bulianta mine, Halagou mine, Shigetai mine, and Ulan Mulun mine is 1470.5 m^3/h. The total volume is 12,667,000 m^3 and tends to increase year by year. The total area of gob is 130,628,000 m^2, and the total water-accumulating area is 39,307,000 m^3. With regard to water resources, mine water has huge potential.

Therefore, transformation of mine water into resources and increase of the reused rate of mine water, are the important ways to ease the tense situation of water resources in Shendong mining area, not only reduce the discharge of waste water, but also save great amount of tap water, reduce the waste of water resources, increase the economic benefit after transformation.

Underground sewage treatment station was constructed in Daliuta mine and Huojitu mine, and treatment mode is mainly coagulation sedimentation and filtration; a part of the treated water is used as underground industrial reused water and another part is drained; the major problems are low reused rate and low treatment efficiency. With Huojitu mine as example, in 2004 2,070,000 m^3 of underground sewage were treated, and 840,000 m^3 were used as underground reused water; in 2005, it is estimated that 1,800,000 m^3 of underground sewage will be treated, 800,000 m^3 will be used as underground reused water, and the reused rates are 41 and 44 %, respectively. The average suspending solid in input water of underground sewage treated in 2004 in Huojitu mine was 217 mg/l, the average suspending solid after treatment was 123 mg/l, and the average treatment efficiency was 43 %; in June 2004, peak period of suspending solids, the suspending solids in input water were up to 920 mg/l, and after treatment, the suspending solids were 617 mg/l, surpassing much more the reused water standard.

For the existing problems, in combination with actual investigation, analysis and study, we think:

- Pretreatment facilities of mine water are not sufficient, and the volume of regulation pool (may be used as primary sedimentation tank) is not enough and therefore, cannot realize the mixed regulation for the pollutants in mine water and remove the large suspending grains, increasing the load of the subsequent treatment. The effective retention time in pool and the mixture action of stage regulation are considered generally in a reasonably designee primary sedimentation pool; 40–60 % of suspending solids are removed. Underground mine water enters to a sewage bin first; when pumped to the surface sewage station, this is basically sewage and mixture of sedimented coal slurry. If an effective sedimentation regulation pool is constructed underground, then mine water enters to the underground regulation pool after sedimentation, according to the water quality in the pool. It is determined whether the water in the pool can be directly reused and pumped to the surface treatment station for treatment; in this way, on the one hand the utilization of water resources can be transferred stochastically and on the other hand, the load of the subsequent water quality treatment can be reduced and the treatment cost is reduced.
- Control of coagu-flocculation reaction. The hydrolyzed polymer of different forms makes coagulant produce coagulation. H^+ generated continuously during hydrolysis will certainly result in the decrease of pH. When the alkalinity in the raw water is insufficient or the dosage of the coagulant is relatively big, pH of water will decrease sharply, influencing coagulation effect. In this case, lime or sodium bicarbonate should be added to maintain pH of water. Water temperature has an obvious impact on coagulation effect. When water temperature is below 5 °C, the hydrolysis speed of coagulant is very slow; hence, treatment efficiency decreases. Therefore, insulation measures should be enhanced in coagu-flocculation reaction pool, ensuring as much as possible water temperature higher than 5 °C. Metering equipment for adding coagulant adopts electromagnetic flowmeter can adjust the dosage at any time.

Too high dosage of coagulant, too low water temperature, and too high viscosity of coagulant are unfavorable to the mutual flocculation of colloidal particles and influence the flocculation effect. Therefore, the water in sedimentation pool before coagulating sedimentation must be measured and tested to determine the suitable dosage and to adjust PH, so as to ensure the effect of coagu-flocculation reaction and to increase the treatment efficiency of suspending solids.

- To enhance the deepened treatment of water after coagulating sedimentation reaction, to increase the reused rate of mine water, to build effective sand filter pool and active carbon adsorption tower to make the mine water reach the standard of drinking water, and to reduce the pressure on the water resources in the area.

- To strengthen the detection intensity of the water quality in mine water treatment station through environmental protection and energy—saving departments, to detect and analyze at any time the reclaimed water and the output water of the primary sedimentation pool, to allocate the treated mine water at any time according to the principle of water of good quality for superior usage and water of poor quality for inferior usage, to ensure the reused rate of mine water, and to avoid the waste of water resources.

With regard to the comprehensive utilization of mine water, Xinhe mine in Xuzhou mining area has used directly mine water as urban water supply source and has supplied totally 40,000,000 m^3 water to Xuzhou City.

The principal thinking is that gob water and production mixed water of good quality are drained by separate system through adopting technical approaches such as cleaning sewage and bypass, drainage and collection, and isolation and sealing.

7.2 Analysis of Water Resource Development and Utilization Potential

The analysis of the development and the utilization potential of water resources have usually two meanings. The first is to compare and analyze the maximum water supply of the water supplying projects and the actual water supply, so as to excavate its potential. The second is to excavate the development and utilization potential of the water resources in the study area and peripheral available new water sources. In the following section, analysis will be conducted in three aspects: the development potential of water supplying projects, the development and utilization potential of new water sources inside and outside the study area.

7.2.1 Analysis of Water Supply Potential of Water Supplying Projects

Water supplying projects include tap water project and reused water project. With regard to tap water project, the water yield of water supplying spring field shows the decreasing trend. For example, the water yield of the water source in Kaokaoligou decreased by 9.0 % annually on the average from 1998 to 2005, and the water yield of water source in Halagou decreased by 5.5 % annually on the average from 1992 to 2005, while Daliuta underground water treatment plant, underground clear water of Ulan Mulun mine, Bulianta underground water treatment plant, and Gongnieergaigou reservoir had reached their maximum water supply capacity. Therefore, general speaking, the water yield of tap water projects do not have any potential to excavate.

With regard to the reused water supplying projects, the industrial reused water projects have 64,778 m^3/d reused water; the water supply is 34,388 m^3/d, the surplus is 30,390 m^3/d. The maximum water supply capacity of afforestation reused water project is 23,000 m^3/d. The water supply is 11,700 m^3/d. The surplus is 11,300 m^3/d. For details, see Table 7.1.

7.2.2 Analysis of the Internal Water Resources Development and Utilization Potential in the Study Area

7.2.2.1 Water Source of Spring Field

Within the study area, apart from the major tributaries already developed and planned to develop such as Gongnieergaigou, Kaokaolaigou, Halagou, and Buliangou, the tributaries with the annual runoff over 1,000,000 m^3 include also Liugengou and the water source of Budaihao spring field. Liugengou spring field is located to the east of Shigetai village at the midstream of Ulan Mulun River, the area is 33.81 km^2, and it is an independent hydrogeological unit. Its major aquifer is the medium-fine sand and silty fine sand of Quaternary Shalawusu Formation. Groundwater is mainly recharged by rainfall and discharged predominantly by springs. The flow is approximately 5,600 m^3/d during the dry season and approximately 7,000 m^3/d during the wet season. In combination with the “11th Five-Year Plan” of Shendong mining area, the maximum water supply potential of Liugengou and Budaihao water sources is 3,000 m^3/d separately. In recent years, many enterprises have got the right of use of different water sources, constructed reservoirs, and facilities intaking water from rivers. There is no available water source along Ulan Mulun River in Ejin Horo Banner, Inner Mongolia. It is suggested to apply for the right of use of medium and small water sources such as Liugengou and Budaihao, so that the study area has certain reserves for tap water supply in future.

In addition, the tributaries of Ulan Mulun River at the south to Daliuta, i.e., spring fields such as Mingaitugou, Xumeigou and Xiaomuhegou, can be used as scattered medium–small-scale water supply sources. But at present, the available extractable reserves cannot be determined. These water sources can be used only as temporal water sources to develop and utilize.

7.2.2.2 Water Sources for Direct Extraction of Groundwater in Water Source Site

At present, the water-intake way in the study area is mainly direct use of spring water. In area where the aquifer in spring field and beach is relatively thick, abundant in water, and topographical conditions are suitable, to intake water

Table 7.1 Analysis of the reused water supply potential (*unit* m^3/d)

Reused water project		Reusable water yield	Water yield already reused	Surplus
Industry	Daliuta mine water	10,154	6920 (including afforestation water 2000)	3234
	Huojitu mine water	5640	2700 (including afforestation water 400)	2940
	Bulianta mine water	16,488	3100	13,388
	Ulan Mulun mine water	7296	1400	5896
	Shangwan mine water	2236	1068	1168
	Halagou mine water	2196	400	1796
	Shigetai mine water	3168	1200	1968
	Majiata infiltration ditch and mine pit water source	10,000	10,000	0
	Rear Bulian mine pit	10,000	10,000	0
	Subtotal	64,778 (2400 afforestation water taken out)	34,388 (2400 afforestation water taken out)	30,390
Afforestation	Heitangou domestic sewage treatment plant	2000	2000	0
	Daliuta domestic sewage treatment plant	6500	2300	4200
	Afforestation reused water of Shangwan mine	3000	3000	0
	Daliuta underground water treatment plant	2000	2000	0
	Huojitu underground water treatment plant	400	400	0
	Afforestation reused water of oxidation pond of Bulianta mine	9100	2000	7100
	Subtotal	23,000	11,700	11,300
Total		87,778	46,088	41,690

through tube well and large-diameter well can sufficiently utilize the storage adjustment function of the aquifer; that is to say, water is overextracted reasonably during the dry season and in the wet season, the overextracted part is recharged completely, reaching the balance between the recharge and the extraction of groundwater in a hydrological year or minor hydrological cycle.

Taking Kaokaolaigou water source site as example, the optimization management model of groundwater was set up to probe into the possibility of underground extraction of groundwater. The extractable quantity is mainly restricted by the water level at control points. Because the difference of the spatial distribution of aquifer thickness is big, the thinnest is only 0.13 m, and the thickest is more than 50 m. Therefore, although the recharge volume in the calculation period in the area is up to 24,575,364 m^3, the total extraction volume of the optimally positioned wells is only 1,370,000 m^3/a, accounting for only 5.57 % of the recharge volume. The total extraction volume of the planned wells, the existing springs, and wells is 7,930,000 m^3/a, accounting for 32.3 % of the total recharge volume.

Thus, under the preconditions of ensuring certain spring flow and groundwater level, it is unsuitable to extract a great quantity of groundwater in water source sites of the study area. But during dry season, groundwater can be suitably extracted at the downstream of the spring exposure points, and in area where the aquifer is relatively thick, it is suitable that the total extraction volume accounts for 20 % of the spring flow. According to the preliminary estimation, under the existing conditions, the direct extraction of groundwater at different water source sites can increase approximately 6,000 m^3/d of tap water.

7.2.2.3 Water Source in Island Beach of Ulan Mulun River

The flood beach and the first-order terrace of Ulan Mulun River are strongly watery. According to the groundwater occurrence characteristics and the actual investigation in the study area, speaking from the significance of water supply, in the flood beach of Ulan Mulun River, there are some temporal water-intaking points in island beach with certain development potential, for example, Shigetai island beach, flood beach of Buliangou mouth, and flood beach of Huhewusugou mouth. Under natural conditions, the major recharge source of groundwater in these sections is the lateral runoff of groundwater, rainfall surface water infiltration during the flood period. Under mining conditions, the natural recharge can increase, surface water seepage is stimulated, and evaporation is reduced; the surface water seepage is the major recharge in mining status.

1. **Shigetai island beach**

   It is located from Shigetaigou mouth to Huhewusugou mouth, i.e., the bank of Ulan Mulun River, approximately 4 km long and 450 m wide maximum. The top of the aquifer is Quaternary alluvial sand. The lower is sand and gravel, poorly sorted fine sand and mud sand filling resulted in poor permeability. The permeability coefficient of the aquifer is 5–10 m/d. The specific water yield is 0.1–0.15, and the influential radius is 60–80 m. This section is suitable for extraction by large-diameter well. The predicted extraction volume is 1,000 m^3/d.

2. **Flood beach of Buliangou mouth**
   The flood beach of Ulan Mulun River, 500 m south to Buliangou mouth, is Quaternary alluvial argillaceous medium-fine sand, sand and gravel, 6–8 m thick in the west part, and 3–4 m thick in the east part. Water is taken through large-diameter well. This section is suitable for extraction through large-diameter well; the predicted extraction volume is 1,000 m^3/d.
3. **Flood beach of Huhewusugou mouth**
   The flood beach of Ulan Mulun River at the downstream of Huhewusu mouth. The aquifer is 5–11 m thick. It is a section where the aquifer is the thickest in the flood beach of Ulan Mulun River in the study area. The permeability coefficient is 5–10 m/d. It is extracted by well of 5 m in diameter. The maximum influential radius is approximately 100 m. If the wells are 300 m apart, 5 wells can be positioned and the total extraction volume is 1,000 m^3/d.

The existing problem is that because the swinging of the main stream line of river and flood of torrent result in difficulties for positioning wells. Tube well may be blocked due to sediments after long-time extraction.

7.2.2.4 Mine Water Resources

1. **Mine inflow**
   The reuse project of mine water is implemented in each mine during the planning period for industry and afforestation. Except that the water source of Heitangou sewage treatment plant and Daliuta sewage treatment plant comes from domestic sewage, the rest of the reused water sources are all mine inflow. From the above analysis (see Table 7.1), it is known that the water supply potential of mine water is 37,490 m^3/d.
2. **Accumulated water in gob**
   The accumulated water in gob of coal mines is the water resources not sufficiently known, developed, and utilized so far. The accumulated water of gob is the accumulated and stored water which continues to enter into the original mining level of seams after coal mining activities stopped along different passages (fractures, voids, faults, etc.). Through statistics, calculation, and analysis, the total volume of accumulated water of gob in mines in the study area is 39,307,000 m^3. After being treated by suitable physical and chemical methods, the accumulated water of gob in the study area can reach the water quality standards for industrial water, domestic water, or afforestation water. Therefore, during the planning period, detection, analysis and study of water quantity, and water quality of the accumulated water of gob must be carried out deeply. Its distribution extent, water-accumulation scale, and situation of water quality must be determined further. And the accumulated water of gob must be taken as "underground reservoir," brought into the systematic management. On the one hand, it can be used as the new water-intake source and on the other hand, it can provide reliable basis for water hazard prevention during further coal mining,

avoiding water inrush accident. In this way, it is capable to decrease the demand on the common groundwater development and utilization, also to ease the contradiction of water supply and water demand in the study area and at the same time, to decrease the filled water volume when mining the underlying seams and to reduce the hidden unsafe hazards due to inrush of accumulated water of gob into mines.

From the above analysis, it can be known that the total development and utilization potential of mine water resources is 37,490 m^3/d (here the development potential of mine inflow is only calculated). It can be seen that the utilization potential of mine water is very big; apart from the own use in mines, mine water can be also used in tap water, industrial, and afforestation reused water and is an effective way to resolve the problem of water use in coal chemical industry in the future in the study area.

7.2.2.5 Intermediate Water Resources

From the above analysis, it is known that the water supply potential of afforestation reused water project is 11,300 m^3/d, of which the potential of domestic sewage reused water project is 4200 m^3/d, with the increase of water consumption in the future in the study area, and the domestic sewage will increase correspondingly also, therefore, to enhance the treatment intensity of the intermediate water resources, and to increase the reuse rate of the intermediate water, powerful guarantee for afforestation water in the planning period will be provided. The development and utilization potential of the internal water sources of the study area is shown in Table 7.2.

7.2.3 Analysis of the Development and Utilization Potential of the Exterior Water Resources of the Study Area

The exterior water sources of the study area refer to the water sources of stable water yield and good quality located in the surrounding area. It includes mainly Baahar Nuur Lake—Subei Bei Lake area (Haoleibaoji water source), Hatoucaidang water source, phreatic water in Yellow River beach at Gushanchuan mouth and Heilonggou—Linyinghui karst spring field, etc.

7.2.3.1 Baahar Nuur Lake—Subei Lake Area (Haoleibaoji Water Source)

Baahar Nuur Lake—Subei Lake area is located on the northwest of the study area, approximately 90 km away from Bulianta mine, a part of Cretaceous artesian basin of Shaanxi, Gansu, Ningxia, and Inner Mongolia, the nearest water-rich section to

Table 7.2 Analysis of water supply potential of the internal water sources in the study area (*unit* m^3/d)

Water source of water supply	Usage	Potential of water supply	Note
Water source of spring field	Tap water	6000	The right of use of Liugengou and Budaihao water sources are needed to be applied for, temporal water source is not included
Groundwater source for direct extraction in water source sites	Tap water	6000	Extra-extraction during the dry season, the total extraction volume is controlled within 20 % of the spring flow
Temporal water source of island beach of Ulan Mulun River	Tap water	3000	Due to the influence of swing of the stream line of river and flood, it is difficult to locate wells; the deposited silty is serious in wells after long-time extraction; these water sources may be used as the temporal water source
Mine water resources	Industrial reused water	30,390	
	Afforestation reused water	7100	
Intermediate water resources	Afforestation reused water	4200	With the increase of water consumption in the future, the domestic sewage will increase correspondingly; the water supply potential of the intermediate water resources will also increase

the mining area, a closed hydrogeological unit. The ground water in this area is divided into porous phreatic water in Quaternary loose deposits and porous fracture confined water in Cretaceous clastic rocks. The phreatic water and the confined water are both collected to the middle of the lake from the periphery, have abundant water yield, of which Subei Lake—Haoleibaoji water-rich section has extractable volume of up to approximately 150,000 m^3/d. At present, a part of the water yield of the water source is used by Coal Liquefaction Corporation of Shenhao Group located in Ordos City.

7.2.3.2 Hatoucaidang Area

Hatoucaidang area is located in the southwest of Dongsheng coal field, contiguous area of Dongsheng undulating plateau and Maowusu desert. The aquifer is the thick Quaternary Upper Pleistocene Shalawusu Formation and has abundant water yield and good quality. The water yield of single well can be up to 2042 m^3/d.

7.2.3.3 Phreatic Water in Yellow River Beach at Gushanchuan Mouth

Yellow River beach at Gushanchuan mouth is located on the east of the study area, within Fugu County, more than 100 km away from the mining area; it is Quaternary Holocene alluvial layer mainly composed of gravel. The aquifer is 20–30 m thick and has abundant water yield. The water inflow of single well is 5782 m^3/d.

7.2.3.4 Heilongou-Linyinghui Karst Spring Field

Heilongou-Linyinghui karst spring field is located on the east of the study area, within Fugu County, more than 100 km away from the mining area. The major aquifer is the upper and the middle members of Middle Ordovician Majigou Formation. The measured water inflow of single well is 22,000–45,000 m^3/d.

The above-mentioned four water sources are water sources with abundant water yield located at the periphery at approximately 100 km away from the study area, at present not applied for the use in the study area. At long term, the exploitation potential of the internal water sources in the study area is limited. From long-term consideration, in consideration of the sustainable development of the study area, these water sources must be brought into the plan of the study area, the right of use should be applied for as soon as possible (to avoid preemption of others), and these water sources should be taken as the perpetual water sources to provide reserves and insurance of water resources for the development of the study area.

Because Haoleibaoji water source has been used by Coal Liquefaction Corporation of Shenhua Group located in Ordos City, for the study area as the coal supply base of the Coal Liquefaction Corporation, the investment to apply for use of the water source together with the Coal Liquefaction Corporation will be relatively less and it will be easier to get a part of the right of use. In combination with the “11th Five-Year Plan” of Shendong mining area, only is considered Haoleibaoji water source as the exterior water source for long-term water supply in the present plan. The water supply potential is 30,000 m^3/d.

7.2.3.5 Analysis of Feasibility of Taking Haoleibaoji Water Source as a Large-Scale Perpetual Water Source of Water Supply

Within 200 km^2 of Haoleibaoji water source site, the reserved water resources are more than 8.9 billion m^3. If the daily extraction is 80,000 m^3, theoretically it can be maintained for 304 years. The water-intaking capacity of the water source is undoubted. The reliability of Haoleibaoji water source is obviously increased due to its following three special conditions: (1) it is located in the internal flow area and is a small basin in Ordos undulating plateau, hydrogeologically a closed system of natural cycle. Therefore, there is no interference of the upstream on the water source, nor interference of the water source on the downstream. It is difficult to avoid these interferences for most other water sources. (2) It is located in the farming-pastoral region, sparsely populated, only approximately 7 persons/km^2 on the average. Local water consumption is very little, and the problem of contending for water against the agriculture and the animal husbandry is very little. (3) Surrounding Haoleibaoji water source site, there are many available reserved water sources for exploitation, such as Zhigentela water source site, Qigaizhuo water-rich section; these water sources have the total extractable water yield of more than 70,000 m^3/d. With these reserved water source sites, the water supply project of Haoleibaoji water source is possible to supplement and extend, and the risk of the project will be greatly reduced.

7.3 Study on the Water Resources Development and Utilization in the Study Area

On the basis of the regional geological and geomorphologic characteristics, with reference to related hydrogeological and meteorological data in Shendong mining area, the development and utilization of water resources in Shendong mining area should follow the following:

- Making overall plans and taking all factors into consideration, overall arrangement, adjusting measures to local conditions, comprehensive utilization.
- Giving priority to domestic water, production water of coal field development, water demand of mating industrial enterprises, and social service sector in cities and towns, giving consideration to the water demand of agriculture.
- Water supply projects of water sources are mainly in the form of multipoints, dispersed spot utilization of local water sources, large-, medium- and small-scale projects are combined together.
- The utilization of water resources should be favorable to improve the environmental conditions of water and protect the ecological environments.
- Following the principle of saving water and improving the economic benefit of water resources, conducting the development and utilization of water resources in the mining area in combination with the characteristics of water shortage of water resources, big and concentrated water consumption, uneven yearly and interannual distribution of river flow, high sand content.

7.3.1 Development and Utilization Mode of Water Resources

On the basis of deep analysis and understanding of the characteristics, development and utilization status, balance between supply and demand, water supply potential of the water resources in Shendong mining area, water resources development and utilization mode conforming to the actuality of the study area was put forward.

- Implementing the comprehensive utilization mode of multiwater sources, multiusers, water supply by quality, and high-quality water for preferential use.
    - The comprehensive utilization mode of water resources can increase the water consumption of the reusable water and save correspondingly the tap water consumption. In this way, it can not only ease the tense situation of water consumption in the study area, but also meet the different demand of users and decrease the water cost for users, achieving the comprehensive utilization of water resources while protecting the water environments.
    - At present, the situation of water supply by quality through tap water system, industrial reused water system, and afforestation reused water system has been preliminary formed in the study area. The analysis of the future balance between supply and demand of water resources in the study area was done also according to water supply by quality.
    - Tap water is mainly used in domestic drinking and users who need water of high quality in the mining area.
    - Industrial reused water (such as water for cooling, coal washing, underground dust removal, flushing) uses mainly the reusable water underground drained and treated which meet the requirement of water quality.

      Afforestation reused water utilizes mainly the treated domestic sewage and is used for irrigation of lawn and trees; domestic sewage contains some organic matters and is very suitable for afforestation water.

- Connotative development mode of excavating the internal water resources potential and increasing the use rate of the reusable water
    - From the above analysis, it can be known that within the study area, some relatively large water sources of spring fields such as Budaihao and Liugengou have been not exploited and utilized so far; so it must apply for development and utilization of these resources as soon as possible, so as to provide certain tap water reserves for the near-future socioeconomic development of the study area.
    - The direct extraction of water source site shows certain potential and suitable overextraction can be conducted during peak period of tap water consumption or dry season. Although the present study has demonstrated preliminary its feasibility and reliability, the extraction of this part of groundwater will influence directly the spring flow; therefore, before extraction, further demonstration should be done approximately well location, control of extracted volume, and monitoring approaches.
    - Island beach of Ulan Mulun River as a temporary water source has also some potential; the key for the development of this part of water resources is the extraction technology and the layout of well location.
    - The utilization potential of mine water resources is also very big. We must give full play to underground water treatment plants in different mines, increase the degree, the scale of underground wastewater and domestic

sewage treatment and the utilization intensity, perfect continuously reused water system, and improve the use rate of mine water. The utilization of mine water must be based on the principle of nearby utilization. The connotative development mode of excavating the internal water resources potential and increasing the use rate of the reusable water can not only develop and utilize effectively the internal water resources in the study area, reduce waste of water resources, and provide powerful guarantee for construction of the study area, but also have short water supply pipeline and low-cost water supply, achieving good economic and social benefits.

- Sustainable development mode of application, development, and rational utilization of exterior water resources
    - The water supply shortage in 2020 in the study area is 17,536 m^3/d, of which tap water shortage is 13,816 m^3/d, with the further increase of future coal production and the further development of pillar industries such as coal power, coal chemistry, the water consumption will increase further in the study area, while the long-term utilization potential of internal tap water sources in the study area is limited, so it must as soon as possible apply for development of large-scale water sources outside the study area, if it does not apply for the right of use of the exterior water sources, the long-term development of the study area will be restricted by water resources. From the above analysis, it can be known that the exterior water resources of the study area, i.e., Haoleibaoji water source and Hatoucaidang water source, have big water yield and good quality. However, because of large investment and long transport distance, the cost of water supply is high. Therefore, when supplying water, it must be based on the internal water sources in the area, on the basis of full utilization of the internal water resources; the exterior water resources are rationally and economically utilized. So if to realize the long-term sustainable social and economic development of the study area, we must adopt the sustainable development mode through application, development, and rational utilization of the exterior water resources.

7.3.2 Scheme of Water Resources Development and Utilization

The study on the comprehensive utilization technology of water resources in the study area is mainly to solve the problem of the imbalance between supply and demand of water resources in the study area, to increase the benefit of the comprehensive utilization of water resources, and so as to formulate the overall scheme of the future development and utilization of water resources through considering the study area as a whole. The general guiding concept of the scheme is to increase water sources and save consumption, to pay attention to the comprehensive utilization of water resources, to solve the problem of the imbalance between supply and demand of water resources, and to realize the sustainable development and utilization of water resources.

7.3.2.1 Setting of the Planning Scheme

From the above analysis, it can be known that in the near future, i.e., from 2006 to 2015, the output of supplying water of the water supply projects can meet the water demand, but, in long term, i.e., from 2016 to 2020, the output of supplying water of tap water cannot meet the demand; the output of supplying water of the industrial reused water in 2020 cannot meet the demand; and from 2016 to 2020, the output of supplying water of the afforestation reused water cannot meet the water demand. Aiming at the results of the balance between supply and demand of water resources during the above-mentioned planning periods, the effective approach to solve the problem of the future imbalance between supply and demand of water resources is to rationally and economically develop and utilize the water supply potential for different kinds of water demand. Here, the problem of the balance between supply and demand during the planning periods is analyzed, studied, and solved through setting the following four situations, i.e., with regard to the tap water, the industrial reused water and the afforestation reused water, the output of supplying water will increase by 10, 25, 50, and 75 %, respectively, on the basis of the output of supplying water of different planning years. The above-mentioned situations are set on the basis of the following consideration: Firstly, because the development of future water supply potential has many uncertain influencing factors, it cannot reach 100 %; therefore, analysis is conducted in combination with different guarantee degree of water supply. Secondly, the analysis of the balance between supply and demand of water resources in the four situations is used to look for the future balance point of water supply and demand and to determine the percentage interval of the economical and rational development and utilization of the future water supply potential.

7.3.2.2 Analysis of the Balance Between Supply and Demand of Water Resources of the Planning Scheme

With regard to tap water supply, the development and utilization of the internal water resources potential in the study is considered alone (Liugengou and Budaihao water sources, the temporal water sources and groundwater of the water sources for over extraction during the dry season are not considered), as shown in Fig. 7.1. When the water supply potential increases by 10, 25, 50, and 75 % on the basis of the output of supplying water in different years, after 2015 the tap water supply cannot meet the demand, to 2020 the shortage of the tap water will be 13,216, 12,316, 10,816, and 9316 m^3/d, respectively. From this, it can be seen that the long-term utilization potential of the internal water sources in the study area is

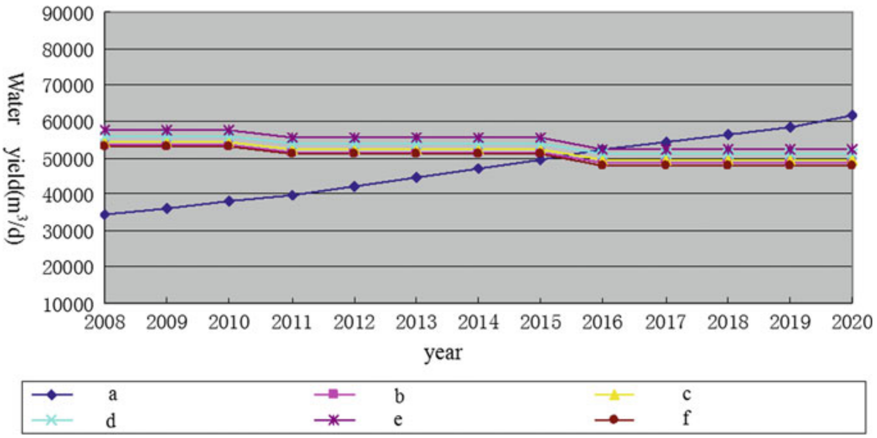

Fig. 7.1 Variation of supply and demand when the tap water supply potential increases by 10, 25, 50, and 75 % (the internal water resources are considered only). *Note a* water demand; *b* output of supplying water after 10 % increase of water supply potential; *c* output of supplying water after 25 % increase of water supply; *d* output of supplying water after 50 % increase of water supply; *e* output of supplying water after 75 % increase of water supply; *f* predicted output of supplying water in the planning periods

limited, even the water supply increased by 100 % (Liugengou and Budaihao water sources), neither can meet the demand.

In the view of the long-term development, from the above analysis of water supply potential and the mode of the development and utilization of water sources, it is suggested to apply for and utilize the exterior Haoleibaoji water source so as to ensure the balance between supply and demand of water resources and the sustainable social economic development in the study area. That is, from 2006 to 2015, because the surplus of tap water supply decreases gradually, the internal water supply potential (Liugengou and Budaihao water sources) must be increased to ensure certain reserves of water supply for tap water. Forward, i.e., from 2016 to 2020, on the above basis, water supply from exterior Haoleibaoji water source outside the study area will be added. The supply and the demand at different percentage are shown in Fig. 7.2 and Table 7.3. From Fig. 7.2 and Table 7.3, it can be seen that with the increase of percentage of water supply potential, the output of supplying water shows the increasing trend. When the water supply potential increases by 10 % on the basis of the output of supplying water in different years, after 2015 the tap water supply during the planning period cannot meet the demand; the shortage will be 612 m^3/d in 2016 and 10,216 m^3/d in 2020. When the water supply potential increases by 25 % on the basis of the output of supplying water in different years, after 2018 the tap water supply during the planning period cannot meet the demand; the shortage will be 612 m^3/d in 2016 and 10,216 m^3/d in 2020.

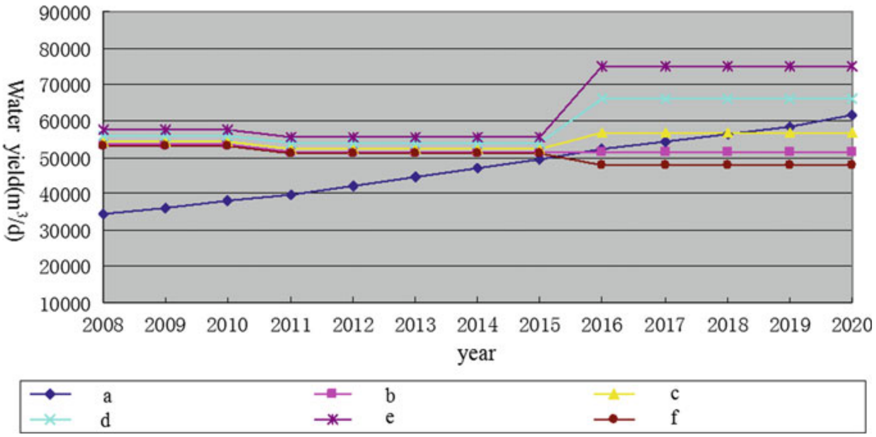

Fig. 7.2 Variation of supply and demand when the tap water supply potential increases by 10, 25, 50, and 75 % (the internal and exterior water resources are considered). *Note a* water demand; *b* output of supplying water after 10 % increase of water supply potential; *c* output of supplying water after 25 % increase of water supply; *d* output of supplying water after 50 % increase of water supply; *e* output of supplying water after 75 % increase of water supply; *f* predicted output of supplying water in the planning periods

The shortage will be 1539 m^3/d in 2019 and 4816 m^3/d in 2020. When the water supply potential increases by 50 and 75 % on the basis of the output of supplying water in different years, the tap water supply during the planning period can meet the demand. In 2020, there is surplus of 4184 m^3/d and 3184 m^3/d, respectively.

From the above analysis, it can be seen that from 2006 to 2015, the internal water supply (Liugengou and Budaihao water sources) must be increased to ensure certain reserves of water supply for tap water; forward, i.e., from 2016 to 2020, on the above basis, water supply from exterior Haoleibaoji water source will be added. When the tap water supply potential increases by 50–75 %, not only the water demand can be met, and there are certain reserves of water supply, but also the development and the utilization of water supply potential are relatively economic and rational.

As regards industrial reused water, it is shown in Fig. 7.3 and Table 7.3 that with the increase of percentage of water supply potential, the output of supplying water shows the increasing trend, when the water supply potential increases by 10, 25, 50, and 75 % on the basis of the output of supplying water in different years; the industrial reused water supply can meet the demand, when the water supply potential increases by 10 %; in 2020 the surplus will be 2132 m^3/d, with the increase of percentage of water supply potential, and the surplus increases too; for example, in 2020, when the water supply increases by 25 %, the surplus will be 6691 m^3/d and when the water supply potential increases by 75 %, the surplus will be 21,886 m^3/d.

Table 7.3 Balance between supply and demand of different water use during different planning years in the study area when water supply potential increases by 10, 25, 50, and 75 % (*unit* m^3/d)

Category of water use	Increase percentage (%)	Water yield	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Tap water	10	Supply	53,500	53,500	53,500	51,500	51,500	51,500	51,500	51,500	51,500	51500	51500	51,500	51,500
		Demand	34,304	36,006	38,025	39,585	42,172	44,621	47,036	49,368	52,112	54,076	56,230	58,439	61,716
		Surplus/shortage	19,196	17,494	15,475	11,915	9328	6879	4464	2,132	−612	−2576	−4730	−6939	−10,216
	25	Supply	54,400	54,400	54,400	52,400	52,400	52,400	52,400	52,400	56,900	56,900	56,900	56,900	56,900
		Demand	34,304	36,006	38,025	39,585	42,172	44,621	47,036	49,368	52,112	54,076	56,230	58,439	61,716
		Surplus/shortage	20,096	18,394	16,375	12,815	10,228	7779	5364	3032	4788	2824	670	−1,539	−4,816
	50	Supply	55,900	55,900	55,900	53,900	53,900	53,900	53,900	53,900	65,900	65,900	65,900	65,900	65,900
		Demand	34,304	36,006	38,025	39,585	42,172	44,621	47,036	49,368	52,112	54,076	56,230	58,439	61,716
		Surplus/shortage	21,596	19,894	17,875	14,315	11,728	9279	6864	4532	13,788	11,824	9670	7461	4184
	75	Supply	57,400	57,400	57,400	55,400	55,400	55,400	55,400	55,400	74,900	74,900	74,900	74,900	74,900
		Demand	34,304	36,006	38,025	39,585	42,172	44,621	47,036	49,368	52,112	54,076	56,230	58,439	61,716
		Surplus/shortage	23,096	21,394	19,375	15,815	13,228	10,779	8,364	6,032	22,788	20,824	18,670	16,461	13,184
Industrial reuse	10	Supply	28,429	35,429	39,429	39,429	39,429	39,429	39,429	39,429	39,429	39,429	39,429	39,429	39,429
		Demand	19,754	26,484	27,426	28,368	29,295	30,264	31,268	32,264	33,269	34,284	35,295	36,299	37,297
		Surplus/shortage	8,675	8,945	12,003	11,061	10,134	9,165	8,161	7,165	6,160	5,145	4,134	3,130	2,132
	25	Supply	32,988	39,988	43,988	43,988	43,988	43,988	43,988	43,988	43,988	43,988	43,988	43,988	43,988
		Demand	19,754	26,484	27,426	28,368	29,295	30,264	31,268	32,264	33,269	34,284	35,295	36,299	37,297
		Surplus/shortage	13,234	13,504	16,562	15,620	14,693	13,724	12,720	11,724	10,719	9,704	8,693	7,689	6,691
Industrial reuse	50	Supply	40,585	47,585	51,585	51,585	51,585	51,585	51,585	51,585	51,585	51,585	51,585	51,585	51,585
		Demand	19,754	26,484	27,426	28,368	29,295	30,264	31,268	32,264	33,269	34,284	35,295	36,299	37,297
		Surplus/shortage	20,831	21,101	24,159	23,217	22,290	21,321	20,317	19,321	18,316	17,301	16,290	15,286	14,288
	75	Supply	48,183	55,183	59,183	59,183	59,183	59,183	59,183	59,183	59,183	59,183	59,183	59,183	59,183
		Demand	19,754	26,484	27,426	28,368	29,295	30,264	31,268	32,264	33,269	34,284	35,295	36,299	37,297
		Surplus/shortage	28,429	28,699	31,757	30,815	29,888	28,919	27,915	26,919	25,914	24,899	23,888	22,884	21,886

(continued)

Table 7.3 (continued)

Category of water use	Increase percentage (%)	Water yield	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Afforestation reuse	10	Supply	14,330	14,830	14,830	16,130	16,130	16,130	16,130	16,130	16,130	16,130	16,130	16,130	16,130
		Demand	9,313	10,042	10,720	11,522	12,273	12,991	13,723	14,448	15,149	15,837	16,514	17,173	17,814
		Surplus/shortage	5,017	4,788	4,110	4,608	3,857	3,139	2,407	1,682	981	293	-384	-1,043	-1,684
	25	Supply	16,025	16,525	16,525	17,825	17,825	17,825	17,825	17,825	17,825	17,825	17,825	17,825	17,825
		Demand	9,313	10,042	10,720	11,522	12,273	12,991	13,723	14,448	15,149	15,837	16,514	17,173	17,814
		Surplus/shortage	6,712	6,483	5,805	6,303	5,552	4,834	4,102	3,377	2,676	1,988	1,311	652	11
	50	Supply	18,850	19,350	19,350	20,650	20,650	20,650	20,650	20,650	20,650	20,650	20,650	20,650	20,650
		Demand	9,313	10,042	10,720	11,522	12,273	12,991	13,723	14,448	15,149	15,837	16,514	17,173	17,814
		Surplus/shortage	9,537	9,308	8,630	9,128	8,377	7,659	6,927	6,202	5,501	4,813	4,136	3,477	2,836
	75	Supply	21,675	22,175	22,175	23,475	23,475	23,475	23,475	23,475	23,475	23,475	23,475	23,475	23,475
		Demand	9,313	100,42	10,720	11,522	12,273	12,991	13,723	14,448	15,149	15,837	16,514	17,173	17,814
		Surplus/shortage	12,362	12,133	11,455	11,953	11,202	10,484	9,752	9,027	8,326	7,638	6,961	6,302	5,661

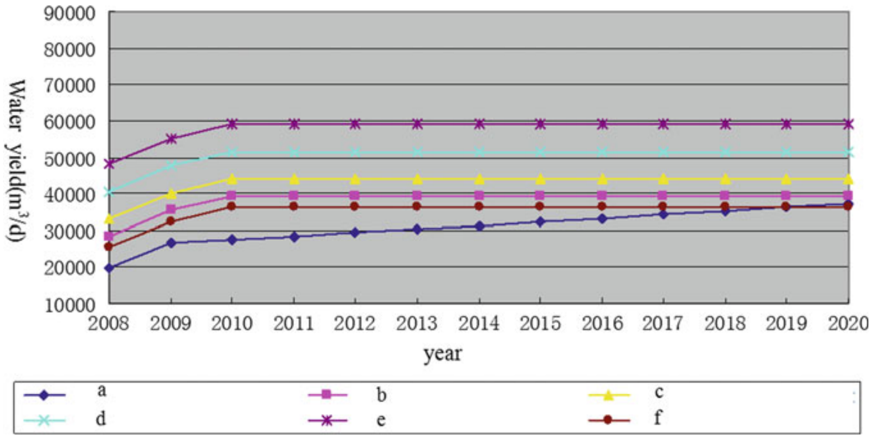

Fig. 7.3 Variation of supply and demand when supply potential of industrial reused water increases by 10, 25, 50, and 75 %. *Note a* water demand; *b* output of supplying water after 10 % increase of water supply potential; *c* output of supplying water after 25 % increase of water supply; *d* output of supplying water after 50 % increase of water supply; *e* output of supplying water after 75 % increase of water supply; *f* predicted output of supplying water in the planning periods

From the above analysis, it can be seen that forward, i.e., after 2015 if the increased reuse volume reaches approximately 10–25 % of the present water supply potential (mine inflow), not only the industrial and production water demand can be met, but also the resources can be saved. The waste of water resources is reduced, while the social and economic benefits increase.

With regard to afforestation reused water, Fig. 7.4 and Table 7.3 show that when the water supply potential increases by 10 %, afforestation reused water supply can meet the demand during the planning period; hence, the shortage will be 384 m^3/d in 2018 and 1684 m^3/d in 2020. When the water supply potential increases by 25 %, the supply of afforestation reused water can meet the demand and then the surplus will be 11 m^3/d in 2020. With the increase of the percentage of the water supply potential, the surplus increases too; for example, in 2020, when water supply potential increases by 50 %, the surplus will be 2836 m^3/d and when the water supply potential increases by 75 %, the surplus will be 5661 m^3/d.

From the above analysis, it can be seen that when the water supply potential of the afforestation reused water increases by 25–50 % during the planning period, the water supply can meet the demand. With the increase of future water consumption in the study area, the domestic sewage will increase correspondingly; therefore, enhancement of the domestic sewage treatment and increase of the reuse rate of intermediate water will provide powerful guarantee for afforestation reused water during the planning period.

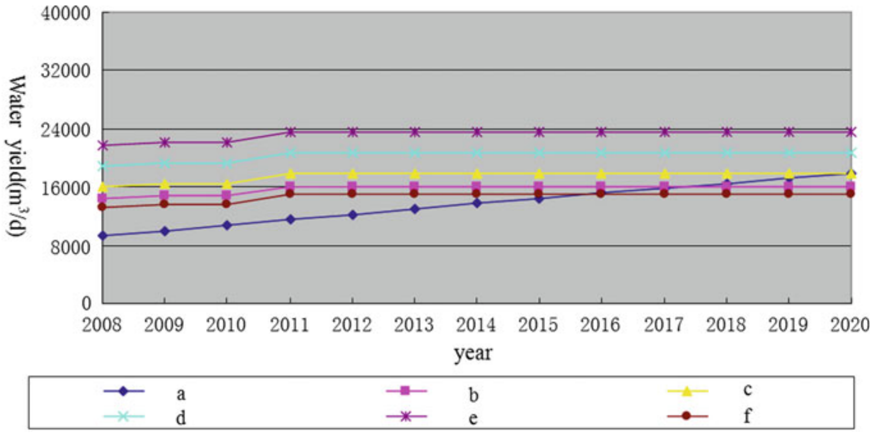

Fig. 7.4 Variation of supply and demand when supply potential of afforestation reused water increases by 10, 25, 50, and 75 %. Note: *a* water demand; *b* output of supplying water after 10 % increase of water supply potential; *c* output of supplying water after 25 % increase of water supply; *d* output of supplying water after 50 % increase of water supply; *e* output of supplying water after 75 % increase of water supply; *f* predicted output of supplying water in the planning periods

7.3.2.3 Feasibility Analysis of the Planning Scheme

Seen from the categories of different water use in the planning scheme, the demand of industrial and afforestation reused water can be met through newly increased water supply from excavation of the internal water supply potential. While with regard to tap water supplying project, the internal and the exterior water sources can be exploited and utilized only after applying for and getting the right of use; otherwise, it is difficult to solve the problem of the long-term imbalance between supply and demand of tap water, so the application for the right of use of these water sources is needed to be enhanced. Because Haoleibaoji water source has been utilized by the Coal Liquefaction Corporation of Shenhua Group located in Ordos City, for the study area as the base of coal supply to the Corporation, if applying for sharing this water source together with the Corporation, the investment would be less and it is easier to get a part of the right of use.

7.3.2.4 Emergency Countermeasures of Water Resources Development and Utilization During Extremely Dry Year and Continuous Dry Years

In the study area in 2005 (normal year), the tap water supply during the dry period was 6700 m^3/d less than the normal, and it can be seen that the output of supplying water during the extremely dry year or continuous dry years is much less than the normal year; the imbalance between supply and demand of water resources is evident. In this case, who to ensure the water demand in the study area is a very concerned problem. Here, the following countermeasures are put forward:

- Excavating the water supply potential of the internal water sources increases the temporal water supply
    - With regard to the reused water, the water supply potential is relatively large; it must increase the reuse rate of mine water and ensure the demand of the industrial reused water.
- Giving full play to the water supply capacity of the exterior water sources, ensuring the basic water supply for livelihood and the key departments.
    - The preconditions for giving full play to the water supply capacity of the exterior water sources is to get the right of development and use; from this the importance of the exterior water sources for the future development of the study area can be seen, particularly during extremely dry year or continuous dry years. After getting and using the right of use of the exterior water sources such as Haoleibaoji water source, during the extremely dry year or the continuous dry years, the full play should be given to the characteristics of stability and high assurance rate of the exterior water sources, realizing the basic guarantee function for the study area, ensuring the basic water supply for livelihood and the key departments so as to reduce the loss due to water shortage.
- Realizing the rational allocation of water resources among sectors, categories, and mining areas of water use
    - During the extremely dry year or the continuous dry years, as regards the sectors of water use, the water demand must be comprehensively reduced, and the priority of water supply should be determined according to the assurance rate of different sectors; water should be supplied selectively to ensure the normal operation of the key departments. With regard to the categories of water use, the mode of operation of different water supply engineering can be changed temporally; the department which has used tap water but does not high requirement on water quality can be temporally supplied water by reuse water engineering of mine. Afforestation reused water may be reduced suitably. With regard to mining areas of water use, the unified allocation among areas within the water supply network is conducted; the water supply capacity during the extremely dry year is increased to realize the coordinate development among the mining areas in the study area.

7.4 Summary

In the chapter, the author has analyzed and studied, respectively, the mine water recycling, the development and utilization potential of water resources in the study area, the development and utilization mode of water resources, the planning scheme of water resources development and utilization, and the safeguard measures of water resources development and utilization plan.

- The mine water in Shendong mining area is mainly Quaternary phreatic water and sandstone fracture water of coal measures and has high suspended solids. After treatment of air floatation, coagulation, sedimentation, and disinfection, the effluent quality can reach the standards of drinking water.
- It put forward that the right of use of the internal water sources such as Liugengou and Budaihaogou water sources, the exterior water sources such as Bahan Lake—Subei Lake area (Haoleibaoji water source), Hatoucaidang water source, phreatic source in Yellow River beach at Gushanchuan mouth, Heilonggou—Linyinghui karst spring field water source should be applied for as soon as possible, so as to provide the powerful reserves and guarantee of water resources for the development of the study area.
- The development and utilization mode of the water resources in the study area was put forward: (1) implementation of the comprehensive utilization mode through water supply of multiwater sources, multiusers by water quality, high-quality water for superior usage; (2) connotative development mode of excavating the potential of the internal water resources, increasing the utilization rate of the reusable water; (3) sustainable development mode of application for development and rational utilization of the exterior water resources.
- In order to solve the problem of the imbalance between supply and demand of water resources during the planning period, taking the study area as a whole, four following situations were set, i.e., for tap water, industrial reused water and afforestation reused water, the balance between supply and demand of water resources during the planning period was studied and solved through the 10, 25, 50, and 75 % increase of water supply potential on the basis of the water supply in different planning years. The analysis concluded that with regard to tap water supply, from 2006 to 2015, the internal water supply (Liugengou and Budaihao water sources) should be increased to ensure certain water supply reserves; forward, i.e., from 2016 to 2020, on the above basis, the water supply from the exterior Haoleibaoji water source will be added. When the tap water supply potential increases by 50–75 % during the planning period, it can meet not only the water demand and has certain water supply reserves, but also the development and utilization of water supply potential are relatively economic and rational. With regard to the industrial reused water, forward, i.e., after 2015, if the additional reuse volume reaches 10–25 % of the present water supply (mine inflow) potential, not only the industrial and production water demand can be met, but also the water resources can be saved and the waste is reduced, the social and economic benefit increases. As regards afforestation reused water,

when the water supply potential of afforestation reused water increases by 25–50 % during the planning period, the water supply can meet the water demand. With the increase of future water consumption, the domestic sewage will increase correspondingly; therefore, enhancing the treatment of domestic sewage and increasing the reuse rate of the intermediate water will provide powerful guarantee for afforestation water during the planning period.

Aiming at the extremely dry year and the continuous dry years occurring during the planning period, the following emergent counter measures for water resources development and utilization were put forward: (1) excavating the internal water source potential, increasing the temporal water supply output; (2) giving full play to the water supply capacity of the exterior water sources, ensuring the basic water supply for livelihood and key departments; (3) realizing the rational allocation of water resources among sectors, categories, and mining areas of water use.

Chapter 8
Conclusion and Suggestions

The study, based on the analysis and systemization of the available data, using the technical approaches such as in-site hydrogeological investigation, laboratory, and field test, supplementary exploration, through theoretic analysis, simulation prediction, investigated the distribution of water resources (including surface water, groundwater, and mine water), the status, and the variation trend of domestic water, agricultural water, production water, and industrial water, from the angle of water system, assessed the water resources in the mining area, determined the status of water resources development and utilization, evolution trend, exploitation, and utilization potential. In combination with the medium- and long-term objectives, the optimal allocation scheme of water resources in different future level years was given. The planning mode of future development and utilization of water resources and the technical scheme of the comprehensive utilization of water resources in the mining area were put forward.

8.1 Major Conclusions

8.1.1 Analysis of the Characteristics of the Water Resources System, Supply, and Demand in the Mining Area

- The surface water system in the area is mainly seasonable water flow system composed of Ulan Mulun River and its tributaries, of which the major spring-field at the east bank of Ulan Mulun River, i.e., Gongnieergaigou, Kaokaolaigou, Halagou, and Liugengou, is the major water source site of water supply; the water-intaking way is to take water directly from springs. In the drainage basin within the study area, the annual average runoff of the mainstream of Ulan Mulun River is approximately 117,000,000 m^3, but very uneven in time, mainly concentrated in unfreezing period (March) and rainy season

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(July, August and September); the runoff volume of these four months accounts for approximately 65 % of the annual total.

- Shalawusu Formation and the burnt rock are the major aquifers of the study area, and both are the unified water-bearing system, having unified water level and good hydraulic connection. The phreatic water in Quaternary loose aquifer is the recharge source of the fracture phreatic water of the underlying burnt rock. Except several springfields at the east bank of Ulan Mulun River, within different major minefields of the study area, the loose porous phreatic aquifer is thin and discontinuous; except local section rich in water, the majority is weakly and medium watery. The watery property is relatively good in the first-order terrace of Ulan Mulun River, medium in the second-order terrace and flood land, and weak in third-order and fourth-order terrace.
- Groundwater resources in the study area were assessed by using the method of water equilibrium, and the study of water equilibrium was conducted by selecting 2004 of which the assurance rate of precipitation was 50 %. The calculation results indicate that the total recharge during the equilibrium period in the whole equilibrium area was 80,797,600 m^3, and the total discharge was 82,294,400 m^3; in 2004, in the whole equilibrium area, the equilibrium was negative, and groundwater reserves decreased by approximately 1,496,800 m^3. The surface water resources in the study area were 119,700,000 m^3, and the total water resources were 130,640,000 m^3.
- Within the study area, the annual average water inflow in Daliuta mine, Huojitu mine, Shangwan mine, Bulianta mine, Halagou mine, Shigetai mine and Ulan Mulun mine is 1,470.5 m^3/h, the total annual inflow is 12,667,000 m^3, and there is increasing trend year by year. The total water-accumulating area of gob is 130,628,000 m^2, and the total accumulated water volume is 39,307,000 m^3.
- pH of groundwater in the mining area ranges generally between 7.00 and 8.40, medium and weak alkaline. The hardness of Quaternary prelatic water is mostly 130–300 mg/l, mainly soft and slightly hard, and if exceptionally the hardness is 320–362 mg/l, it is hard water. The hardness of sandstone fracture water is generally 35.77–300 mg/l, very soft water and slightly hard water. The hardness of the burnt rock water is 120–224 mg/l, soft water and slightly hard water. The surface water is soft water and slightly hard water.
- From the isotope test and study, it is found that the precipitation with big rainfall and the melt water in early spring recharge the groundwater, particularly the sandstone fracture aquifer in the area. Groundwater level drop induced by consumption and runoff of water resources has approximated to the static reserve of groundwater in the area.
- Generally speaking, the groundwater in the mining area is freshwater and slightly brackish water, the mineralization is moderate, the water quality is good, and it is suitable for domestic water, industrial water, and irrigation water. But when the surface water is used as drinking water, attention must be paid to pollutants in surface water, particularly volatile phenol and mercury ion. Suitable measures must be taken to conduct treatment through adsorption and degradation.

Table 8.1 Analysis of current balance between supply and demand of water resources (*unit* m^3/d)

Water yield		2003	2004	2005
Tap water	Supply	27,300	32,000	37,500
	Demand	22,761	23,622	28,377
	Surplus/shortage	4539	8378	9123
Tap water during dry period	Supply	20,800	27,000	30,800
	Demand	22,761	23,622	28,377
	Surplus/shortage	−1961	3378	2423
Reused water	Supply	19,993	21,500	25,193
	Demand	17,900	19,300	21,100
	Surplus/shortage	2093	2200	4093
Total water resources	Supply	47,293	55,500	62,693
	Demand	40,661	42,922	49,477
	Surplus/shortage	6632	12,578	13,216

- The mine water in the area has high content of suspended solids. The content of suspended solids varies with mine inflow and is quite different. The mine water contains trace organic pollutants and pollutants of trace toxic hazardous elements, but the content of the toxic hazardous pollutants is much lower than the limit of the national discharge standard for wastewater pollutant in coal mines.
- According to the results of hydrogeochemical test, assessment, and analysis of water quality in the mining area, the water quality of the water resources in the mining area is qualitatively zoned by excellent quality, medium quality, and poor quality.
- After analysis of the existing water supply engineering, water supply output, and water consumption in Shendong mining area, the balance between supply and demand of water resources was obtained, as shown in Table 8.1.
- GM (1, 1) was used to predict the water demand in the study area; on this basis, the future balance between supply and demand of water resources in Shendong mining area was analyzed and studied. The results are shown in Table 8.2.

Table 8.2 Balance between supply and demand of water resources in different years in the study area (*unit* m^3/d)

Year	2006	2007	2008	2009	2010	2011	2012	2013
Supply	82,890	86,990	91,490	98,990	102,990	102,290	102,290	102,290
Demand	55,735	59,445	63,371	72,533	76,171	79,474	83,740	87,876
Surplus /shortage	27,155	27,545	28,119	26,457	26,819	22,816	18,550	14,414
Year	2014	2015	2016	2017	2018	2019	2020	
Supply	102,290	10,2290	99,290	99,290	99,290	99,290	99,290	
Demand	92,027	96,080	10,0530	10,4197	10,8039	111,911	116,826	
Surplus /shortage	10,263	6210	−1240	−4907	−8749	−12,621	−17,536	

From 2006 to 2015, the output of the water supply projects can meet the water demand, but from 2016 to 2020, the output of the water supply projects cannot meet the water demand. From 2015 to 2020, the output of tap water supply cannot meet the tap water demand, and the shortage will be up to 13,816 m^3/d in 2020. Only in 2020, the output of the industrial reused water cannot meet the water demand, and the shortage will be 907 m^3/d. The output of afforestation reused water cannot meet the water demand from 2016 to 2020, and the shortage will be 2814 m^3/d in 2020.

- Through the study of the impact of coal mining on the water resources system, the following conclusions are obtained:
  - Coal mining has changed the conversion relation of "three waters" between surface water and groundwater. The reduction of flow of Ulan Mulun River drainage basin in recent years mainly resulted from the conjoint action of the sharp reduction of precipitation and the increase of industrial, agricultural, and domestic water consumption along the banks of the river; the precipitation has plaid the dominant role, and the impact of mining is relatively small.
  - Coal mining has formed the vertical fractures, making the phreatic water of Quaternary loose layer and the burnt rock fractures transferred to and stored in gob.
  - Groundwater level in springfields shows the decreasing trend overall, the drop amplitude is not big, the major reason for water level drop is the reduction of recharge from precipitation, and mine drainage induced by coal mining has only local influence on the groundwater flow field nearby water-gushing area and little influence on the flow field of the whole area.

8.1.2 Optimal Allocation and Comprehensive Utilization of Complex Water Resources System

Through the systematic study, the techniques of the comprehensive utilization of water resources to realize the sustainable development of resources and environments in Shendong mining area include the following four aspects: internal optimal allocation of water resources; increasing the utilization efficiency of water resources; increasing the reuse rate of mine water; excavating the development and utilization potential of water resources inside and outside the study area; and formulating scientific and rational development and utilization mode of water resources, plan, and guarantee measures.

8.1.2.1 Internal Optimal Allocation of Water Resources in Shendong Mining Area

Through setting up the optimized allocation model of water resources by multi-objectives, multiusers, and different quality, MATLAB was used to realize optimization algorithm of the model. And taking 2005 as reference year, the optimal allocation of multiobjectives, multiwater sources, and multiusers was conducted for water resources in planning level years 2008, 2010, 2015, and 2020 respectively, so as to achieve the aim of the maximum assurance rate and the lowest water cost. The optimal technical plan of the comprehensive utilization of water resources between different water sources and different users was put forward.

- Through the analysis of the results of optimization calculation for 2008, 2010, 2015, and 2020, it can conclude that the total water supply can meet the total water demand from 2008 to 2015 and cannot from 2016 to 2020, and tap water shortage occurs and shows the rising trend.
- Results of optimal allocation of water resources in different level years: The total water supply capacity in the whole area in 2008 is 91,490 m^3/d, which meets the water demand of 63,373 m^3/d. There is surplus of 28,117 m^3/d. The total output of supplying water can meet the water demand.
- The total water supply capacity in the whole area in 2010 is 102,990 m^3/d, while the water demand is 76,171 m^3/d. According to the optimal solution, the optimal allocation of water resources supplies totally 78,080.6 m^3/d, the water supply assurance rate is 102.5 %, there is surplus of 24,909.4 m^3/d, and the total output of supplying water can meet the water demand.
- The total water supply capacity in the whole area in 2015 is 102,290 m^3/d, while the water demand is 96,075 m^3/d. According to the optimal solution, the optimal allocation of water resources supplies totally 96,075 m^3/d. There is surplus of 6215 m^3/d. Although the total water supply can meet the water demand, all industrial reused water is used up. The surplus of afforestation reused water is 8853 m^3/d. Tap water supply is not sufficient. The shortage is 2638 m^3/d.
- The total water supply capacity in the whole area in 2020 is 99,290 m^3/d, while the water demand is 116,826 m^3/d. The total water supply cannot meet the water demand. The shortage is 17,536 m^3/d. All industrial reused water is used up. The shortage of tap water supply is 25,420 m^3/d. The surplus of afforestation reused water is 7885 m^3/d.

8.1.2.2 Excavating the Water Resources Potential in Shendong Mining Area

Further excavation of the potential, the rational development and utilization of water resources are the important ways to solve the problem of tap water shortage after 2015 and the insufficient total water supply in 2020. The water resources which have exploitation potential in the area include two parts, i.e., internal potential water resources and external potential water resources.

Internal potential water resources

- Inside the study area, there are water sources in Liugengou and Budaihao springfields and water resources in the tributaries of Ulan Mulun River on the south of Daliuta, i.e., Mingaitugou, Xumeigou, and Xiaomuhegou springfields. Preliminary estimation shows that after the exploitation of the above-mentioned water sources, the tap water can be increased by 6000 m^3/d from the current basis.
- Under preconditions of ensuring certain spring flow and certain water level in water source sites of the study area, groundwater can be suitably extracted in sections of thick aquifer and at downstream of spring emersion point during the dry period or water consumption peak. The suitable total extraction volume is 20 % of the spring flow. The preliminary estimation shows that under current conditions, the direct extraction of water source sites can increase 6000 m^3/d of tap water.
- The watery property in the flood land, the first-order terrace of Ulan Mulun River, is relatively good. This conclusion is based on the characteristics of groundwater occurrence and the actual investigation and study in the flood land of Ulan Mulun River. Shigetai river island beach, flood land at Buliangou mouth, and flood land at Huhewusugou mouth can increase approximately 1000 m^3/d of tap water from extraction of groundwater at different water-intaking points under current conditions.
- The total development and utilization potential of mine water resources is 37,490 m^3/d. The total accumulated water volume in gob of different mines of the study area is 39,307,000 m^3.
- After physical and chemical treatment, the accumulated water in gob can reach the quality standards for industrial, domestic, and afforestation water. In the extremely dry year or during the water consumption peak period, the development of the water resources of gob is also an effective way to ease the shortage of water resources.
- The water supply potential of afforestation reused water projects is 11,300 m^3/d, of which the water supply potential of the domestic sewage recycling projects is 4200 m^3/d; with the increase of future water consumption in the study area, the domestic sewage will increase also correspondingly; the enhancement of treatment of the intermediate water resources and the increase of the recycling rate of the intermediate water will provide powerful guarantee for afforestation water during the planning period.

The development and utilization potential of the internal water sources in the study area is shown in Table 8.3.

Table 8.3 Potential of the internal water sources in the study area (*unit* m^3/d)

Water supply source	Use	Water supply potential	Note
Water source of springfield	Tap water	6000	Water sources in Liugengou, Budaihao, Mingaigou, and Xumeigou, temporal water sources not included
Water source for direct extraction of groundwater at water source site	Tap water	6000	Rational overextraction during the dry season, the total extraction volume limited within 20 % of the spring flow
Temporal water source at island flood beach of Ulan Mulun River	Tap water	3000	Influenced by swing of river streamline and flood, difficult to set well location, serious sedimentation in well after long-term extraction may be used as temporal water source
Mine water resources	Industrial reused water	30,390	
	Afforestation reused water	7100	
Intermediate water resources	Afforestation reused water	4200	In the future, with the increase of water consumption, domestic sewage will increase also correspondingly, and the water supply potential of the intermediate water resources will increase too

External water resources of Shendong mining area

There are some water sources with stable water yield and good quality around the study area, mainly including Bahan Lake–Subei Lake area (Haoleibaoji water source), water source in Hatucaidang area, phreatic water of Yellow River flood land at Gushanchuan mouth, and Heilonggou–Linyinghui karst springfield.

- Bahan Lake–Subei Lake area (Haoleibaoji water source) is located to the northwest of the study area, approximately 90 km away from Bulianta mine, and is a part of Cretaceous artesian basin of Shaanxi, Gansu, Ningxia, and Inner Mongolia, the nearest water-rich section, a closed hydrogeological unit with abundant water yield. Within 200 km^2 of Haoleibaoji water source site, the reserved water resources are 8.9 billion m^3; if 800,000 m^3 are extracted per day, they can last for 304 years.
- Hatoucaidang area is located to the southwest of Dongsheng coal field, a contiguous area of Dongsheng undulating plateau and Maowusu desert. The phreatic aquifer is the huge thick Quaternary Upper Pleistocene Shalawusu Formation and has abundant water yield and good water quality. The water inflow of single well can reach 2042 m^3/d.

- Yellow River flood land area at Gushanchuan mouth is located to the east of the study area, in Fugu County, approximately 100 km away from the mining area, and is a Quaternary Holocene alluvial layer, mainly composed of sand and gravel. The aquifer is 20–30 m thick and has abundant water yield. The water inflow of single well is 5782 m^3/d.
- Heilonggou–Linyinghui karst springfield is located to the east of the study area, in Fugu County, approximately 100 km away from the mining area, and the major aquifer is the middle and upper members of Middle Ordovician Majiagou Formation.

The above-mentioned four water sources are located at the periphery, approximately 100 km away from the study area, have abundant water yield, and have been not applied for the use so far by the study area. At long term, the development potential of the internal water sources in the study area is limited; therefore, in consideration of the sustainable development of the study area, these water sources must be brought into the planning extent and used as the perpetual large-scale water supply sources, so as to provide the powerful reserves of water resources and guarantee for the long-term development of the study area.

8.2 Major Innovative Achievements

- The systematic theory and method for the optimal allocation and the comprehensive utilization of the large regional complex water resources system were formed. The dissertation, taking Shendong mining area as the typical representative, under conditions of large regional extent, multiple subsystems and impact of mining, conducted the assessment of regional water supply and demand, groundwater simulation, management, assessment of mining impact, assessment and optimal allocation of large regional water resources, and comprehensive development and utilization of water resources. It is a complete system for analysis, assessment, simulating management, and optimal allocation of water resources in terms of theory and method.
- A set of brand new parameter inversion methods including preliminary selection of hydrogeological test, adjustment of parameters by water level fitting, and estimation of the spatial variability of sediments by random hierarchic structure for determination of hydrogeological parameters were innovatively put forward and successfully applied in the numeric simulation of the large regional complex groundwater system. The core of the parameter inversion method is as follows: Firstly, the hydrogeological parameters of aquifers in different wells and boreholes, obtained from multisets of pumping tests, can be used as the representative parameters of aquifer in the parameter zone where wells and boreholes are located, and on this basis, the water level data measured at the end of simulation period are used to adjust hydrogeological parameters; finally, through the study of the spatial variability of the hydrogeological parameters, the hierarchic

structure is used to estimate the impact of the spatial correlative structure on permeability, and the random statistics and the optimization theory are used to determine finally hydrogeological parameters.

- The multiobjective planning model of water resources of the mining area was set up, and the optimal allocation of the complex water resources system was realized. According to the planned objective of Shendong mining area, the criteria for setup of the model were formulated; the objective function, the decision variable, the objective constraint, and the constraint conditions of the planning model of multiobjectives, multiwater sources, multiusers, and different water quality were established. The multiobjective optimization function fgoalattain in the optimization toolbox of MATLAB was used to realize the optimization algorithm of the model. The optimal allocation of water resources was conducted by taking different level years as reference. It is put forward the optimal technical scheme for allocation and comprehensive utilization of water resources among different water sources and different users, achieving the aim of the maximum assurance rate and the lowest water cost of water resources supply.

8.2.1 There Are Distinct Features at the Following Aspects

- GM (1, 1) was used to predict the regional water demand. Gray prediction method is to conduct data processing on time series by using gray system theory, to set up the gray model with the generated sequence of number of strong regularity, and further to conduct prediction. This method can conduct modeling and prediction in case of few data and information, has high accuracy, and is simple and practical. The prediction of water demand is to use suitable method to estimate and infer the future water demand, needs to consider the change of the realistic conditions and environments, and is influenced by many factors; it is difficult to describe the influence of individual factor on water demand. It includes not only the known information, but also unknown or uncertain information and is a gray system. So on the basis of the characteristics of time sequence of the historic water demand, the gray system GM (m, n) model is used to seek for the inherent information of the gray volume itself. Due to its characteristics of dynamic memory, the gray system is very suitable for the prediction of water demand. On the basis of the available data and the actual situation, the dissertation has selected GM (1, 1) to predict the water demand in the study area.
- The numeric model of moisture migration in zone of aeration was applied to improve the accuracy of infiltration coefficient of rainfall and to settle a good base for assessment of water resources quantity. In the area, precipitation is the important recharge source of groundwater, and the infiltration coefficient of precipitation is an important parameter to calculate rainfall recharge. However,

the recharge of rainfall infiltration to groundwater is a very complicated process and is controlled by precipitation intensity, evaporation intensity, burial depth of groundwater level, soil texture, and water content in aeration zone in early stage. Through analysis of variability, the dissertation simulated rainfall infiltration numerically, filtered the parameters of meteorological factors, and selected the classification of soil proposed by US Ministry of Agriculture to determine the parameters used in the model, to adjust and give the initial and boundary conditions, so as to ensure that more accurate rainfall infiltration coefficient is obtained from the numeric model of moisture migration in aeration zone.

8.3 Suggestions

- Long-term monitoring of groundwater dynamics, including groundwater level, temperature, hydrochemical components, flow of wells and springs, level and flow of surface water which has hydraulic connection with groundwater, water emersion points in mines and other underground engineering, water discharge, and water level elevation.
- If the combined extraction of wells and springs is conducted in springfields inside the area, the extraction scheme, well location, well interval, water yield, well completion technology should be designed more detailedly, and during extraction, the observation of the flow of springs, water quality, and dynamic groundwater level should be strengthened.
- For the temporal water-intaking points in Ulan Mulun River beach, if they are listed in the plan, the feasibility and reliability should be assessed further before the implementation of the project.
- Enhancing the comprehensive utilization of mine water, when the conditions are suitable, it can follow the example of the method of mine water utilization in Xinhe mine, Xuzhou, to increase tap water supply.
- To utilize fully hydrological information system software to strengthen the management of hydrological and hydrogeological data.
- To apply for the right of use of Liugengou and Budaihao water sources inside the study area and Haoleibaoji water source outside the study area.
- To carry out in a deep going way the detection and analysis of the accumulated water volume and quality in gob, to further determine the distribution extent, water-accumulating scale and water quality.