Study on farmland salinization and its mechanism in the Loess Plateau

[黄土高原における農地の塩性化とその発生メカニズムに関する研究]

Hong Li

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The following abbreviations are the major abbreviations used in this doctoral thesis:

DGWL = Deep groundwater water line
EC = Electrical conductivity
GD = Groundwater depth
GMWL = Global meteoric water line
LMWL = Local meteoric water line
LRWL = Luo River water line
MC = Moisture content
SAR = Sodium adsorption ratio
YRWL = Yellow River water line

1 General introduction

1.1 Background of research

Water is important and special since it takes part in almost all of the processes that form and shape the Earth. Nearly 96.5% of all water is found in the oceans, which cover two-thirds of the Earth's surface. 1.7% is frozen in icecaps. Less than 2% of all the water on Earth is available for consumption, and most of it is found in aquifers underground (Zhang, 2007).

The most important water use in agriculture is for irrigation. Irrigation makes a major contribution to supply the soil moisture by making a whole range of crops viable in an otherwise unreliable climate, and improving crops grow conditions. Irrigation is an artificial application of water in agriculture to overcome scarcity in rainfall for crop growth. It is usually used to assist in the growing of agricultural crops, maintenance of landscapes, and revegetation of disturbed soils in arid and semiarid regions where natural rainfall is either inadequate or erratic to fulfill the water demand of crops. And it has significantly contributed to poverty alleviation, food security, and improving the quality of life for rural populations (Zhang, 2007; Du, 2009).

Irrigation water can be divided into two main categories: surface water irrigation and groundwater irrigation. The surface water use diversion and obtain their supplies from rivers. Groundwater irrigation use deep and shallow wells to obtain water from the groundwater aquifer. However, environmental impacts in the Luohui Irrigation District are the changes in quantity and quality of soil and water as a result and the ensuing effects on water and salt movement (**Fig. 1-1**).

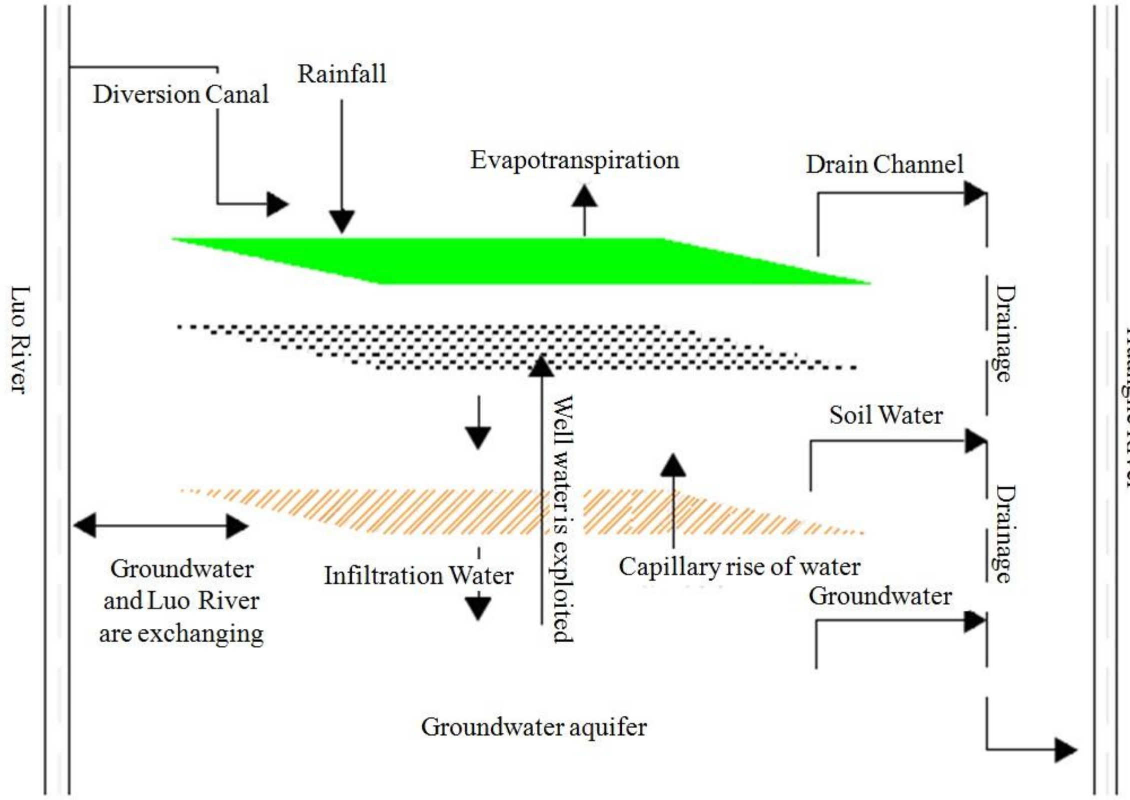


Fig. 1-1 Diagrammatic sketch of water movement in the Luohui Irrigation District

Luohui canal is the largest diversion project since the complete of “Longsou Canal” built in the period of Emperor Wu of Han dynasty, which get water from the Luo River for irrigation. The Luohui canal was designed by the famous hydraulic engineer Li Yizhi and promoted by General Yang Hueheng in the 1930s (Li, 1995). The canal has been extended and improved for several times after liberation, so that the irrigation develops vigorously and the benefit raises progressively. The Luohui Irrigation District has become an important base for marketable grain and high quality cotton, and is an advanced irrigation district.

With the rapid development of irrigation agriculture, the irrigation area has been increasing continuously (Liu *et al*., 2007). However, the unreasonable exploitation and utilization mode and insufficient management pattern of water resources in the irrigation districts have resulted in many serious local eco-environmental problems, including groundwater quality deterioration, land desertification and soil secondary salinizaition (Zhang *et al*., 2007). The lack or inadequate irrigation and drainage structures, and excessive application of water to irrigation fields in most cases cause for groundwater table rise. Consequently, it is crucial to understand and to find the source of water and salt in the eastern block of the Luohui Irrigation District.

The groundwater moves and stores in many types of aquifer; those known as aquifers are of most importance. It is commonly understood to mean water occupying all the voids within a saturated geologic stratum, including the water into the pore spaces and fractures in rock and sediment below the Earth’s surface. Consequently, groundwater is an important part of water resources. It is one of the important source of water for agricultural irrigation, industries, and urban. However, over-recharge, can cause major problems to crop production and to the soil salinization. The most evident problem is a rising of the water table. In the Luohui Irrigation District of China, for example, groundwater levels between two to three meters from the surface of the soil have risen 10 meters since 1950, and the rate of rise is accelerating. Rising water table may, in turn, cause other problems such as saltwater intrusion because there is the saltierra (saline deposit) layer in depth from 40-50 meter in the Luohui Irrigation District.

Soil water is necessary for plant growth and survival, which effect not only the trees, field crops, vegetables, and fruit production, but also effect the distribution of plant in the Earth's surface. It mainly comes from rainfall, snow, irrigation water and groundwater. The soil reactions (salinization, and cation or anion exchange) take place in the context of the soil solution. Thus, it is evident that the water movement of a soil is a key property. The flow direction of water in saturated soil occurs when there is a difference in total potential between two points, like energy transfers, will be in the flow direction of the point having the lowest potential (Zhang, 2008).

Isotopes are atoms with the same number of protons and electrons but differing numbers of neutrons (differing mass numbers), including stable isotopes and radioisotopes. Stable isotopes are not radioactive, and energetically stable and do not decay. For example, the most common isotope of oxygen is ^{16}O, where 16 is the atomic mass (the sum of neutrons and protons), and 8 is the atomic number (number of protons or electrons); the number of neutrons can be determined by difference in the same element. Stable isotopes are commonly used to identify the sources, infer the processes, and determine the proportional inputs. We usually analyze stable isotopes include oxygen (^{18}O) and hydrogen (^{2}H). Stable isotopes have been used in hydrological investigations for many years, and more and more hydrological studies are finding stable isotopes (mostly carbon, hydrogen and oxygen) to be extremely useful (Li, 2008).

Warp soil dressing is a saline soil improvement method by introducing muddy water which comes from the Loess Plateau in flood seasons to salt affected fields surrounded by an embankment. The introduced muddy water is stored for a long term, approximately 6 months. The stored water leaches salts out downward (leaching effect) and it deposits its suspended sediments on the original soil surface (soil dressing effect). Consequently, warp soil dressing was introduced as one of measures against the problem.

On the other hand, check dam is constructed across the gully bed to prevent gully erosion and conserve water and soil. Check dam can create a large arable land by intercepting silt deposition in front of the dam. More than million check dams have been constructed in the Loess Plateau. Meanwhile, check dam provides a huge surplus labor market with the Grain for Green policy.

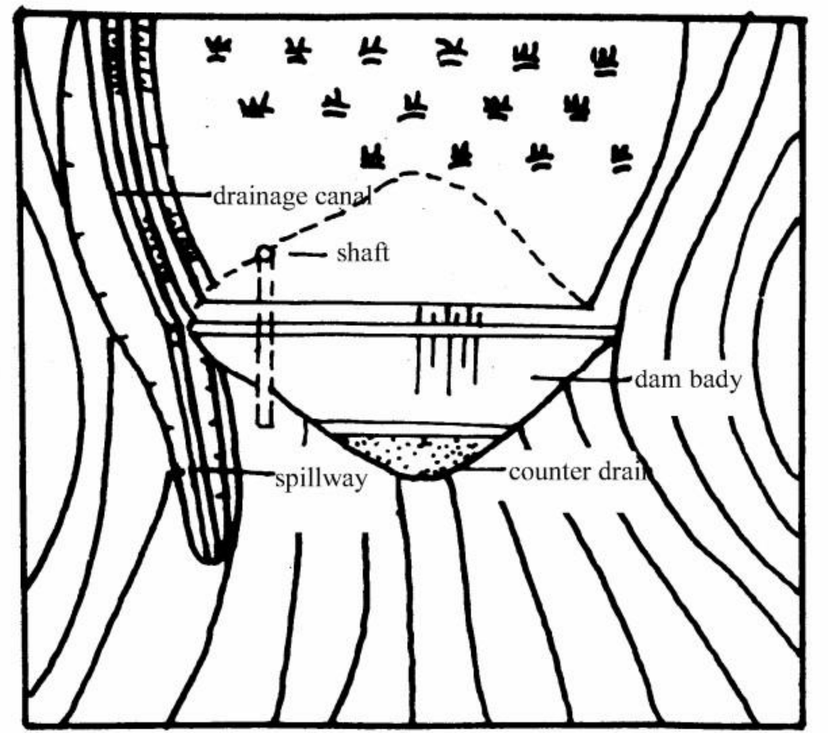
Check dam constructed on gullies are intended to perform the following five functions: (1) Stabilize the gully, preventing bank collapse by scouring in gully bank, stop the expansion of the gully bank, and reduce channel erosion. This is referred to as a consolidation dam shown as **Fig. 1-2**.

(2) Trap silt to form newly arable land for farming, and increasing grain yield.

(3) Reduce flood peaks coming from upper gullies, detain sediment of flood, and protect downstream safety.

(4) Reasonable utilization of water resources before gain large newly arable land in the project, to solve the problems of the local water source for industrial and agricultural production.

(5) Change gullies into fertile arable land to solve food problem in order to develop animal husbandry and sideline, and developing the Grain for Green for improving environment.



http://www.irtces.org/pdf-hekou/138198E.pdf

Fig. 1-2 Sketch map for a check dam

1.2 Content of research

This thesis is composed of two case studies conducted in Dali County and Zizhou County, Shaanxi Province, China. Luohui Irrigation District in Dali County is an already developed irrigation area in semiarid region, however, the unreasonable exploitation and utilization mode and insufficient management pattern of water resources in the irrigation district have resulted in many serious local eco-environmental problems, such as groundwater quality deterioration, land desertification and soil secondary salinizaition, and that is why it was selected as case study for finding the source of water and salt. On the other hand, the Caomao check dam in Zizhou County, has some serious problems, such as salt accumulation in the farmlands and soil salinization that seriously affect crop growth, which are related to shallow groundwater level. This thesis is organized into eight chapters.

In chapter 1, I introduced general concept of water, irrigation, stable isotope, warp soil dressing and check dam in the research background. Also, I discussed the content and the method in the scope of the research.

In chapter 2, a review of literatures related to application of stable isotope and chemical analysis used to identify the origin and sources of salinity in an irrigation area. Meanwhile, I mentioned the history of introduction, development, and distribution of check dams.

In chapter 3, the main objective of this part was to identify groundwater recharge sources by using stable isotope tracers and investigate the groundwater movement in semiarid region contributed to the optimization of water resource management and prevention of salinization in the Luohui Irrigation District. I investigated the stable isotopes content of the precipitation and Luo River water, and determined the local meteoric water line (LMWL) and the Luo River water line (LRWL). Furthermore, the high differences in groundwater depth and terrace elevation in the study area provide an excellent possibility to detect recharge areas of groundwater using stable isotope as tracer.

I define groundwater depth as a vertical distance between ground surface and groundwater level. I then reported the stable isotope ratios of groundwater by means of the mass balance of water and a tracer mass balance for calculating the recharge percentage of river water and precipitation to groundwater in the Luohui Irrigation District, China. I demonstrated in this study that geographical and stable isotopes data provided important supplemental information for studying groundwater recharge, salt movement, and allocating the utilization of canal systems and wells for reasonable water resources management.

In chapter 4, the Luohui Irrigation District has been facing salinization problem through time, which demands remedies targeted on preventing new salinization processes and rehabilitating salinized areas. Consequently, I applied the chemical analysis and stable isotope technology to find the movement and source of salt through water can be regulated by controlling the quality of irrigation water, based on the relationships among surface topography, groundwater depth, and regional hydrogeology.

As typical mitigation measures to minimize on eliminate salinization problems, I commonly apply soil conditioners and much amount of water to leach down the salt, install surface or subsurface drainage structures, and cultivate salt-tolerant crop. In chapter 5, I selected typical soil sections to do the soil water and salt movement experiment by stable isotope and chemical analysis, and analyzed the soil water-salt dynamic feature and its influencing factors based on analyzing the geological properties in unsaturated zone.

Consequently, the aim of the study is to prevent soil degradation by salinization and reclaim salinized soils, and it is crucial to understand the regulation of salt movement through water in unsaturated zone.

In chapter 6, in the Luohui Irrigation District, I analyzed the physical and chemical characteristics of the soil after conducting warp soil dressing, and evaluated the sustainability and effects of saline soil improvement by warp soil dressing.

In chapter 7, I clarify the groundwater level movement and soil salinization at Caomao check dam in Zizhou County, Shaanxi Province, China.

Finally, conclusions and recommendations of this research are given in Chapter 8.

1.3 Technical route

The research uses the technical route that combines the theoretical research and case analysis to find and analyze the source of water and salt. Based on a great deal of information of geochemistry (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-) and analysis data of stable isotope (^{18}O, ^2H), analyze the regular model of water and salt movement. Then, study the source and circulation characteristics of water and salt with regional hydro-geological condition in the study area. The methods mainly used include chemical analysis, stable isotope analysis, comparative analysis, isotope tracing, etc. The research was conducted based on the process shown in **Figs. 1-3** and **1-4**.

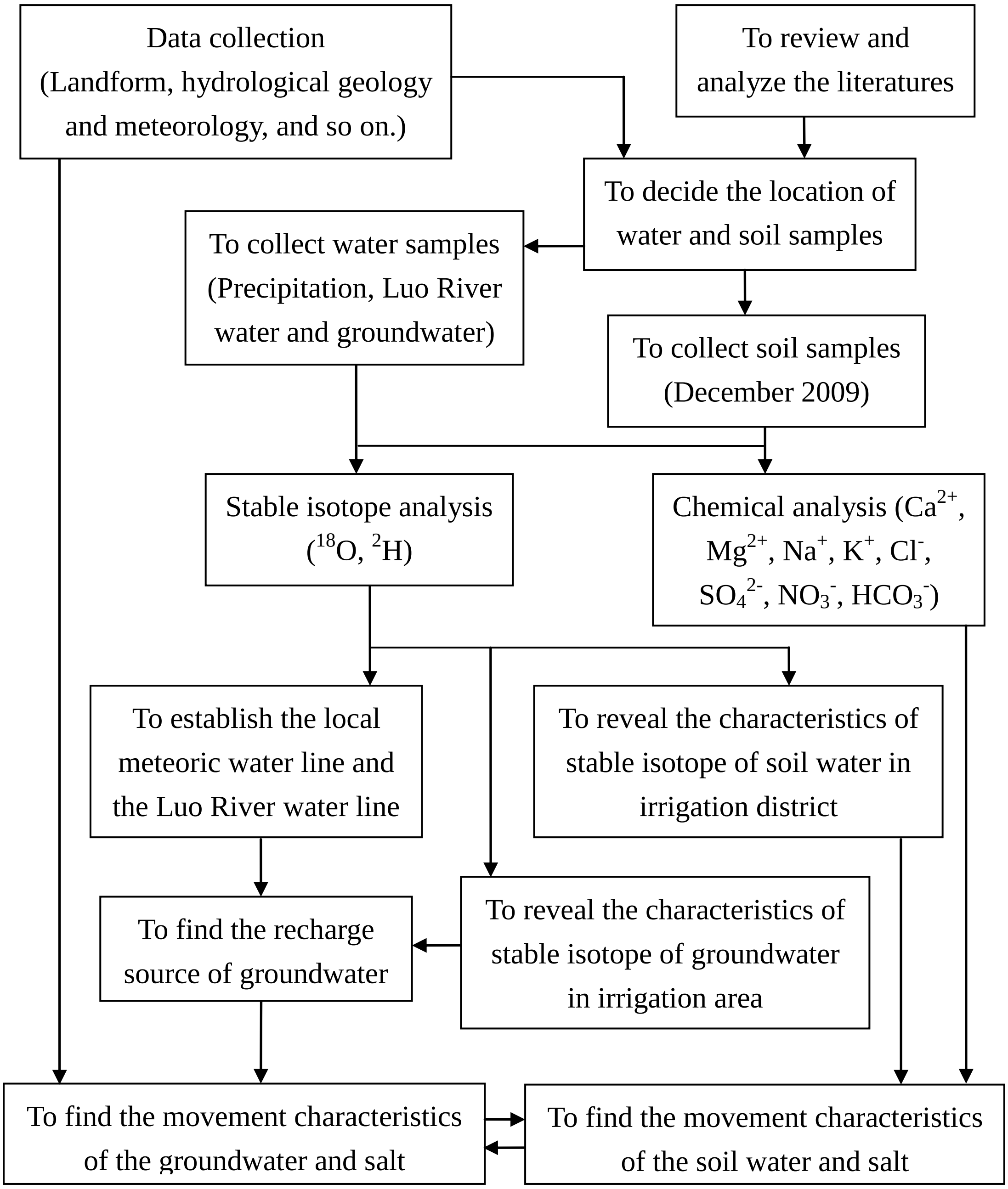


Fig. 1-3 Comprehensive research plan to be conducted in the Luohui Irrigation District of Dali County, Shaanxi Province, China

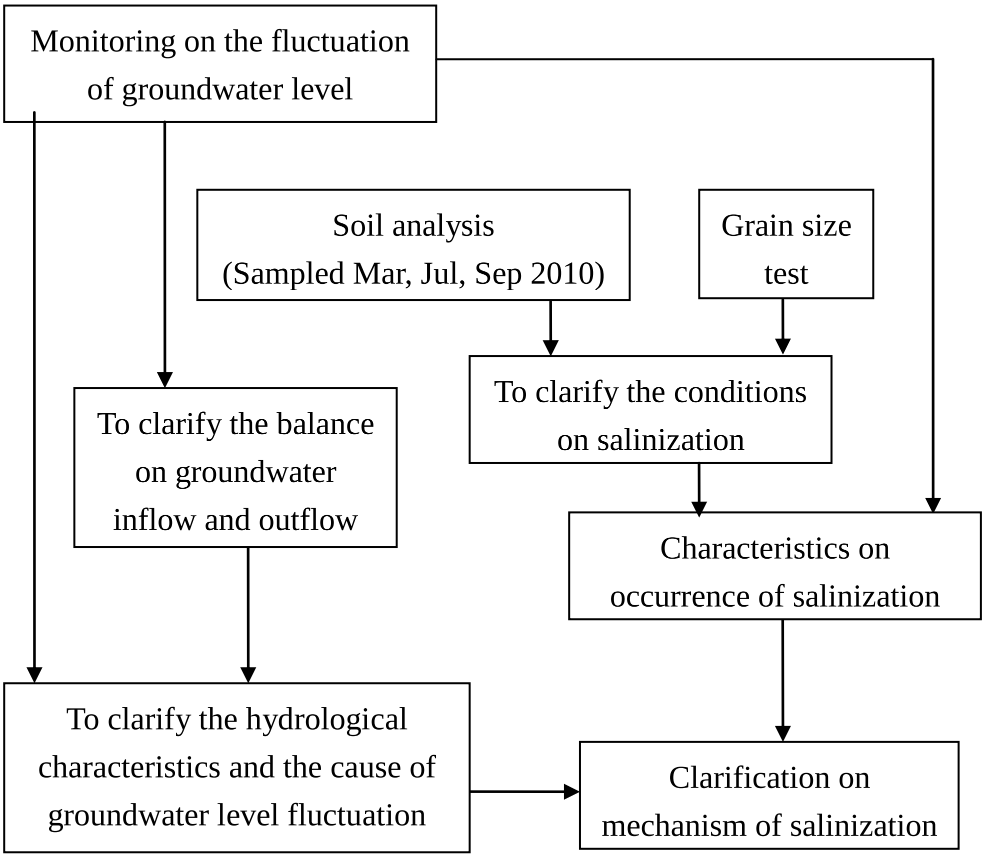


Fig. 1-4 Comprehensive research plan to be conducted in the Caomao check dam of Zizhou County, Shaanxi Province, China

2 Literature review

There are four parts of literature review in this chapter, including chemical analysis, stable isotope, water and salt movement, and check dam:

2.1 Chemical analysis

One of the most important methods to reveal the evolutionary process of groundwater solute is to make research on the relationship between the major ions and Cl^-. Through the research on the ratio of the major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, and SO_4^{2-}) and Cl^- in confined aquifer system of the Nobi Plain and Southeast area in Japan, Yamanaka, M. and Kumagai, Y. (2006) found that there were strong correlation ($r > 90\%$) between Na^+, K^+, Ca^{2+}, Mg^{2+} and Cl^-, and their ratio are close to that of current seawater. Combined with the local hydrological and geological conditions, it seems that the salinity of local groundwater is decided due to the mixture of the current seawater and ground freshwater.

The existence form and contents of the groundwater dissolved substances is related to its recharge resource, and the water-rock interaction or blending in the runoff process, as well as the human pollution. In the nature environment of the coastal region, the groundwater mainly comes from the rainfall, and the ratio between the major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, and SO_4^{2-}) and Cl^- is close to that of the seawater. However, because of the interaction in the runoff process, in combine with some other interactions，including ion exchange, dissolution-precipitation or oxidation-reduction reaction, the ratio deviate from the sea water, but it still shows relatively strong correlation with the Cl^-. With the influence of the human activities, the major ion contents in the groundwater are controlled by the pollution, and the relativity between the ionic substances reduced remarkably.

The chlorine is the most widely distributed halogen element in nature, and it is usually in the form of Cl^-. In the chemical research, Cl^- is normally considered as a conservative element, and rarely occurs with a fractionation phenomenon. Besides, Cl^- owns a strong ability to dissolve, and it is not easy to be adsorbed by clay, also not easy to produce chloride precipitation. From this point of view, we can conclude the existence of the following two features of the distribution of Cl^-: (1) The amount of Cl^- is different in different resources. The amount of Cl^- in the rain which only comes from the sea can be treated as the strong dilute of the sea water contents, and the Cl^- in the rain which would be influenced by the air pollution will be changed regionally, and the Cl^- in the rain which was influenced by human pollution only changes perceptible around the pollution source. (2) Normally, Cl^- does not stay in the permeable rock, especially in the effective circle of groundwater, Cl^- is obviously not produced in the aquifer (Appelo and Postma, 1993; Junge and Werby, 1958).

Consequently, Cl^- becomes the important index to trace the changes of underwater environment. Except for using the relationship between Cl^- and major ions to make research on evolution of groundwater circulation, I also can use the relationship between Cl^- and other halogen elements (Br, F, I) in the groundwater to make research on the source of salts in groundwater. In addition, the combination of the Cl^- and stable isotopes (^{2}H, ^{18}O) in water can be used as an effective method to make research in the historical rainfall recharge and vapor cycle (Allison *et al*., 1984). Usually, the Cl^- in terrestrial groundwater comes from the atmosphere, and evaporation and concentration occurred during the recharge. These results indicate that in the arid and semiarid area, the existence of a large amount of fresh groundwater is the strong evidence to suggest its humid climatic conditions in geological history. While the high content of salt in the shallow aquifer can reveal that the much more arid climate left the salt as remnant in the past 4000 years (Gonfiantini *et al*., 1974).

2.2 Stable isotope technology

Stable isotopes (^{18}O, ^{2}H) are the environmental isotope which are natural products and widespread. Due to their relative mass difference, I can trace the fractionation of physical and chemical reactions. So since the early 1950s, hydrogen and oxygen isotope techniques have been used in the hydrogeology research. After decades of continuous research, stable isotopic method has been proved to be the special tool in identifying the source and evolution of the groundwater.

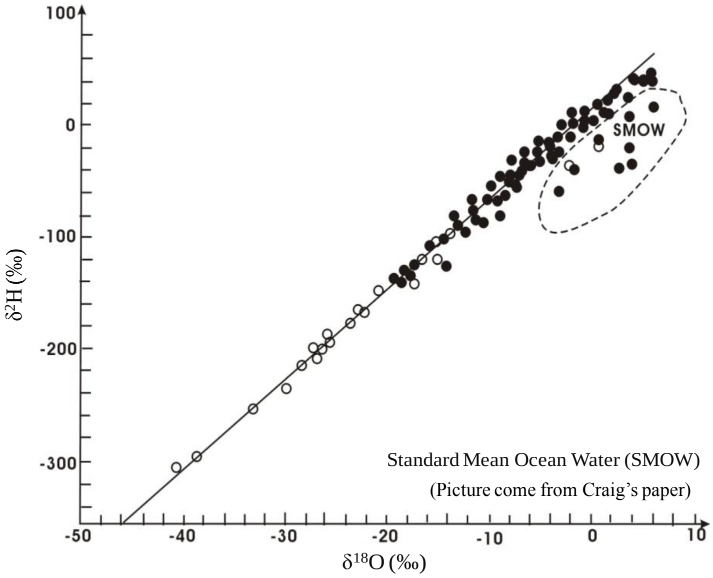
Temperature is the key factor to influence the above process. Its relationship with

δ^2H−δ^{18}O controls the position of precipitation on the global meteoric water line (GMWL), from this, temperature effect, latitude effect, continental effect, altitude effect, amount effect and season effect can be deduced. Besides, the factors of salt and else can also make influence on the isotope fractionation. According to the needs of the research, I have described the characteristics and applications of the related stable isotopes (^{2}H, ^{18}O) as follows:

2.2.1 Global meteoric water line

Craig (1961) analyzed the 400 isotope data of rainfall samples that come from the rivers and lakes all over the world, and found that there were some correlation between ^{2}H and ^{18}O in the global fresh water, and then defined this linear relationship as the global meteoric water line (GMWL) to reflects the relationship between ^{2}H and ^{18}O in global precipitation (**Fig. 2-1**).

However, due to the change of climate and geographical parameters, many local or regional precipitation lines tend to deviate from the GMWL, and those lines were called the local meteoric water line (LMWL). Compared with the LMWL, the GMWL is actually the representative of average global scale water line, and this line acts as a contrast line in the research of isotopic composition of precipitation, and also the line provide us the reference of the source of groundwater.



Standard Mean Ocean Water (SMOW)
(Picture come from Craig's paper)

Fig. 2-1 Craig's relationship between δ^2H and δ^{18}O of the precipitation

2.2.2 Application of stable isotopes in groundwater studies

2.2.2.1 Research on the mixing effect of groundwater

Zuppi *et al*. (1974) studied the hot mineral springs of high temperature in Latium, and obtained the conclusion that the springs are mixed with deep hot water and atmospheric precipitation. Andrew *et al*. (2004) pointed out that to determine the proportion of supply source in a small water body, the existence of great differences in the contents of stable isotopes from each supply source is prerequisite.

2.2.2.2 Research on the aquifer supply problems in ancient climate

For large confined aquifer, the excessive mining often caused declining of the groundwater potential line, and this may cause exhaustion on progressive drying up of “ancient fossil water”. However, for the water in unconfined aquifer, it is not sure whether it is also supplied by the precipitation in ancient climate or not? Through the isotope comparison between the ancient water and modern water in Taiyuan Basin, Li *et al*. (2006) could come to the conclusion that the supply process is similar in different periods. Vimeux *et al*. (2001) used the four records of deuterium excess to study the hydrogeology cycle in the ancient time.

2.2.2.3 Research on water salinity

Saltwater may come from seawater (such as the invasion of seawater), also may come from the salinization of continental water, and so on. To find out the causes of water salinity, I can use the relationship between $\delta^{18}O$ and $\delta^{2}H$. Merivat and Vuillaume made research on the deuterium profile of two wells which were only several miles along the flow direction of groundwater in Marseille of France, and found out that there was no marked difference in $\delta^{2}H$ of shallow groundwater (0-13 m) between the two wells, and they considered that the groundwater were not directly supplied by the infiltration of precipitation (Lin, 2007). Otherwise, in the following months, the $\delta^{2}H$ values in two wells should show obvious seasonal changes. Cheikh (2001) made an intensive study of the process of saline environment and determined the principle of salinization.

2.2.2.4 Research on the source and groundwater recharge

By scientifically collecting samples of precipitation, river water and groundwater and measuring the isotopic composition to determine the recharge sources of groundwater; the recharge amount of groundwater can be calculated according to the mass balance theory. It is an important method to use the hydrogen and oxygen isotope method to evaluate recharge sources of groundwater (Banoeng-Yakubo *et al*., 2009). In addition to the above situation, the hydrogen and oxygen isotope also can be used in the research of groundwater pollution. Chen *et al*. (2006) have used the hydrogen and oxygen isotope in the research of nitrate concentrations in groundwater.

2.2.3 Application of stable isotopes in soil water studies

Soil water is the part of water circle, but the research on it has always been the difficult point and weak links on the research of isotope water circle. There are great values both in theory and reality in analyzing moisture dynamic changes in the soil in the unsaturated zone, and in analyzing the effect of the amount of precipitation and precipitation process, as well as in analyzing the proportion in groundwater recharge.

The main applications of stable isotope in the research of soil water are as follows: by analyzing isotope profiles of soil water, to reveal the movement process of soil water, the evaporation process and the amount of evaporation loss of soil water, to estimate the evapotranspiration of vegetation by the water balance model. It is mainly in the arid and semiarid region that to do the research of calculating the amount of precipitation infiltration by using the method of analyzing the isotope changes in the soil water.

Sharma and Gupta (1985) estimated that the infiltration amount in the Thar desert occupies 6−14% of the precipitation. Zimmerman *et al*. (1967) had done the research first on the feature of hydrogen isotope of the soil water which has been influenced by evaporation, and found that the evaporation from the saturated soil could lead to the enrichment of ^{2}H near the surface of soil, and the value of ^{2}H declined with the depth increased. And later on, many indoor soil column experiments and field experiments also observed the enrichment phenomenon of ^{2}H and ^{18}O near the soil surface. They made some theory explanation on this phenomenon and applied this to evaluate the rate of evaporation (Hsieh *et al*., 1998). Melayah *et al*. (1996) had studied the movement of soil water by stable isotope in the unsaturated zone, and this research improved the simulation of the soil profile in the process of soil water evaporation in the most natural condition.

2.3 Water and salt movement

The research on the theory of salt and water movement is the foundation of the researches on the whole salt and water movement system. Schofield and Clasimov had made the research on salt and water balance in 1930s, and they helped people to scientifically recognize and analyze the changes of factors in the salt and water movement. The theory of salt and water balance combined with the scientific law of Darcy is the basic theory frame in the modern salt and water movement research. In the arid and semiarid region, the main factor to influence the salt and water situation is the climate (precipitation and temperature) and geography (Zhang, 2007; Du, 2009).

The law of salt and water movement is the main basis for protecting the agriculture and ecology environment and land improvement in the arid and semiarid region. The water in soil not only acts as the solvent of the salt, but also as the carrier of the salt. Zhang (2007) and Du (2009) have considered water as the important material to improve the saline soil. Consequently, salt and water dynamics and salt and water balance are the important theory to improve saline soils and to prevent soil salinization. They thought that in the strong evaporation condition of arid and semiarid regions, the salts in soil or the soluble salt in groundwater can accumulate in the surface through the vertical or lateral movement of water. This is the most normal form of soil salt accumulation, and it is also the main reason of the salinization.

2.4 Check dam

Check dams construction is successful and effective project by intercepting sediment, conserving soil and water, reclaiming of arable land, and increasing food production in the Loess Plateau. It is a successful experience accumulated by the masses of the people to struggle against water loss and soil erosion over a long period of time for improving environment. There are several hundred years of development history. According to literature record, the original check dam was formed naturally 400 years ago. Alluvial land in Zizhou County, Shaanxi Province was formed which was caused by silt deposition in the year of 1569. After that, the first check dam of 60 m height and more than 54 ha arable land was constructed by local people. Check dam construction has been a rapid development since the year of 1949, and the department of soil and water conservation, ministry of water resources of China conducted an experimental demonstration of check dam. Check dam has been employed as the framework of major projects for gully erosion control and high yield arable land construction. According to investigation statistics, after 50 years of construction, there are more than 110,000 check dams in the Loess Plateau, and more than 300,000 ha newly arable land have been gained in front of the dam. In addition, 36,816 check dams have been built in Shaanxi Province (Xu *et al*., 2002; Hu *et al*., 2004).

3 Recharge sources and groundwater movement in a semiarid region

3.1 Introduction

Irrigation agriculture is developing rapidly in China, and the area under irrigation is continuously increasing (Liu *et al*., 2007). Unfortunately, excessive exploitation and poor management of water resources in irrigation districts have led to many serious local eco-environmental problems, such as groundwater quality deterioration, land desertification, and secondary soil salinization (Zhang *et al*., 2007).

Salinization, the build-up of salts in the soil, is a worldwide problem, especially in arid and semiarid areas (Solomon *et al*., 2005). In such areas, high evapotranspiration, low precipitation, the presence of soluble salts, and shallow groundwater depth create favorable conditions for the transport of soluble salts from the groundwater to the surface through capillary water rise (Bohn *et al*., 1985; Dochartaigh *et al*., 2010). The movement of salts in water can be regulated, however by controlling irrigation water quality and the groundwater levels (Levy, 1984).

To utilize water resources effectively and to achieve sustainable development, the interaction between surface water and groundwater and the renewability of groundwater in different aquifers must be understood (Zhang *et al*., 2009). Groundwater is a highly useful and often abundant resource for irrigation, but its overuse, or overdraft, can cause the major problems to local environment (Banoeng-Kakubo *et al*., 2009). Consequently, in assessing regional water resources in irrigation districts, studies of groundwater recharge are very important to prevent serious water problems such as continuous water level declines and the deterioration of water quality (Tang *et al*., 2004; Li *et al*., 2007). To properly understand the recharge process, detailed knowledge of hydrological processes and the interaction of precipitation and groundwater is essential (Bouchaou *et al*., 2009).

Stable isotopes (^{18}O, ^{2}H) are widely present in water, and different waters have distinctive isotope compositions because of isotopic fractionation as they circulate among precipitation, surface water, groundwater, soil moisture, and plant water (Kattan, 2008). Differences in isotopic content can therefore be used to investigate phenomena such as the exchange of surface water with groundwater and leakage between aquifers (Kohfahl *et al.*, 2008). Stable isotopes have also been used to estimate regional groundwater recharge and to trace water flow, and have thus contributed remarkably to our understanding of the water cycle and diverse hydrological processes (Davisson and Criss, 1993).

Although many stable isotope studies have been carried out in arid regions, few have been conducted in semiarid regions or in irrigation districts (Lu *et al.*, 2008; Du, 2009). Du *et al*. (2008) analyzed stable carbon isotopes in halophytes under environmental stress in the Luohui Irrigation District, and used stable isotope tracers to analyze groundwater recharge based on the global meteoric water line (GMWL) and the Yellow River water line (YRWL). The isotopic tracer techniques are useful tools for the quantitative evaluation of groundwater recharge, assessment of water resource availability, and the protection of fragile eco-environmental systems (Barnes and Allison, 1988).

The objective of this study was to identify groundwater recharge sources by using stable isotope tracers and investigate groundwater movement in the eastern block of the Luohui Irrigation District to assist in optimization of water resource management and prevention of salinization there. I investigated the stable isotope contents of precipitation and Luo River water, and determined the local meteoric water line (LMWL) and the Luo River water line (LRWL). Large differences in groundwater depth and terrace elevations in the study area provide an excellent opportunity to use stable isotope tracers to detect groundwater recharge areas. I also used groundwater stable isotope ratios, the water mass balance, and the tracer mass balance to calculate the relative contributions of Luo River water and precipitation to groundwater recharge in the eastern block of the Luohui Irrigation District, China. Our results demonstrate that topographic and stable isotope data can provide important information for studies of groundwater recharge and salt movement, and for appropriate management of water resources, irrigation canal systems and wells.

3.2 Study area

3.2.1 Location

The eastern block of the Luohui Irrigation District has an area of about 32,000 ha and is located on the left bank of the Luo River near its confluence with the Wei River, which is a tributary of the Yellow River, in Shaanxi province, China. It is situated at the foot of the Loess Plateau between (latitude 34°45'23"–34°56'05" N, longitude 109°45'22"–110°10'23" E; elevation, 329–400 m above mean sea level) (**Fig. 3-1**).

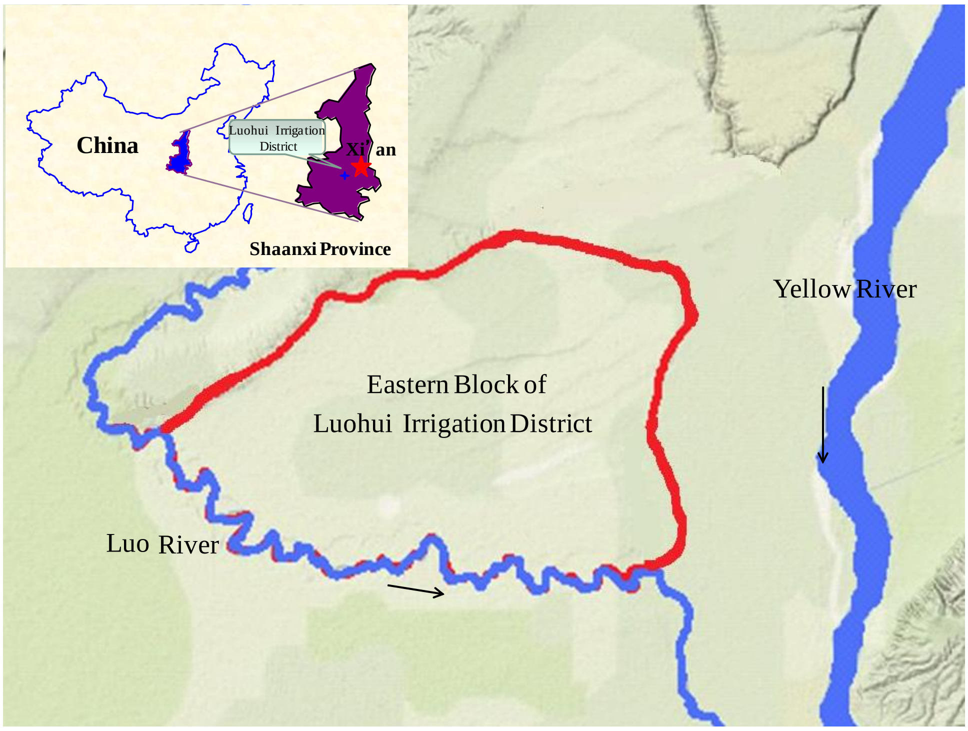


Fig. 3-1 Topographic map of the eastern block of the Luohui Irrigation District

In this study, I used as observation point about 30 groundwater wells (**Fig. 3-2**), which had been drilled for various agricultural (irrigation, drinking, mixing insecticides) and non-agricultural (pulp factory, concrete mixing) purposes. Each well is identified by a number assigned by the local officials. The number hasn't specific order and there are wells having well ID of 100 and 101 unlike the total number (30). In some cases some wells are also numbered as Well 53'. The local coding of these wells is used in this study.

Besides, the study area also includes a salt lake (into which most of the irrigation canals drain) and several town and villages (settlements).

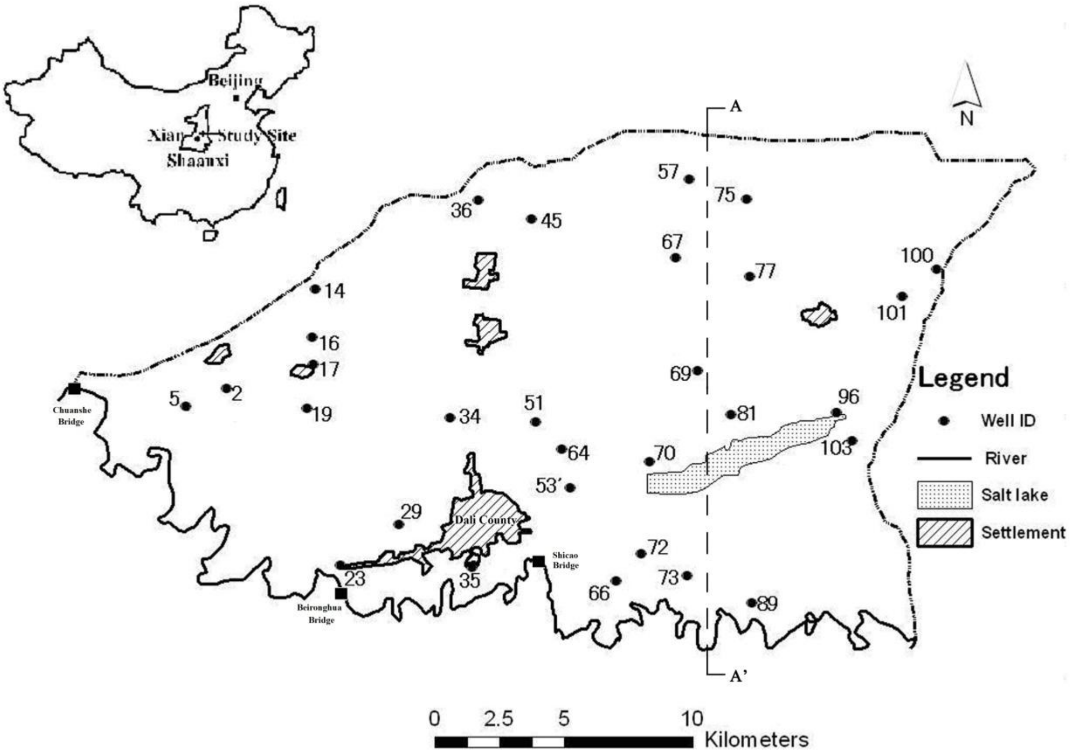


Fig. 3-2 Location of well in the eastern block of the Luohui Irrigation District

3.2.2 Geology and landforms

In geology, a terrace is a step-like landform. A terrace consists of a flat or gently sloping geomorphic surface, called a tread, which is bounded typically one side by a steeper ascending slope, which called a "riser" or "scarp". The tread and the steeper descending slope (riser or scarp) together constitute the terrace.

In this study, the terrain goes down from north to south, with the altitude between 330 to 400 m, and the area is characterized by three main geomorphic features, namely, the third, second, and first fluvial terraces, whose surfaces are at 330−360, 350−380, and 370−400 m above mean sea level, respectively (Li, 1995) (**Fig. 3-3**).

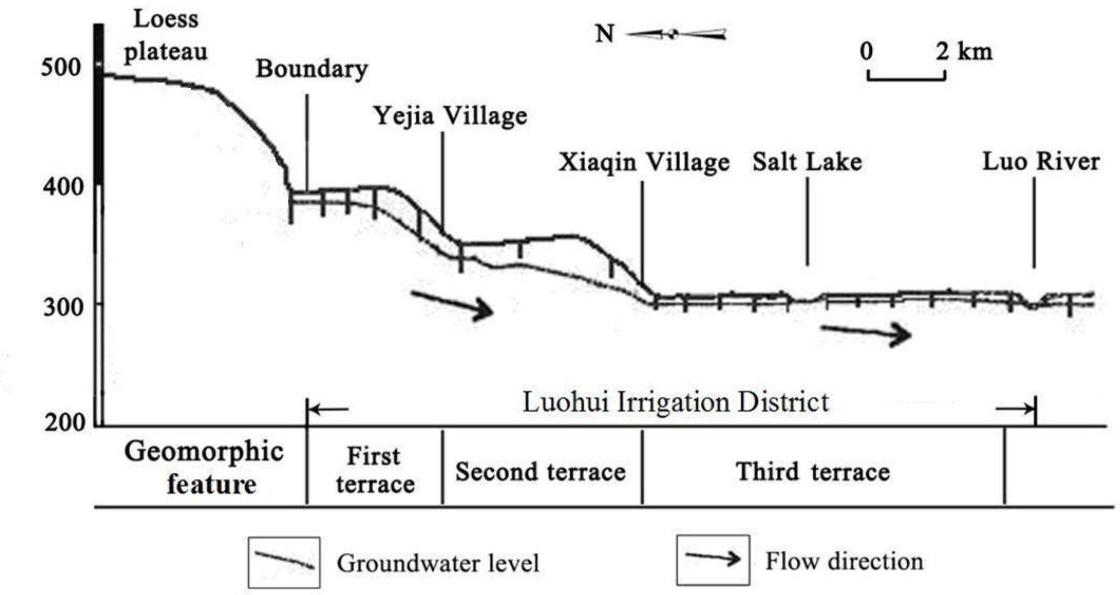


Fig. 3-3 Section of A–A’ profile in the eastern block of the Luohui Irrigation District

3.2.3 Meteorology

The climatic condition of the area is a semiarid type with average annual precipitation of 484.2 mm, which is too low for rainfed agriculture. The rainy season is typically from July to September, and the average annual temperature is around 13.5˚C **(Fig. 3-4)**. The average potential evaporation (1690.3 mm) is about three times of the annual precipitation, which means that irrigation agriculture is likely to cause soil salinization.

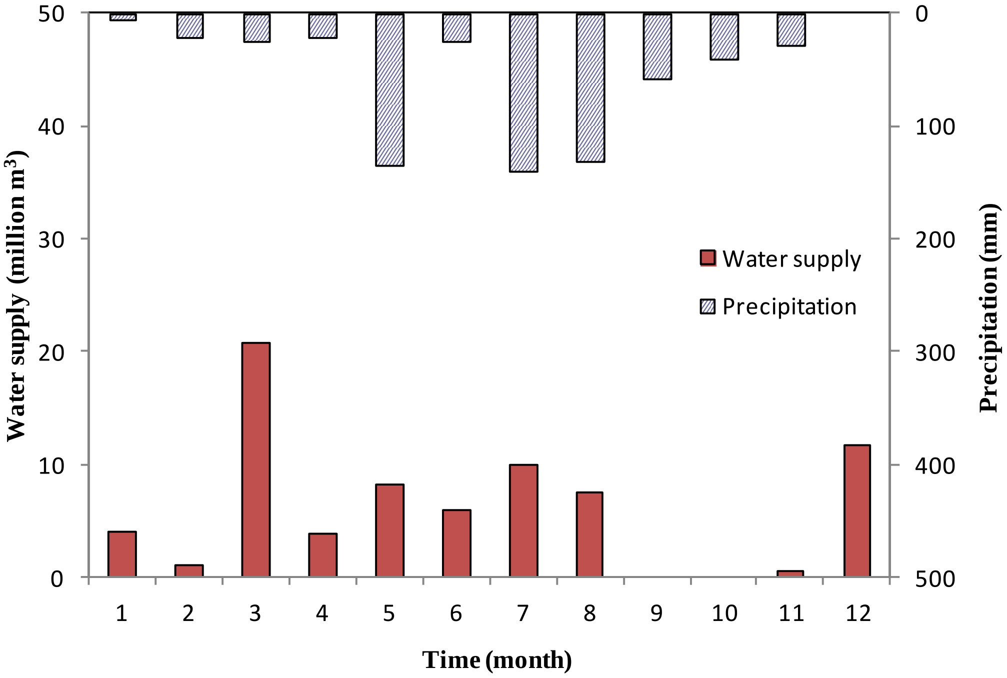


Fig. 3-4 Variation of irrigation water supply and precipitation in the eastern block of the Luohui Irrigation District in 2009

3.2.4 Crops

The Luohui Irrigation District is fertile land, sufficient sunlight, and the frost-free period is longer. Consequently, it is the good agricultural regions; the main crops are wheat, maize, cotton, rape seed, vegetables and orchard. Seen from **Table 3-1**, the total irrigation area has not charged, but the cultivated area decreased as the orchard increased in the Luohui Irrigation District in 1998–2002.

Table 3-1 Statistical data of proportion of crop cultivated in the Luohui Irrigation District

Year	Irrigation area (ha)	Cultivated area (ha)	Multiple crop index (%)	Proportion of crop (%)					
				wheat	maize	cotton	rape seed	vegetables	orchard
1998	75,000	60,000	162	70	54	18	5	3	12
1999	75,000	59,500	161	64	56	20	3	4	14
2000	75,000	58,800	152	53	49	25	2	5	18
2001	75,000	57,900	136	40	35	31	2	6	22
2002	75,000	57,400	138	39	38	30	1	6	24

3.3 Materials and methods

The geographic coordinates of the wells are determined with a global positioning system. Elevation data of the wells, which had been collected by direct survey, were provided by the Luohui Irrigation Management Bureau. I measured the temperature and groundwater depth (GD), defined as the vertical distance from the ground surface to the groundwater level, temperature and groundwater level were measured directly at each well in the field. Moreover, water samples from each well (at 50−100 cm depth below the water surface), Luo River water and rainwater were collected for later measurement of the stable isotopes in the laboratory. All samples were collected in 5-ml polypropylene bottles, which were carefully filled to prevent air entrapment and closed with watertight caps, and stored at 4 ˚C (to prevent evaporation fractionation) until analysis. The stable isotope analysis of the water samples was carried out in May 2010 at Xi’an University of Technology in China with a MAT-253 Mass Spectrograph (**Fig. 3-5**) equipped with two equilibration units for the online determination of ^{18}O and ^{2}H isotopic composition.

Fig. 3-5 MAT-253 Mass Spectrograph in Xi’an University of Technology, China

Oxygen (^{18}O) and hydrogen (^{2}H) isotope abundances are expressed in delta notation (δ) as permil differences relative to the Vienna Standard Mean Ocean Water (VSMOW) (Lu *et al*., 2008), as follows:

$$\delta^{18}\mathrm{O}\left(\delta^{2}H\right)=\left(R_{sp}/R_{st}-1\right)\times 1000 \tag{3.1}$$

Where R_{sp} and R_{st} are the ^{2}H/^{1}H or ^{18}O/^{16}O ratios in the sample and standard, respectively. δ^{18}O and δ^{2}H were measured by a MAT-253 Mass Spectrograph with an analytical precision of ±0.1‰ and ±1.0 ‰, respectively.

3.4 Results and discussion

3.4.1 Isotopic composition of precipitation

Because most of the world’s precipitation is derived from evaporation of seawater, δ^{18}O and δ^{2}H are linearly correlated in precipitation throughout the world. This relation, known as the GMWL, is expressed as $\delta^2H = 8\delta^{18}O + 10$ (Liu *et al.*, 2007). Because precipitation was scarce during the study period, between March 2008 and September 2009 only eight rainwater samples were collected during three precipitation events (**Table 3-2**). Using these data, I calculated the LMWL to be $\delta^2H = 7.71\delta^{18}O + 3.71$. In general, the LMWL differs among regions, and isotope values of precipitation exhibit seasonal effects. The mean isotopic values of the precipitation samples collected on 10 September 2009 ($\delta^{18}O$ = –5.48‰ and δ^2H = –40.22‰) were lower than those in the 9 September samples (–3.08‰ and –25.36‰, respectively), because condensation of water vapor in the atmosphere leads to isotope fractionation. Less-negative isotopic values were also observed during heavy rain events and after long periods of rain because of continuing isotopic depletion of the precipitation.

Table 3-2 Stable isotopes in precipitation in the Luohui Irrigation District

Sample No.	Sampling site	Date (month/day/year)	$\delta^{18}O$ (‰)	δ^2H (‰)
P_1	Luohui Irrigation Management Bureau	3/29/2008	-2.52	-10.81
P_2		4/1/2008	-6.50	-55.39
P_3		4/9/2008	-3.58	-11.71
P_4		4/11/2008	-6.44	-40.16
P_5		9/9/2009	-2.65	-20.11
P_6		9/9/2009	-3.51	-30.61
P_7		9/10/2009	-4.10	-35.92
P_8		9/10/2009	-6.86	-44.51

3.4.2 Isotopic composition of surface water

The Luo River is a tributary of the Yellow River in China, which is source for irrigation in the study area. The isotope values of river water also has the seasonality effect due to the precipitation is one of river water sources. Therefore, water samples from Luo River were analyzed in September and December 2009 (**Table 3-3**), then I could get the Luo River water line (LRWL) and expressed as follows: $\delta^2H = 4.34\delta^{18}O - 42.61$. **Table 3-3** shows the mean isotope values of Luo River water in summer were –7.42‰ for $\delta^{18}O$ and –74.64‰ for δ^2H, and in winter were –8.01‰ for $\delta^{18}O$ and –77.54‰ for δ^2H. The Yellow River water line (YRWL) obtained using data in the upper reach of Yellow River were $\delta^2H = 4.66\delta^{18}O - 22.75$ (Liu *et al.*, 2007). Overall, Luo River water in summer is enriched in both $\delta^{18}O$ and $\delta^{2}H$, indicating the evaporation is quite serious in the Luohui Irrigation District.

Table 3-3 Stable isotopes in Luo River water in the Luohui Irrigation District

Sample No.	Sampling site	September 2009		December 2009	
		$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
R_1	Longshou	-7.30	-73.33	-7.93	-75.90
R_2	Chuanshe Bridge	-7.51	-73.68	-7.79	-78.86
R_3	Beironghua Bridge	-7.54	-76.84	-8.21	-78.10
R_4	Shicao Bridge	-7.32	-74.73	-8.10	-77.29

Table 3-4 General characteristics and isotopic data of groundwater samples in the Luohui Irrigation District in summer 2009

Well No.	Terrace	Altitude (m)	Canal System	T (˚C)	Depth (m)	Groundwater Level (m)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
29	3	354.70	West	17.5	16.37	338.33	-7.627	-75.022
23	3	356.55	West	17.8	22.79	333.76	-7.544	-72.441
35	3	350.50	West	17.8	14.87	335.63	-7.625	-68.023
64	3	352.41	Middle	17.9	7.40	345.01	-7.028	-73.463
53'	3	351.09	Middle	20.3	6.71	344.38	-7.148	-65.979
70	3	346.04	Middle	18.4	2.84	343.20	-7.390	-67.775
72	3	348.86	Middle	18.3	12.60	336.26	-7.523	-75.690
73	3	346.07	Middle	17.4	18.65	327.42	-7.570	-71.666
66	3	344.19	Middle	18.0	8.10	336.09	-7.299	-75.346
81	3	347.01	East	17.1	7.77	339.24	-7.353	-71.530
96	3	346.55	East	17.2	12.06	334.49	-7.614	-73.735
103	3	356.37	East	19.3	25.75	330.62	-7.593	-72.634
89	3	347.93	East	16.9	20.83	327.10	-7.447	-77.132
34	2	354.43	West	19.0	3.45	350.98	-7.544	-71.809
51	2	350.73	Middle	15.3	2.25	348.48	-7.282	-70.937
5	2	366.70	West	24.4	14.05	352.65	-7.546	-72.261
2	2	366.62	West	16.1	3.10	363.52	-7.328	-71.916
16	2	367.77	West	15.7	5.10	362.67	-7.593	-72.594
17	2	361.20	West	16.6	1.05	360.15	-7.489	-69.972
19	2	360.08	West	15.4	4.20	355.88	-7.715	-78.419
101	2	370.13	East	17.9	23.20	346.93	-7.506	-77.173
100	2	376.83	East	18.2	30.20	346.63	-7.306	-74.671
69	2	362.44	East	19.3	13.45	348.99	-7.375	-71.564
14	1	387.08	West	18.8	8.15	378.93	-7.347	-72.045
36	1	382.33	Middle	19.7	0.93	381.40	-7.334	-69.363
45	1	371.20	Middle	19.3	1.85	369.35	-8.552	-84.714
77	1	382.35	East	16.7	17.90	364.45	-7.582	-73.691
75	1	379.42	East	15.7	4.50	374.92	-7.917	-79.612
67	1	377.26	East	17.4	10.60	366.66	-8.250	-77.038
57	1	383.34	East	16.6	3.00	380.34	-7.356	-68.179

Table 3-5 General characteristics and isotopic data of groundwater samples in the Luohui Irrigation District in winter 2009

Well No.	Terrace	Altitude (m)	Canal System	T (˚C)	Depth (m)	Groundwater Level (m)	δ^{18}O (‰)	δ^{2}H (‰)
29	3	354.70	West	12.2	15.82	338.88	-7.638	-76.141
23	3	356.55	West	10.7	20.30	336.25	-7.631	-73.081
35	3	350.50	West	10.8	14.71	335.79	-7.706	-69.714
64	3	352.41	Middle	11.7	7.29	345.12	-7.084	-73.688
53'	3	351.09	Middle	13.0	6.62	344.47	-7.381	-69.473
70	3	346.04	Middle	12.5	2.69	343.35	-7.599	-75.074
72	3	348.86	Middle	12.9	12.12	336.74	-7.900	-76.189
73	3	346.07	Middle	9.4	17.02	329.05	-7.601	-78.544
66	3	344.19	Middle	11.0	7.49	336.70	-7.462	-76.126
81	3	347.01	East	10.8	7.60	339.41	-7.535	-77.434
96	3	346.55	East	13.2	11.55	335.00	-7.921	-75.403
103	3	356.37	East	11.6	25.48	330.89	-7.806	-73.893
89	3	347.93	East	10.3	19.04	328.89	-7.573	-66.396
34	2	354.43	West	9.7	3.34	351.09	-7.636	-75.783
51	2	350.73	Middle	12.1	2.11	348.62	-7.520	-72.473
5	2	366.70	West	10.5	13.39	353.31	-7.640	-73.440
2	2	366.62	West	12.7	2.83	363.79	-7.375	-73.736
16	2	367.77	West	13.0	4.80	362.97	-7.736	-73.898
17	2	361.20	West	11.5	1.51	359.69	-7.596	-70.047
19	2	360.08	West	10.3	4.15	355.93	-7.727	-79.533
101	2	370.13	East	10.9	22.10	348.03	-8.176	-81.192
100	2	376.83	East	11.2	29.10	347.73	-8.028	-76.015
69	2	362.44	East	11.1	13.45	348.99	-7.592	-76.148
14	1	387.08	West	12.2	7.95	379.13	-7.740	-75.493
36	1	382.33	Middle	10.2	1.27	381.06	-7.516	-74.493
45	1	371.20	Middle	14.1	1.58	369.62	-8.227	-80.920
77	1	382.35	East	10.5	17.95	364.40	-7.808	-85.119
75	1	379.42	East	10.5	4.42	375.00	-7.937	-83.858
67	1	377.26	East	11.3	10.40	366.86	-8.253	-86.823
57	1	383.34	East	8.9	3.10	380.24	-7.808	-76.560

3.4.3 Isotopic composition of groundwater

In general, the isotopic values of the groundwater in the eastern block of the Luohui Irrigation District differed depending on the water source (**Tables 3-4** and **3-5)**, and we used these differences to infer the sources of groundwater recharge.

3.4.3.1 Recharge sources of groundwater in summer

Groundwater samples were collected for stable isotope analysis from 4 to 10 September 2009, after the end of the summer irrigation period (20 May to 20 August 2009) in the study area. The meteorological data showed that at this time 78.7% of annual precipitation had already fallen (**Fig. 3-4**). As a result, the influence of groundwater depth on the recharge source was very significant.

According to Li (1995), for GD < 3 m, there is high risk of salt accumulation caused by capillary water rise due to evaporation; and for GD > 10 m, it is difficult for surface water to infiltrate through the unsaturated zone into the groundwater. Therefore, in this study I examined the isotope compositions of water from three depth intervals: GD < 3 m, 3 m< GD < 10 m, 10 m < GD.

I compared δ^{18}O and δ^{2}H in groundwater in summer with the LMWL and the LRWL (**Figs. 3-6** and **3-7**), they are described as follows:

(1) When GD < 3 m: the isotope concentration more enriched than groundwater from other depths, which suggests the recharge source of the shallow groundwater was mainly precipitation. Moreover, the shallow groundwater from almost all of the wells was affected by the evaporation fractionation. However, the isotope compositions of Well 45 (δ^{18}O = −8.55‰, δ^{2}H= −84.71‰) was very depleted, indicating recharge from deep groundwater (groundwater from deeper than 15 m below the groundwater level. At 15 m, the groundwater became abruptly saltier because the eastern block of the Luohui Irrigation District has large concentrations of soluble salts at 40−50 m below the ground surface) (Li, 1995). Well 45 was likely recharge mainly by deep groundwater because it is at a relatively high elevation on the first terrace (**Table 3-4**) and because there is no irrigation canal near the well.

(2) When 3 m < GD < 10 m and GD > 10 m: the isotope composition of groundwater in the wells mainly plotted near the LRWL, and the recharge source for evaporation fractionation is small because the low isotopes and the high GD. These results indicate that the main recharge source of the groundwater was the Luo River water used for irrigation in the area. Groundwater from Wells 35 (δ^{18}O = −7.63‰, δ^{2}H = −68.02‰) and 53' (δ^{18}O = −7.15‰, δ^{2}H= −65.98‰), however, were particularly enriched isotopically, indicating that precipitation was an important source of recharge of water in these wells.

(3) **Fig. 3-7** shows the relationships of groundwater isotopes between δ^{18}O and δ^{2}H for terrace on summer 2009, the results of the mean isotopic value of groundwater samples from the third terrace to the second, and then to the first terrace are −7.44‰ and −72.34‰, −7.47‰ and −73.13‰, −7.76‰ and −74.95‰ for δ^{18}O and δ^{2}H, respectively. These results indicate that in the same climatic conditions, stable isotope composition of groundwater in the study area have spatial characteristics, which isotopic enrichment of groundwater from the first terrace to the third terrace along with the groundwater flow direction is gradually increasing. However, the mean isotopic value of third terrace and second terrace almost the same because the terrace influence is not primary factor in summer.

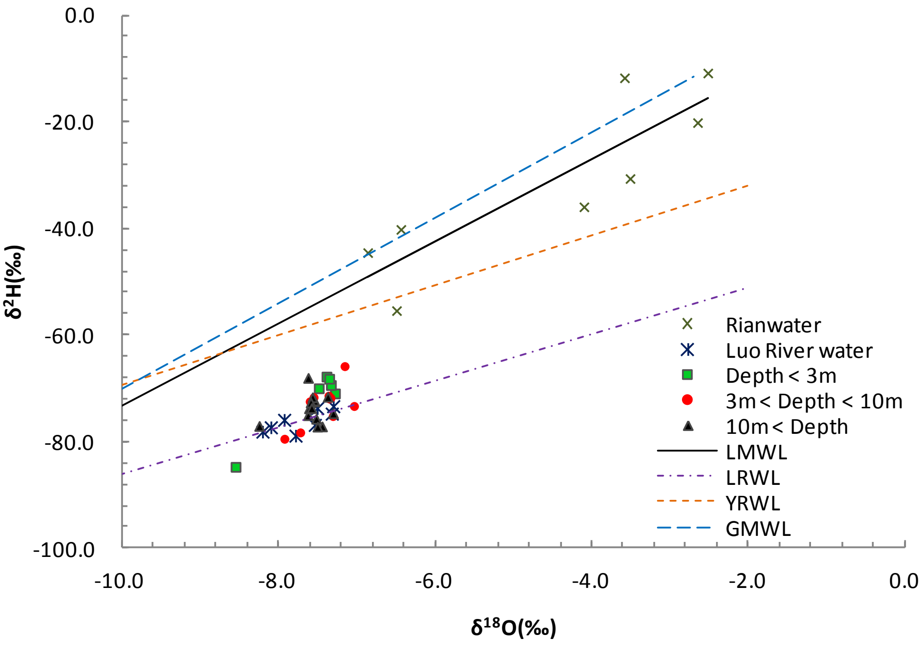


Fig. 3-6 Relationship between δ^{18}O and δ^{2}H according to GD in summer 2009

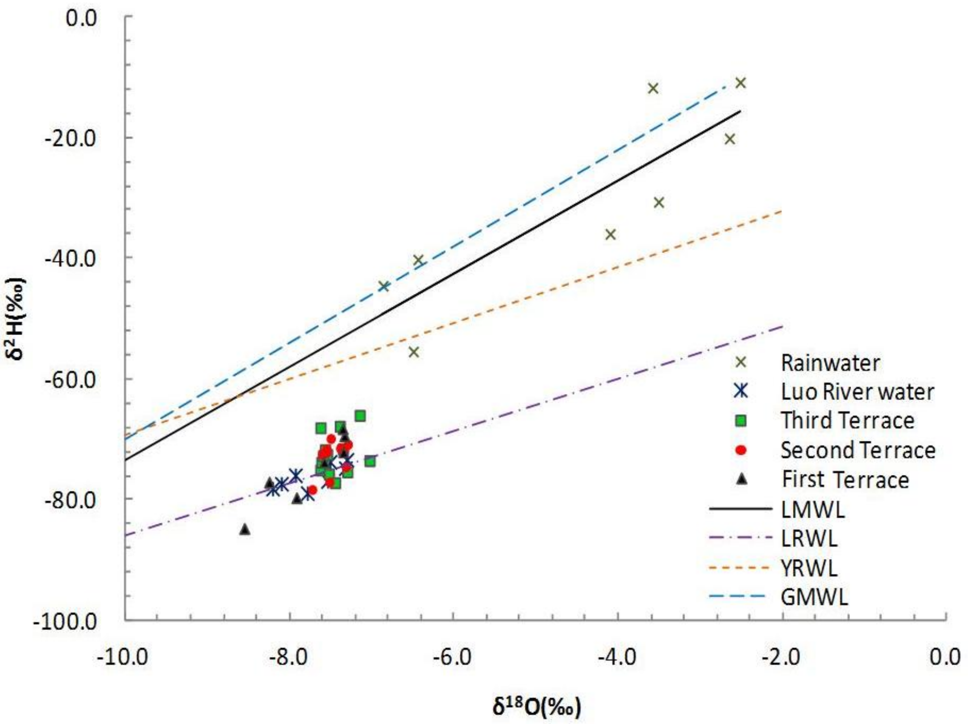


Fig. 3-7 Relationship between δ^{18}O and δ^{2}H according to fluvial terraces in summer 2009

3.4.3.2 Recharge source of groundwater in winter

The groundwater samples were collected for isotopic analysis from December 17 to 23, 2009 in winter irrigation period (from November 27, 2009 to February 20, 2010) in the study area. I used the same way with last part to analyze the stable isotope of groundwater samples on winter 2009. According to the LMWL and LRWL, I set up the relationship of groundwater isotopes between δ^{18}O and δ^{2}H in winter 2009 (**Figs. 3-8** and **3-9**):

(1) **Figs. 3-8** and **3-9** show the relationships of groundwater isotopes between δ^{18}O and δ^{2}H by depth and terrace in winter 2009. Mean δ^{18}O and δ^{2}H of groundwater samples were respectively –7.60‰ and –73.94‰ from the third terrace, –7.70‰ and –75.23‰ from the second terrace, and –7.93‰ and –80.47‰ from the first terrace. Therefore, under the same climatic conditions, groundwater can be differentiated spatially by its stable isotope composition. The groundwater shows isotopic enrichment in the direction of groundwater flow, which is from the first to the third terrace.

(2) Groundwater samples from the third and second terrace plot around the LRWL,

indicating the residence time of groundwater is short because renewability is high, and the recharge source is mainly irrigation water (Luo River water). Samples from Wells 89, 35, 53' (third terrace), and 17 (second terrace), show greater isotopic enrichment and plot close to the LMWL, suggesting that in these wells the groundwater is recharged in part from precipitation. (**Fig. 3-9**), but the stable isotope value of Well 17 more enrich by evaporation fractionation in the Luohui Irrigation District is possible because the depth of Well 17 is only 1.51 m (**Fig. 3-8**).

(3) Most of the first terrace samples plot below the LRWL, only the samples from Wells 14, 36, and 57 plots along the LRWL. The stable isotope compositions of different possible recharge sources are obviously different. Therefore, the depleted isotopic values of groundwater from most of the first terrace wells likely reflects a contribution of relatively salty, deep groundwater because saltwater intrusion can cause isotope depletion (Song *et al.*, 2010). In contrast, the groundwater in Wells14, 36, and 57 is likely derived mainly from irrigation water (Luo River water) as they are located near the main irrigation canal.

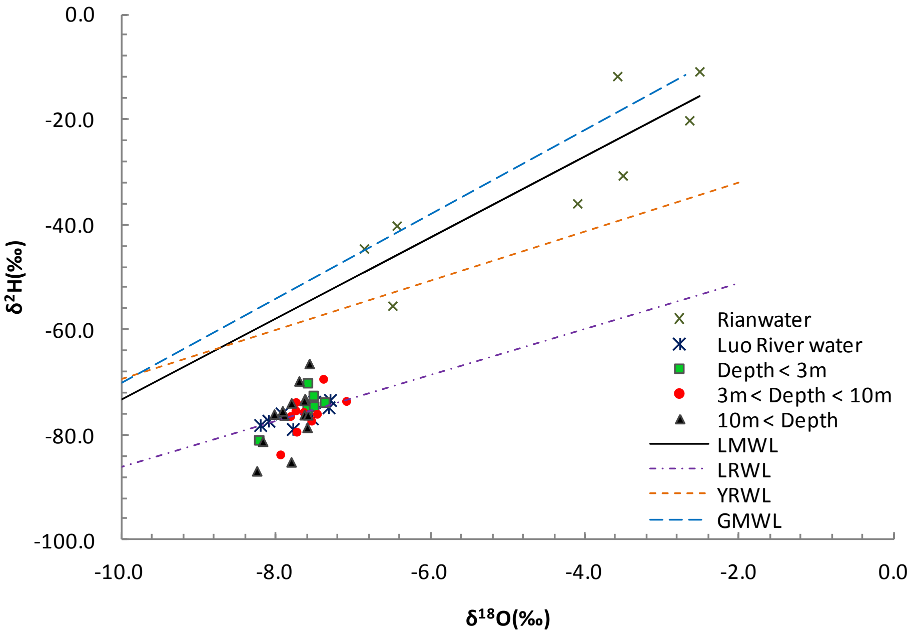


Fig. 3-8 Relationship between δ^{18}O and δ^{2}H according to GD in winter 2009

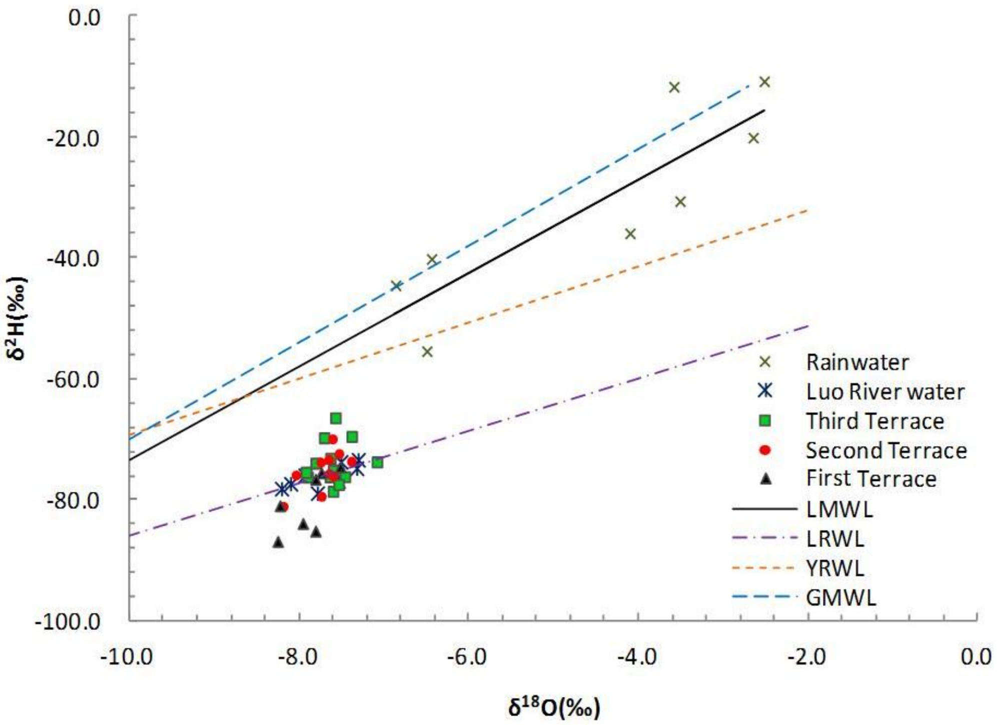


Fig. 3-9 Relationship between δ^{18}O and δ^{2}H according to fluvial terraces in winter 2009

3.4.3.3 Spatial-temporal distribution

The stable isotopes (^{18}O, ^{2}H) of groundwater from the Luohui Irrigation District, have the same spatial variation characteristics in summer or winter. And the δ^{18}O and δ^{2}H isotopes of groundwater enriched as the groundwater flow direction from the first terrace to the third terrace increased (**Figs. 3-7** and **3-9**).

Seen from **Fig. 3-10**, most plots of δ^{18}O in summer more enriched than in winter except Well 45. It indicated that, form the climatic condition, the fractionation of groundwater caused by evaporate effect more in summer than in winter. The recharge source of groundwater is mainly Luo River water (irrigation water) and precipitation. However, the recharge source of groundwater in Well 45 is mainly deep groundwater because the δ^{18}O of groundwater is very depleted. Overall, the δ^{18}O and δ^{2}H isotopes of groundwater in the Luohui Irrigation District had the obvious seasonal variation characteristic, and have received certain evaporation effects when the groundwater accepted recharge from precipitation and the Luo River.

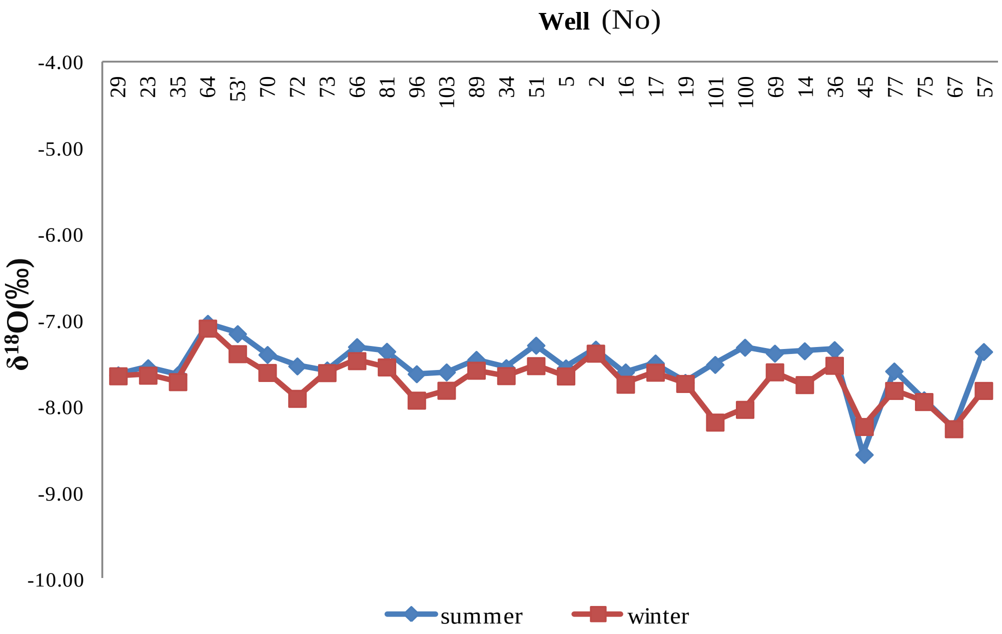


Fig. 3-10 Relation of δ^{18}O and well in the eastern block of the Luohui Irrigation District in summer and winter 2009

3.4.4 Characteristics of groundwater components

I analyzed the groundwater components by assuming zero lateral groundwater recharge from outside of the Luohui Irrigation District. This assumption is justified by the geographical position of the study area and by local irrigation practices (three times a year, and usually no irrigation between March and April). In the Luohui Irrigation District, Luo River water plays a key role in the recharge of groundwater. Therefore, it is important to take into account the temporal and spatial contribution of Luo River water to groundwater in the management of local water resources. Our isotope analysis results showed that the groundwater in the Luohui Irrigation District is derived mainly from local precipitation and Luo River water, except those of Well 45 in summer and Wells 45, 77, 75, and 67 in winter. The groundwater recharge sources can be described by a two-component (local precipitation and Luo River water) separation model. I used a two-component separation model based on the water mass balance and the tracer mass balance following Pearce *et al*. (1986):

$$Q_{LR} + Q_p = Q_g \tag{3.2}$$

$$\delta_{LR}\, Q_{LR} + \delta_p Q_p = \delta_g Q_g \tag{3.3}$$

I derived Eq. (3.4) (below) from Eqs. (3.2) and (3.3) and used it to calculate the contribution of Luo River water to groundwater (using only the oxygen isotope data):

$$\begin{aligned} \text{Per} &= Q_{LR}/\ Q_g \text{ x } 100\ (\%) \\ &= [(\delta_g\text{-}\delta_P)/(\ \delta_{LR} - \delta_P)] \text{ x } 100\ (\%) \end{aligned} \tag{3.4}$$

Where Q_g, Q_{LR}, and Q_p are groundwater, Luo River water, and precipitation volumes, respectively; δ_g, δ_{LR}, and δ_P are the corresponding tracer concentrations, and Per is the percentage of Luo River water in the groundwater.

The natural tracer technique requires that the tracer signatures must be conservative and that the signatures of different water components must be distinct. Our results showing a significant difference in the oxygen isotope composition between precipitation and Luo River water are suitable for the use of this separation model. All δ^{18}O values of Luo River water and precipitation (compiled in **Tables 3-2** and **3-3**) were averaged to obtain δ_{LR} (–7.71‰) and δ_P (–4.52‰). The δ^{18}O values of all groundwater samples were averaged by season to obtain δ_g = –7.49‰ and –7.65‰ for summer and winter, respectively. Using Eq. (3.4), I calculated the mean contribution of Luo River water in groundwater in summer to be 93.10% using the average δ^{18}O value of 29 groundwater samples (apart from Well 45), supporting its key role as a groundwater sources. Accordingly, the mean contribution of the precipitation to groundwater was 6.90%. These results indicate that under a warming climate in this semiarid region, management of the scarce water resources in the Luohui Irrigation District should emphasize the efficient use of Luo River water.

In winter, I calculated the mean contribution of Luo River water to groundwater as 98.10% using the average δ^{18}O value of 26 groundwater samples (apart from Wells 45, 77, 75, and 67), and the mean contribution of the precipitation was thus 1.90%. The lower contribution of precipitation in winter reflects the precipitation in the months before irrigation began, which allowed more irrigation water (Luo River water) to infiltrate into the groundwater. The high percentage of Luo River water in groundwater can be attributed to deep percolation of irrigation water from the Luo River in conjunction with limited deep percolation of rainwater. Because of the rare occurrence and low intensity of precipitation, despite the comparatively high water-holding capacity of the soil in the study area (usually 200–300 mm m^{-1} for loess soils; Chen *et al*. 2007), most of the rainwater may be trapped and retained in the upper soil layers, where it evaporates or is taken up by plants.

3.5 Conclusions

I investigated the distribution of stable isotopes in relation to groundwater depth and topographic features to determine the recharge sources and movement of groundwater in the study area. Our main findings are summarized as follows:

(1) I calculated the LMWL and the LRWL as $\delta^{2}H = 7.71\delta^{18}O + 3.71$ and $\delta^{2}H = 4.34\delta^{18}O - 42.61$, respectively;

(2) In summer, the influence of groundwater depth on the recharge source was very large. Our stable isotope results showed that for GD < 3 m, in all wells groundwater recharge was mainly from precipitation (except in Well 45, which was recharged from deep groundwater). Isotopic enrichment of the shallow groundwater due to evaporation fractionation was also very strong. For GD > 3 m, the main recharge source was irrigation water from the Luo River infiltrating into the groundwater via the canal system and field irrigation.

(3) In winter, the recharge source of groundwater was mainly controlled by the fluvial terraces in the study area. Groundwater in most wells in the third and second terrace were recharged by irrigation water from the Luo River, except Wells 89, 35, 53', and 17, which also received recharge water from precipitation. Groundwater in wells in the first terrace was recharged mainly from deep groundwater, except Wells 14, 36, and 57, which were also recharged from Luo River water. Furthermore, $\delta^{18}O$ and $\delta^{2}H$ of groundwater in the study area varied spatially, with isotopic enrichment of groundwater increasing from the first terrace to the third terrace, the direction of groundwater flow.

(4) The stable isotopes ($\delta^{18}O$, $\delta^{2}H$) of groundwater in the eastern block of the Luohui Irrigation District showed obvious seasonal variation with respect to recharge sources and also due to evaporation fractionation effects.

(5) I used a two-component separation model based on the water and tracer (oxygen isotope) mass balance to determine the relative contribution of precipitation and Luo River water to groundwater. The results showed that in summer, the mean contribution of Luo River water to groundwater was 93.0%, whereas in winter, it was 98.1%.

4 Chemical and stable isotopic characteristics of groundwater

4.1 Introduction

Soil salinization can be regarded as the concentration of salts (over 0.3%) in the soil solution which is too high to increase the grain yield in the arable land. The main source of salts in the soil is the groundwater for irrigation. Salinity can occur over time wherever irrigation is practiced, because almost all water contains some dissolved salts. Meanwhile, the salts are left behind in the soil and begin to accumulate when the plants use the water from irrigation. Therefore, the plant is more difficult to absorb soil moisture after soil salinization in irrigation district. Salinization from irrigation water is also greatly increased by poor drainage and use of saline water for irrigating crops. Salinity in irrigation district often results from the combination of irrigation and groundwater processes (Zhang, 2007; Yidana and Yidana, 2010).

In recent years, irrigated agriculture in China developed rapidly as irrigation area increased, and there has been an increase in magnitude and intensity of salt-affected soils due to unreasonable irrigation methods, overuse of chemical fertilizer, severe deforestation, etc. It is estimated that tens of millions of hectares of land are degraded every year (Liu *et al.*, 2007; Zhang *et al.*, 2007; Dochartaigh *et al.*, 2010). Soil salinization is caused by excessive accumulation of salt at the soil surface. Soluble salts in the soil with groundwater move to the soil surface by capillary transport and then accumulate due to evaporation. They can also be concentrated in the soil due to human activity, for example the potassium fertilizer was used for high grain yield, which can form sylvite, a naturally occurring salt. The salt effect may lead to the degradation of soil and vegetation with soil salinity increase. Soil salinization is a process: (1) High salt content in the soil; (2) Movement of water table with salt; (3) Climatic change; (4) Human activities. Consequently, it is very important to know and to find the source of groundwater and salt in irrigation district (Solomon, *et al.*, 2005; Banoeng-Yakubo, *et al.*, 2009; Carol, *et al.*, 2009; Zhang and Wu, 2009).

Meanwhile, stable isotopes (^{18}O, ^{2}H) extensively exist in various kinds of water. The difference of isotopic content in different water can provide some important information to investigate the exchange of surface water with groundwater and the leakage between aquifers (Kohfahl *et al.*, 2008; Wu, *et al.*, 2009; Song, *et al.*, 2010). Moreover, stable isotopes were used to estimate regional recharge of groundwater, trace water flow that have contributed remarkably to our understanding of the water cycle and related diverse hydrological processes (Davisson *et al.*, 1993; Criss, *et al.*, 1996; Harvey and Sibray, 2001; Duan and Wang, 2006).

The eastern block of the Luohui Irrigation District, the study area, was established 70 years ago. The canal has been extended and improved for several times after liberation, so that the irrigation develops vigorously and the benefit raises progressively. The Luohui Irrigation District has become an important base for marketable grain and high quality cotton, and is an advanced irrigation district. However, the attention given to the management aspect or wise application of irrigation water in most places is poor and has its own negative consequences to the environment and makes the sustainability of irrigated agriculture questionable. The insufficient or inadequate irrigation and drainage structures, and excessive application of water to irrigation fields in most cases cause for groundwater table rise. Consequently, the shallow water table inevitably contributes to secondary salinization. Based on the collected and obtained data, salt-affected areas had been expanded from 1140 ha in 1953 to 4410 ha in 1974. After identification of the problem and installation of drainage facilities, it later decreased to 3000 ha in 1980. However, it again increased to 3910 ha in 1987 due to aging and lack of effective maintenance of drainage structures (Solomon, *et al.*, 2005; Du, *et al.*, 2008; Du, 2009).

In this study, the Luohui Irrigation District has been facing salinization problem through time, which demands remedies targeted on preventing new salinization processes and rehabilitating salinized areas. Consequently, I applied the chemical analysis and stable isotope technology to find the movement and source of salts through water which can be regulated by controlling the quality of irrigation water and the level of groundwater table, based on the relationships among surface topography, groundwater depth, and regional hydrogeology.

In the study area, the joint research project of the Core University Program of Japan-China has launched research on Combating Desertification and Development in

Inland China, in which the effort to prevent salinization problem (component of water management research) is among the main targets.

4.2 Study area

4.2.1 Location

The eastern block of the Luohui Irrigation District, having an area of about 32,000 ha, is located in the left bank of the Luo River nearby the confluence with the Wei River (one of the tributaries of the Yellow River) in Shaanxi province, China. It is situated at the foot of the Loess plateau between latitudes 34°45'23" to 34°56'05" N and longitudes 109°45'22" to 110°10'23" E, at an elevation of between 329 and 400 m above sea level (**Fig. 4-1**).

In this study, there are about 39 groundwater wells serving as observation points and used for various agricultural (for irrigation, drinking, and mixing insecticides) and non-agricultural (pulp factory, and concrete mixing) purposes.

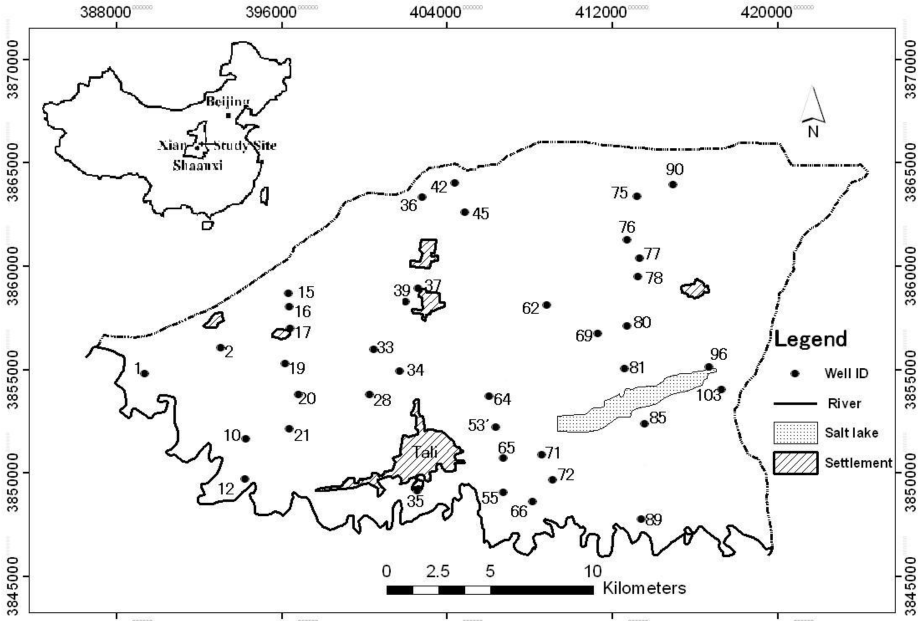


Fig. 4-1 Location of the eastern block of the Luohui Irrigation District

4.2.2 Canal system

The irrigation and drainage network of the Luohui Irrigation District consist of 60.2 km primary irrigation canals, 91 km secondary canals, and 689.2 km tertiary canals and 36.5 km primary drainage canals, 64.5 km secondary canals, and 388 km tertiary canals (Li, 1995).

There are three canal systems in the eastern block of the Luohui Irrigation District, including canal system in east Luohui Irrigation District, canal system in middle Luohui Irrigation District, and canal system in west Luohui Irrigation District. The canal system in east Luohui Irrigation District have Xiqutou, Longmen, Anren, and Tixu stations for water management; the canal system in middle Luohui Irrigation District have Xuzhuang and Pohe stations for water management; the canal system in west Luohui Irrigation District have Hongcun and Nianqiao stations for water management (**Fig. 4-2**).

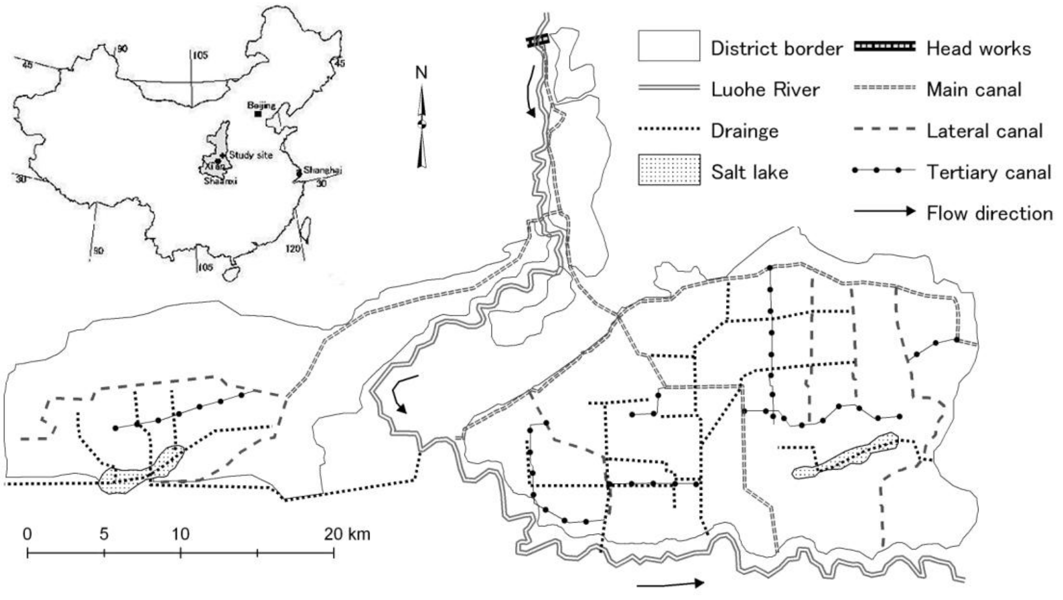


Fig. 4-2 Canal system of the Luohui Irrigation District

4.2.3 Geology and landforms

The area is underlain by three main geological terrains: third terrace, second terrace and first terrace. Available data (Li, 1995) indicate that the elevations for these ranges 330-360 m, 350-380 m, and 370-400 m above mean sea level, respectively (**Fig. 4-3**).

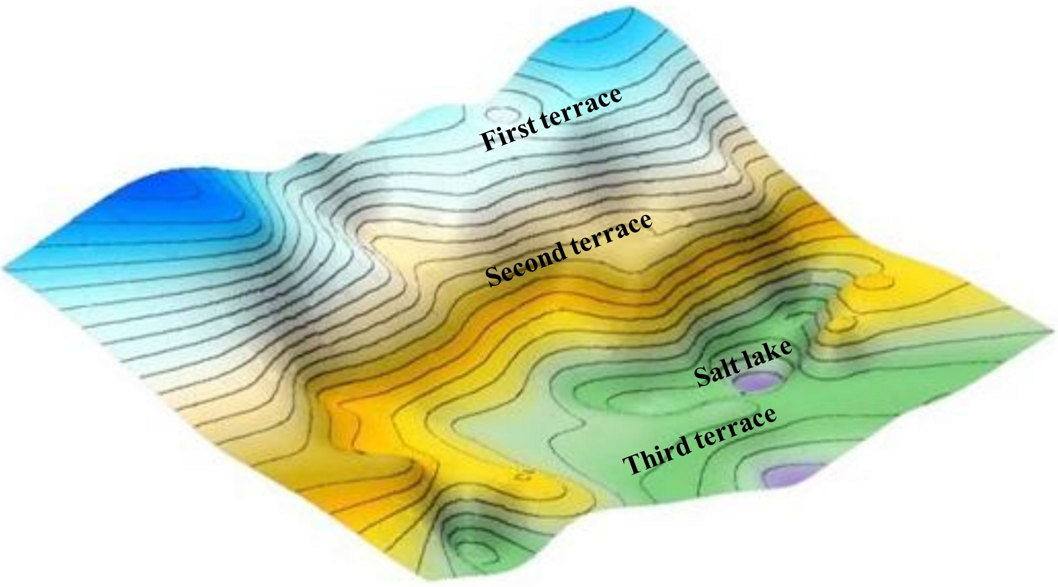


Fig. 4-3 Geomorphological map of the eastern block of the Luohui Irrigation District

4.2.4 Meteorology

The climatic condition of the area is warm-temperate and semiarid type having an annual rainfall of 521.5 mm and the annual volume of water supply for irrigation was 73.43 million m^3 from June, 2009 to May, 2010, which is inadequate for main fed agriculture. The rainy season is typically from July to September, and the average annual temperature is around 13.5 ℃ **(Fig. 4-4)**. The average potential evaporation (1690.3 mm) is about three times the annual precipitation.

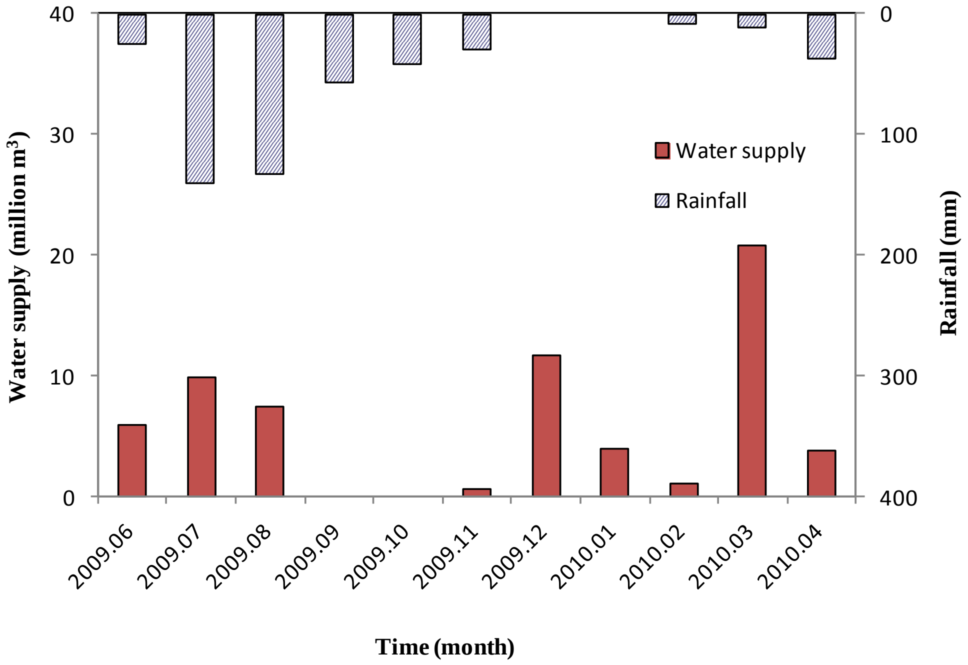


Fig. 4-4 Variation of irrigation water supply and rainfall during June 2009 - April 2010

4.3 Materials and methods

Water samples in the Luohui Irrigation District were collected from 2 to 7 March 2010 for stable isotope studies (^{18}O, ^{2}H) and, in the case of groundwater and surface water, also for major ion (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, HCO_3^{-}) analysis. Water samples were obtained using the grab technique at 1 m below the water level. For all samples collected, parameters such as electrical conductivity (EC), temperature (T) and groundwater level values were measured in the field.

The samples were generally collected in 250 ml sterilized polythene bottles, and, immediately after returning back from the field, all the samples were preserved in a refrigerated room (T below 5˚C) until the time of analysis for major ion. The water samples were analyzed at the Laboratory of Environmental Soil Science, Faculty of Agriculture at the Tottori University, Japan. On the other hand, all samples were stored in polypropylene bottles (5 ml.) with watertight caps which were carefully filled without any air entrapment for stable isotopes analysis. After sampling all samples were stored at 5˚C to prevent evaporation. The stable isotopes (^{18}O, ^{2}H) analyses were carried out at Xi'an University of Technology in China using a common equilibration technique with a

MAT-253 Mass Spectrograph. Measurement accuracy for $\delta^{18}O$ and $\delta^{2}H$ are ±0.1‰ and ±1.0‰ versus VSMOW, respectively (Bouchaou *et al.*, 2009).

4.4 Results and discussion

The chemical compositions of groundwater, Luo River water and Salt Lake water in the eastern block of the Luohui Irrigation District are given in **Tables 4-1** and **4-3**. General characteristics of isotopic composition in groundwater, Luo River water and Salt lake water are shown in **Tables 4-2** and **4-3**.

Table 4-1 Chemical compositions of groundwater in the Luohui Irrigation District on March 2010

Well No.	$\mathrm{Ca^{2+}}$ (meq $\mathrm{L^{-1}}$)	$\mathrm{Mg^{2+}}$ (meq $\mathrm{L^{-1}}$)	$\mathrm{Na^{+}}$ (meq $\mathrm{L^{-1}}$)	$\mathrm{K^{+}}$ (meq $\mathrm{L^{-1}}$)	$\mathrm{HCO_3^{-}}$ (meq $\mathrm{L^{-1}}$)	$\mathrm{Cl^{-}}$ (meq $\mathrm{L^{-1}}$)	$\mathrm{SO_4^{2-}}$ (meq $\mathrm{L^{-1}}$)	$\mathrm{NO_3^{-}}$ (meq $\mathrm{L^{-1}}$)
12	1.39	4.21	12.21	0.03	8.98	3.52	9.43	0.01
21	1.22	2.09	7.15	0.52	5.57	2.79	3.45	0.30
35	1.27	6.59	13.55	0.13	7.94	7.02	9.94	0.76
28	0.97	8.25	22.09	0.12	11.70	8.43	19.89	0.92
20	1.62	14.82	16.95	0.15	9.10	7.85	17.92	8.13
1	1.18	8.73	8.30	0.13	8.36	5.54	9.03	0.83
10	1.45	5.32	4.66	0.11	5.48	2.34	3.03	0.42
15	2.97	11.07	11.23	0.14	8.39	6.46	13.32	0.09
19	2.05	14.79	39.81	0.13	8.38	21.05	48.20	1.88
16	2.89	9.42	31.14	0.34	9.49	17.02	23.64	0.42
17	7.12	14.23	40.44	0.10	13.98	18.74	57.12	1.92
2	1.88	9.62	18.23	0.12	8.13	8.43	24.28	1.31
72	1.37	6.70	9.60	0.13	7.69	5.61	6.11	0.66
71	0.97	6.61	11.10	0.12	7.93	5.92	7.82	0.54
66	1.87	8.43	15.24	0.19	7.02	9.33	14.56	2.26
65	0.48	2.49	20.98	0.12	8.95	5.35	10.23	0.47
53'	1.31	3.85	22.47	0.17	8.71	8.01	12.98	0.67
64	3.93	10.92	21.11	0.55	7.02	9.91	25.62	0.42
55	2.22	15.30	14.19	0.08	11.08	11.67	13.39	2.51
33	3.34	26.63	89.14	0.17	14.97	48.18	78.25	4.10
39	3.82	26.18	53.13	0.20	12.70	39.21	47.70	2.51
37	6.81	17.36	55.79	0.54	13.68	30.18	64.46	0.23
36	6.65	15.90	17.06	0.15	9.92	13.82	24.61	1.08
42	1.57	7.93	19.21	0.14	6.98	10.87	19.60	0.25
45	16.16	35.01	120.35	0.85	4.17	80.64	251.76	0.47
96	0.65	2.71	24.60	0.13	15.34	7.93	14.46	0.01
103	1.05	5.49	17.50	0.13	10.31	7.49	13.27	0.53
81	0.53	2.61	30.33	0.11	13.06	6.84	14.38	0.23
89	0.58	1.09	11.66	0.12	7.21	2.52	3.31	0.10
85	2.15	5.51	46.13	0.17	11.62	13.01	15.51	0.54
69	0.42	1.73	12.21	0.11	4.25	3.49	4.29	0.13
78	0.24	2.65	23.46	0.03	13.95	3.90	10.28	0.65
80	0.56	1.85	10.19	0.08	5.65	3.17	4.51	0.13
62	0.88	8.39	17.47	0.05	10.63	6.73	12.81	0.28
77	1.48	6.55	7.37	0.03	4.38	5.75	4.96	1.58
75	1.66	10.61	18.91	0.15	8.09	13.94	19.66	0.15
90	0.88	10.13	25.47	0.03	9.27	12.43	22.82	0.59
76	4.74	22.59	43.04	0.45	5.04	26.09	26.79	28.56

Table 4-2 General characteristics of isotopic data of groundwater in the Luohui Irrigation District on March 2010

Well No.	Canal system	Terrace	Altitude (m)	T (˚C)	Groundwater depth (m)	EC (S m^{-1})	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
12	west area	3	347.19	10.80	8.72	0.17	-7.43	-75.00
21	west area	3	357.78	11.10	17.47	0.13	-7.44	-71.76
35	west area	3	350.50	12.80	14.50	0.31	-7.29	-67.14
28	west area	3	354.62	11.90	7.32	0.37	-7.58	-70.76
20	west area	2	357.61	10.70	12.05	0.21	-7.85	-74.93
1	west area	2	366.85	12.10	20.45	0.19	-7.69	-72.22
10	west area	2	361.22	10.90	18.81	0.11	-7.86	-79.83
15	west area	2	373.63	12.70	7.80	0.22	-7.52	-75.81
19	west area	2	360.08	10.70	4.05	0.50	-7.78	-73.83
16	west area	2	367.77	12.40	4.37	0.30	-7.65	-75.08
17	west area	2	361.20	11.80	1.05	0.50	-7.73	-76.03
2	west area	2	366.62	13.60	2.41	0.34	-7.69	-73.91
72	middle area	3	348.86	11.70	11.75	0.17	-7.57	-73.31
71	middle area	3	351.21	12.40	11.73	0.19	-7.39	-73.56
66	middle area	3	344.19	12.80	8.24	0.27	-7.58	-71.25
65	middle area	3	349.93	11.20	7.76	0.22	-7.42	-76.18
53'	middle area	3	351.09	13.20	6.42	0.26	-7.37	-69.88
64	middle area	3	352.41	11.60	7.16	0.70	-7.38	-75.44
55	middle area	3	347.89	13.20	11.43	0.29	-7.59	-77.74
33	middle area	2	359.85	14.20	4.80	0.94	-7.91	-76.60
39	middle area	2	366.80	11.80	3.86	0.27	-7.77	-77.40
37	middle area	2	367.90	10.60	1.73	0.62	-7.28	-69.78
36	middle area	1	382.33	9.80	1.12	0.39	-7.94	-76.59
42	middle area	1	383.53	10.20	1.05	0.34	-7.68	-76.07
45	middle area	1	371.20	15.10	1.19	1.63	-8.24	-82.00
96	east area	3	346.55	10.20	11.40	0.27	-7.22	-69.25
103	east area	3	356.37	13.60	25.61	0.24	-7.63	-75.24
81	east area	3	347.01	12.90	7.42	0.28	-7.59	-73.37
89	east area	3	347.93	11.60	20.39	0.15	-7.64	-77.00
85	east area	3	346.18	13.10	13.45	0.27	-7.64	-66.68
69	east area	2	362.44	12.30	13.43	0.13	-7.76	-81.68
78	east area	2	366.01	12.70	10.23	0.23	-7.93	-76.57
80	east area	2	365.40	9.80	17.05	0.13	-7.65	-75.29
62	east area	2	360.02	11.40	9.60	0.25	-7.75	-78.00
77	east area	1	382.35	11.50	17.95	0.15	-8.05	-81.48
75	east area	1	379.42	10.90	4.35	0.32	-8.02	-79.64
90	east area	1	384.66	10.70	6.21	0.34	-8.17	-80.79
76	east area	1	380.53	11.10	12.12	0.78	-8.59	-86.03

Table 4-3 General characteristics and stable isotopic data of water samples in the Luohui Irrigation Distirct on March 2010

Samples No.	EC (S m^{-1})	T (°C)	Ca^{2+} (meq L^{-1})	Mg^{2+} (meq L^{-1})	Na^{+} (meq L^{-1})	K^{+} (meq L^{-1})	HCO_3^- (meq L^{-1})	Cl^- (meq L^{-1})	SO_4^{2-} (meq L^{-1})	NO_3^- (meq L^{-1})	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
34-2m	0.66	12.9	14.82	25.32	115.38	0.61	9.43	31.28	59.50	1.97	-7.73	-75.50
34-4m	0.67	13.2	14.64	25.31	114.32	0.65	10.23	30.14	57.84	1.94	-7.79	-73.46
34-6m	0.67	12.5	14.68	25.34	114.32	0.74	10.19	29.96	57.19	1.91	-7.97	-75.04
34-8m	0.69	12.5	14.26	25.42	114.20	0.76	10.39	30.13	59.32	1.71	-7.63	-77.96
34-10m	0.71	12.7	14.77	25.28	114.47	0.82	10.35	29.59	60.82	1.42	-7.78	-78.91
34-12m	0.71	12.9	14.79	25.10	115.37	0.75	10.64	31.22	64.31	1.35	-7.95	-78.01
34-14m	1.06	14.1	14.81	24.42	116.37	0.74	12.89	56.74	123.94	1.38	-8.08	-76.77
34-16m	1.97	12.5	16.09	24.91	118.61	0.78	11.86	117.20	283.39	0.31	-8.97	-87.50
34-18m	1.94	12.9	15.85	25.05	119.10	0.80	13.49	136.73	311.28	0.36	-8.90	-88.44
34-20m	1.90	14.7	15.80	25.09	120.05	0.83	13.71	126.27	304.45	0.28	-8.66	-88.09
R3	0.16	10.3	2.92	5.32	6.67	0.19	4.03	4.80	10.37	0.31	-8.21	-76.10
R2	0.15	5.6	2.83	5.18	6.09	0.18	3.84	4.96	9.05	0.30	-8.23	-76.90
R4	0.15	7.8	2.67	4.78	7.30	0.15	3.94	4.60	9.66	0.26	-8.10	-79.29

Note: depth from groundwater level to sampling point.

4.4.1 Vertical characteristics of groundwater

The groundwater samples of Well 34 which located in the canal system of west Luohui Irrigation District were collected (**Table 4-3**). The chemical indexes which included Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NO_3^-, HCO_3^- were measured and analyzed in the laboratory. The stable isotope experiment work of ^{18}O and ^{2}H on the above samples was carried out on May 2010.

4.4.1.1 Chemical analysis

According to the chemical characteristics of Well 34 in the Luohui Irrigation District, I analyzed the cation and anion composition. **Fig. 4-5** shows that the negative ions mainly distributed in the zone where the strong acid was bigger than the weak acid, and $SO_4^{2-} > Cl^- > HCO_3^-$. Most SO_4^{2-} average milligram equivalent percents surpassed 60%, and the total of SO_4^{2-} and Cl^- surpassed 80%. The positive ions were mainly the enrichment alkali metals, and $Na^+ + K^+ > Mg^{2+} > Ca^{2+}$. The chemical type in the canal system of west Luohui Irrigation District is relatively single and mainly Cl^--SO_4^{2-}-Na^+.

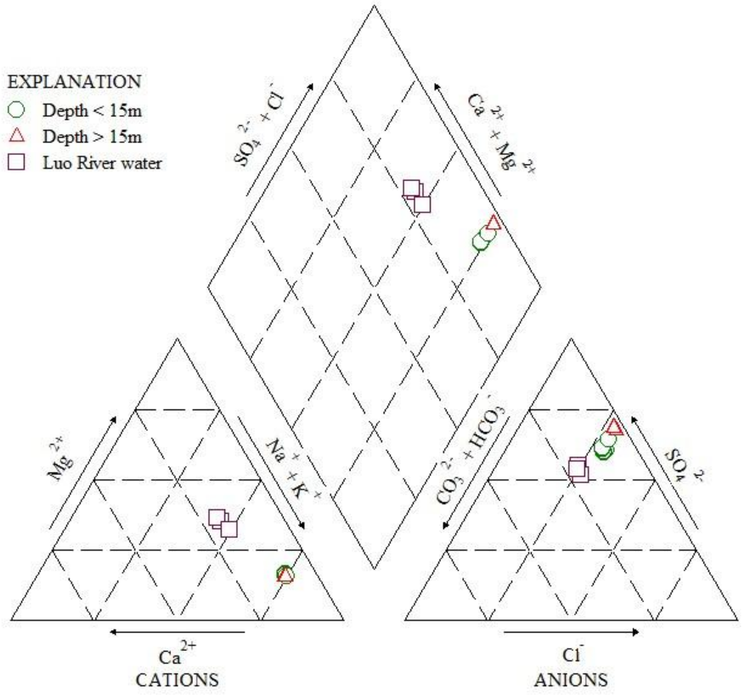


Fig. 4-5 Piper Tri-linear diagram of the groundwater samples of Well 34 in the Luohui Irrigation District

4.4.1.2 Spatial distribution of chemical components

For the sampling sites present the linear distribution along Well 34 from the surface groundwater to the deep groundwater, it is difficult to allsidedly control the irrigation district. So, the research mainly analyzed the rule of chemical components of groundwater along the depth (from groundwater level to deep groundwater) variation from the groundwater level. **Fig. 4-6** shows that the variations of Cl^-, SO_4^{2-} and EC with the depth from the groundwater level in Well 34 in the Luohui Irrigation District, the contents of Cl^-, SO_4^{2-}, and EC of groundwater grown as the depth from the groundwater level increased, and the concentrations abruptly rose in 15 m from the groundwater level. In contrast, the contents of NO_3^- of groundwater decreased as the depth, and the concentration abruptly declined in 15 m (**Fig. 4-7**). Moreover, the contents of Na^+, K^+ and HCO_3^- in the groundwater grown as the depth from the groundwater level increased, and the concentrations in 15 m increased, but the variation range was smaller. In addition, the contents of some major ion components such as Ca^{2+} and Mg^{2+} presented the fluctuation variation as the depth from the groundwater level increased and had the unobvious rise or decline trend (**Fig. 4-7**).

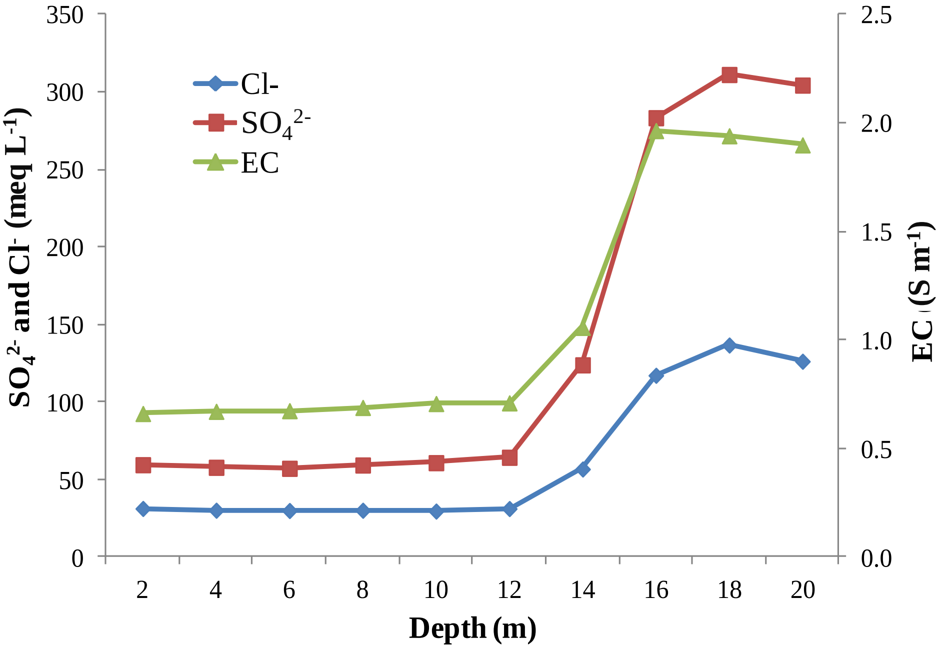


Fig. 4-6 Variations of Cl^-, SO_4^{2-} and EC with the depth in Well 34

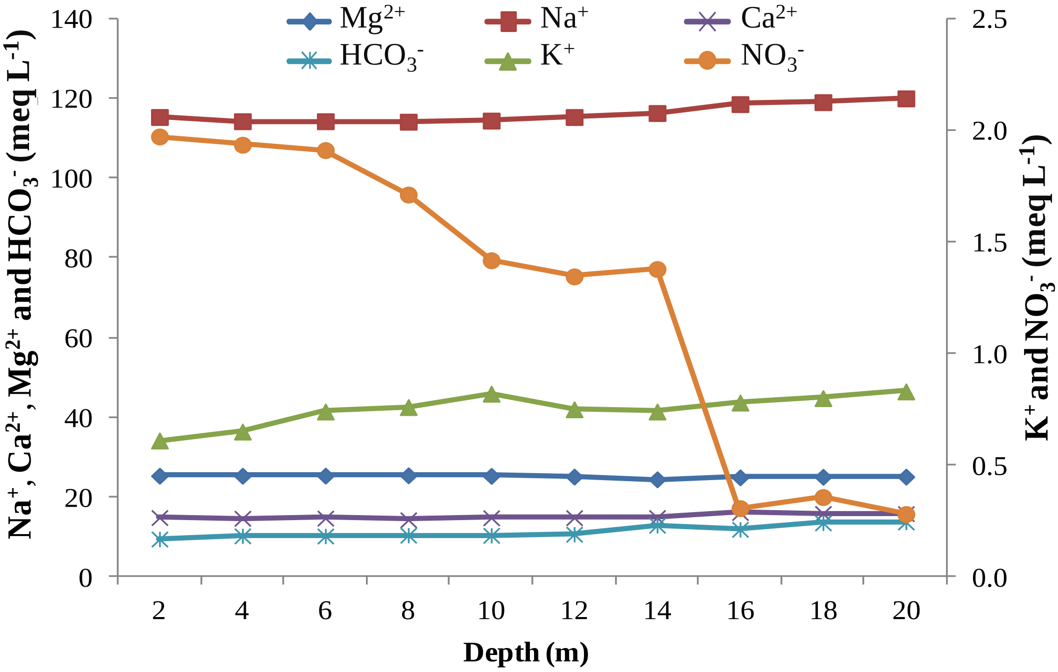


Fig. 4-7 Variations of Ca^{2+}, Na^+, Mg^{2+}, K^+, HCO_3^- and NO_3^- with the depth from the groundwater level in Well 34

4.4.1.3 Formation reason of chemical characteristics

The formation of chemical characteristics of groundwater was controlled by many elements. Besides the influences of climate condition, landform and so on, it also had the close relationships with every kind of physical and chemical effects of formation lithology and human activity. Seen from the above analysis on the spatial distribution of chemical components, the routine components of groundwater generated the abrupt grow phenomenon in 15 m from the groundwater level, such as Cl^-, SO_4^{2-}, and so on. The research mainly analyzed the formation reason of phenomenon.

4.4.1.3.1 Relationship between the chemical characteristics of groundwater and the evaporation concentration effect

The Luohui Irrigation District is in the semiarid climate zone, and the annual rainfall is smaller than 550 mm, the annual evaporation amount is 1689 mm, the average temperature of groundwater is 13.1°C on March 2010. In addition, the contents of Ca^{2+}, Na^+, K^+, HCO_3^- and SO_4^{2-}, Cl^- and EC of groundwater grown as the depth from the groundwater level increased (**Figs. 4-6** and **4-7**). So, the variation of chemical components of groundwater had no obvious correlation with evaporation, it is mean that the evaporation condensation effect was not the main element which caused the abrupt variation of chemical characteristics of the Well 34 in the Luohui Irrigation District.

4.4.1.3.2 Relationship between the chemical characteristics of groundwater and human activity

The influence of human activity, agricultural irrigation, on the chemical characteristics of Well 34 is the biggest. **Fig. 4-7** shows that NO_3^- existed in the groundwater, it illustrated that the groundwater was affected by the agricultural irrigation fertilization. Meanwhile, the content of NO_3^- in Well 34 presented the growth variation and had abrupt variation phenomenon in 15 m from the groundwater level. Consequently, the agricultural irrigation was the main element which affected the chemical characteristics of groundwater in the Luohui Irrigation District.

4.4.1.3.3 Relationship between the chemical characteristics of groundwater and the brine invasion

The eastern block of the Luohui Irrigation District has the massive soluble salts at 40-50 m in depth from ground surface. However, Cl^- is the most main stable constant element in the brine and is sensitive to reflect the salt water invasion. **Fig. 4-8** shows that the correlation between Cl^- and Na^+, SO_4^{2-}, I can easy to know that Na^+ and SO_4^{2-} presented the strong correlation relationship with Cl^-, and they all abruptly changed with the abruptly variation of Cl^- concentration. It indicated that their sources were same and might all come from the deep groundwater.

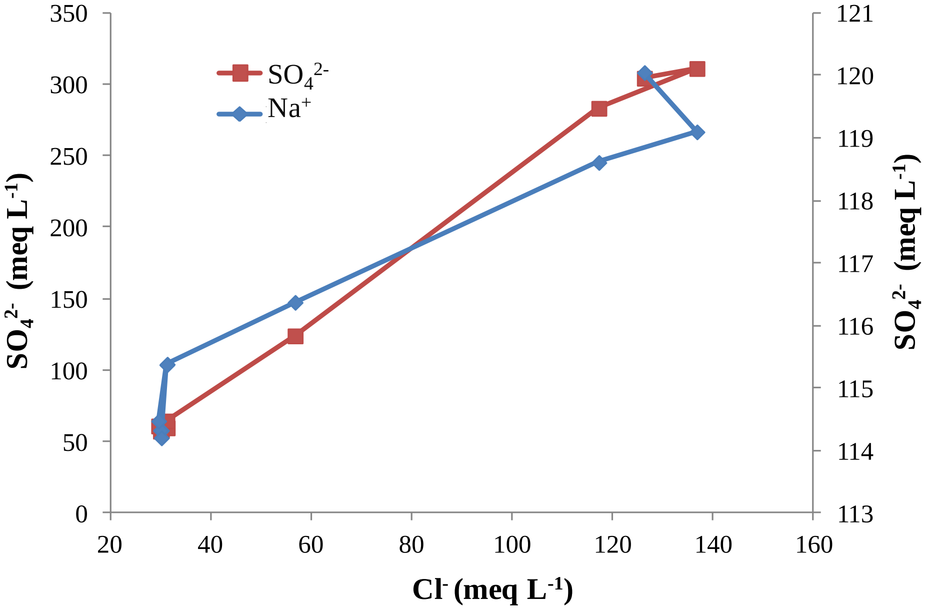


Fig. 4-8 Correlation between Cl^- and Na^+, SO_4^{2-} of groundwater in Well 34 in the Luohui Irrigation District

The different water has the different characteristics ions, Cl^- is the most stable constant element in the brine, and HCO_3^- is the main stable constant element in the groundwater. Consequently, their ratio can clearly reflect two kind of water difference and can be the sign that judges the brine invasion. On the other hand, Na^+ is the first positive ion in the brine, and the content is higher than in the fresh groundwater. The sodium adsorption ration (SAR) is selected as the judgment index of brine invasion − it judges the degree of brine invasion from the main positive ion ratio in the salt and fresh groundwater.

(1) HCO_3^-/Cl^- method

According to the results of chemical analysis of groundwater (**Table 4-3**), the results show that HCO_3^-/Cl^- of groundwater of Well 34 are during 0.098−0.349 (**Fig. 4-9**). In 14 m range from the groundwater level to deep groundwater, HCO_3^-/Cl^- of groundwater is higher and is during 0.227−0.349 which is 2−3 times than outer 15 m from the groundwater level. And HCO_3^-/Cl^- is lower and has the abrupt variation phenomenon in the range bigger than 15 m depth (from groundwater level to the deep groundwater) and the ratio value is during 0.098−0.108. It is thus clear that the abrupt variation of chemical characteristics of groundwater has the relationship with the brine invasion, and the influence range is just consistent with the abrupt variation range groundwater chemistry (**Fig. 4-6**) (Song, *et al.*, 2010).

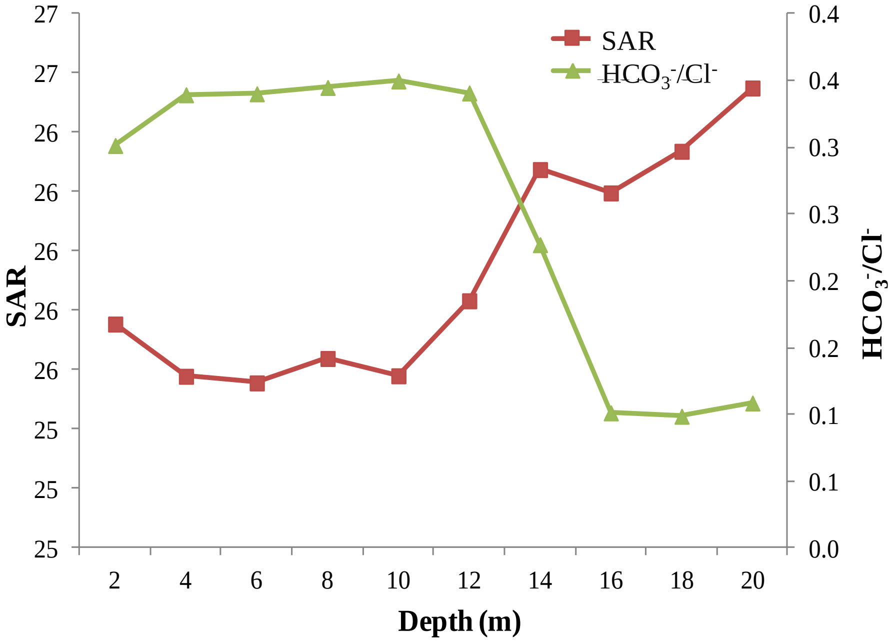


Fig. 4-9 Variations of HCO_3^-/Cl^- and SAR with the depth in Well 34 in the Luohui Irrigation District

(2) SAR method

On the other hand, the sodium adsorption ratio (SAR) of groundwater was computed using the equation (Solomon, *et al.*, 2005; Song, *et al.*, 2010):

$$SAR = Na^+ \Big/ \sqrt{(Ca^{2+} + Mg^{2+})/2} \tag{4.1}$$

where Na^+, Ca^{2+}, Mg^{2+} are sodium, calcium and magnesium in milliequivalent per liter (meq L^{-1}), respectively.

After the calculation, SAR of groundwater in the Luohui Irrigation District is during 25.56–26.55, **Fig. 4-9** shows that SAR grows as the depth from the groundwater level increased, and abruptly raised in 15 m from the groundwater level. The result indicated that the abrupt variation of chemical characteristics of groundwater has the relationship with the brine invasion, and the influence range is just consistent with the abrupt variation range groundwater chemistry (**Fig. 4-6**).

4.4.1.2 Stable isotope analysis

The stable isotopes of different recharge source water are obviously different, thus, the recharge source of groundwater can be identified according to the components of stable isotope in the groundwater.

Base on the local meteoric water line (LMWL: $\delta^2H = 7.71\delta^{18}O + 3.71$) and Luo River water line (LRWL: $\delta^2H = 4.34\delta^{18}O - 42.61$), I have used stable isotope data (**Table 4-3**) to set up the $\delta^{18}O$ versus δ^2H data for groundwater samples of Well 34 on March 2010. **Fig. 4-10** shows that the three plots of Luo River water around the LRWL, the results indicate that the value of stable isotope of Luo River is not big charge between 2009 and 2010, for this reason, I can use the LMWL on 2009 to study this part. On the other hand, the seasonality of isotope enrichment in precipitation was not considered in this study because the major part of rainfall occurs during the summer period, consequently, I use the same LMWL to study in the Luohui Irrigation District.

Fig. 4-10 shows that the plots of Well 34 are different with depth. The contents of stable isotope in the up groundwater, down groundwater have the obvious difference. The content of $\delta^{18}O$ in 15 m from the groundwater level abruptly decreased from −8.08 to −8.97‰. The results show that the groundwater in Well 34 accepted the water recharge of different source. Consequently, it is easy to know that the source of groundwater is different: (1) when depth < 15 m, the plots of groundwater around the LRWL, the main source of groundwater is mainly come from Luo River water, but come from rainfall and deep water is probable; (2) when depth > 15 m, the isotope values of groundwater is very depleted, indicating the source of groundwater is come from deep water. Therefore, I used three samples of Well 34 when depth more 15 m, to get the deep groundwater water line (DGWL) and expressed as follow: $\delta^2H = 1.04\delta^{18}O – 97.21$, meanwhile, the mean isotope values of Well 34 when depth more 15 m in the Luohui Irrigation District were −8.84‰ for $\delta^{18}O$ and −88.01‰ for δ^2H.

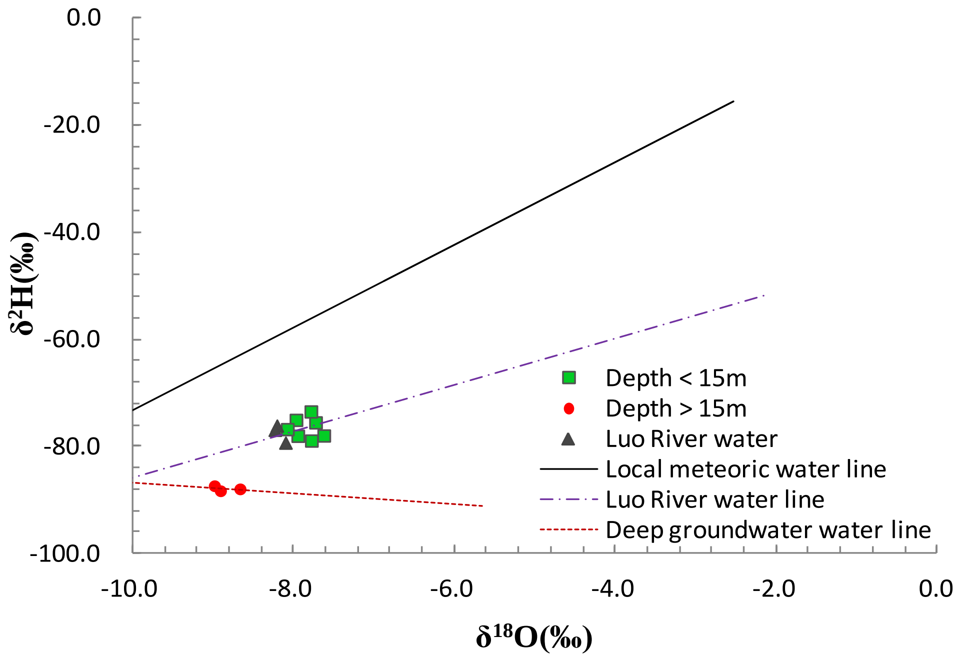


Fig. 4-10 $\delta^{18}O$ versus δ^2H data for groundwater samples of Well 34 in the Luohui Irrigation District on March 2010

4.4.2 Horizontal characteristics of groundwater

The groundwater samples of 38 wells which distributes along canal system were collected (**Fig. 4-1**). The chemical indexes which included Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NO_3^-, HCO_3^- were measured and analyzed in the laboratory (**Table 4-1**). The stable isotope experiment work of ^{18}O and ^2H (**Table 4-2**) on the above samples was carried out on May 2010.

4.4.2.1 Chemical analysis of groundwater

Seen from **Fig. 4-11**, the negative ions mainly distributed in the zone where the strong acid was bigger than the weak acid, and $SO_4^{2-} > Cl^- > HCO_3^-$. Most SO_4^{2-} average milligram equivalent percents surpassed 50%. The positive ions were mainly the enrichment alkali metals, and $Na^+ + K^+ > Mg^{2+} > Ca^{2+}$. But the mean concentration of SO_4^{2-}, Cl^-, Na^+ and Mg^{2+} from terrace in the eastern block of the Luohui Irrigation District: first terrace > second terrace > third terrace. Consequently, the chemical type in the eastern block of the Luohui Irrigation District is relatively single and mainly $Cl^- - SO_4^{2-} - Na^+$, then is $Cl^- \cdot SO_4^{2-}$–$Na^+ \cdot Mg^{2+}$. Meanwhile, the content of Cl^- and SO_4^{2-} of groundwater decreased as flow direction of groundwater from first terrace to third terrace which is about from 85 to 60%.

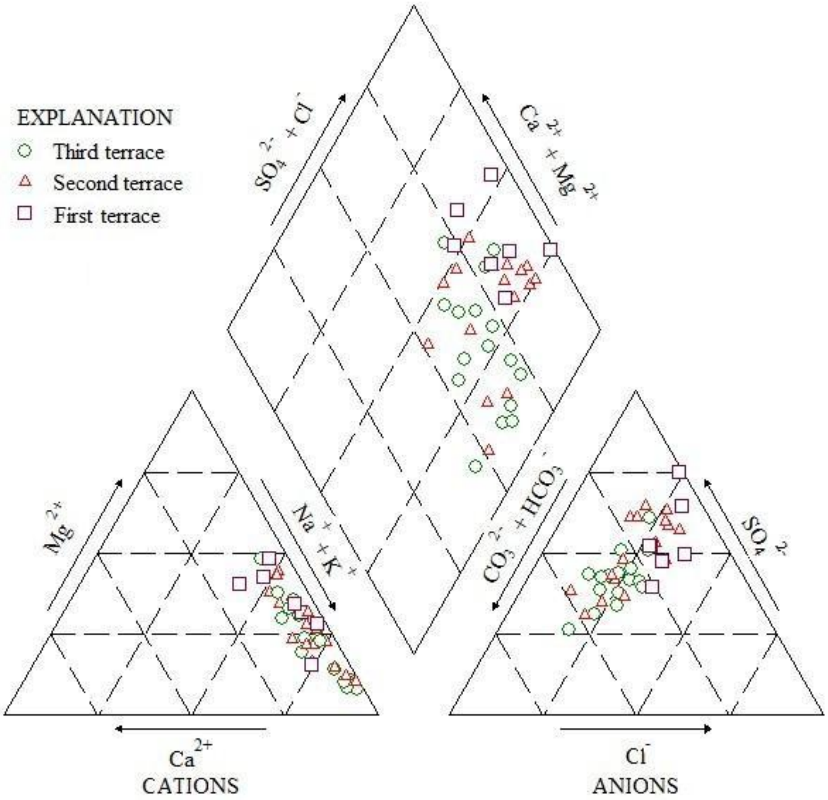


Fig. 4-11 Piper tri-linear diagram of groundwater in the eastern block of the Luohui Irrigation District

Seen from **Fig. 4-12**, the content of Na^+, Mg^{2+}, SO_4^{2-} is linear with Cl^- in groundwater, and the related coefficients (R^2) are 0.9151, 0.8069 and 0.8656, respectively. The result shows that the source of salt is the same. Though their relationship are straight lines, these slope are not unity (k: 1.45, 0.46, and 2.56), it indicated that the mean concentration of $SO_4^{2-} > Na^+ > Mg^{2+}$.

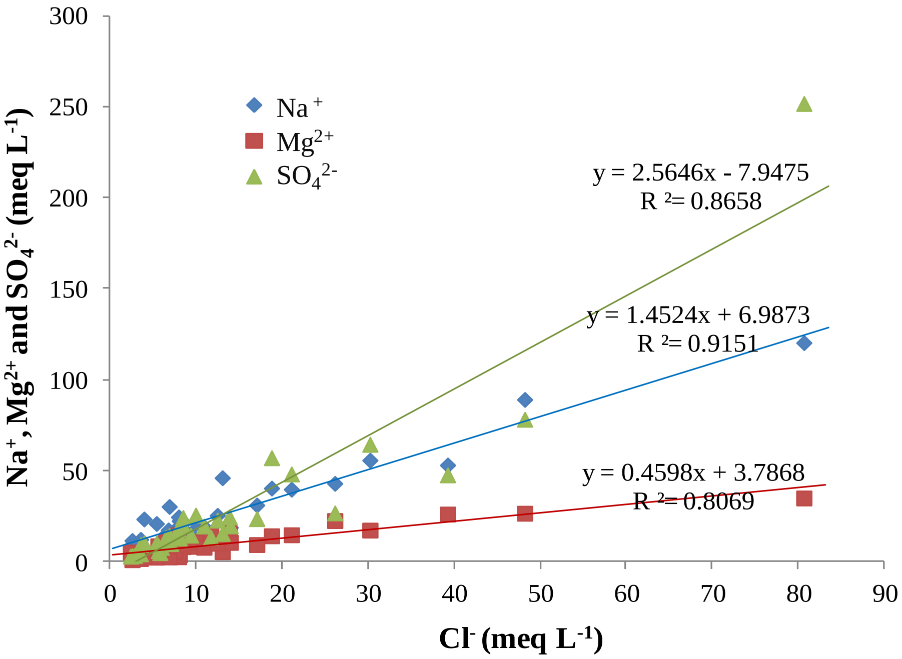


Fig. 4-12 Correlation between Cl^- and Na^+, Mg^{2+}, SO_4^{2-} of groundwater in the Luohui Irrigation District

Seen from **Fig. 4-13**, the mean concentration of Cl^- and ^{18}O from third terrace to first terrace are 7.21 meq L^{-1} and −7.52‰, 12.93 meq L^{-1} and −7.80‰, 27.41 meq L^{-1} and −7.97‰， respectively. The results shown that the plots of groundwater in the third terrace distribution are very crowded and the values of isotope are enriched, it indicated that the recharge source of groundwater mainly comes from the precipitation. But, in contrast, the recharge source of groundwater in first terrace mainly comes from the brine.

Meanwhile, the content of Cl^- in groundwater decreased with the flow direction of groundwater from third first to third terrace, it indicated that the recharge source of groundwater probably come from the fresh water to dilute the content of Cl^-.

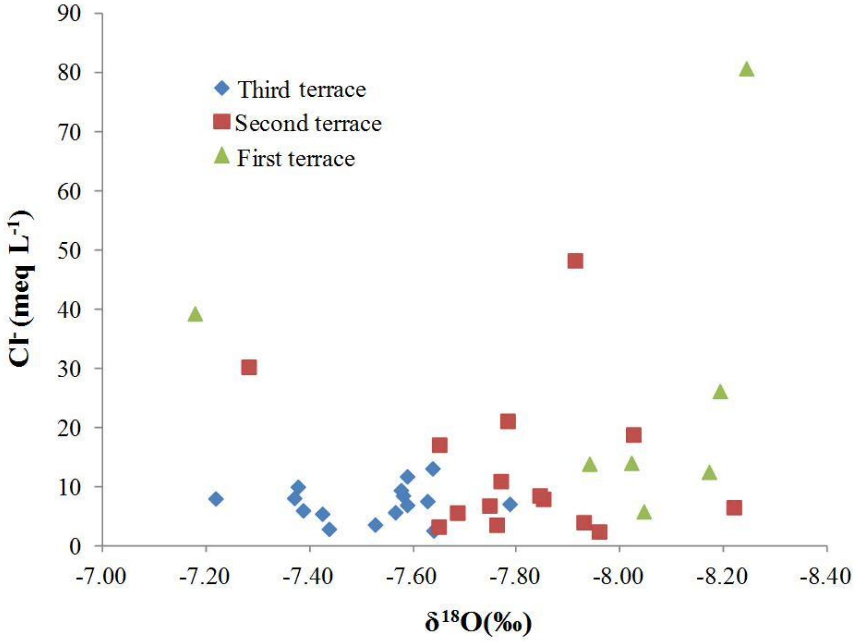


Fig. 4-13 Variations of δ^{18}O values versus Cl^{-} of groundwater in the Luohui Irrigation District

Fig. 4-14 shows that the variations of δ^{18}O values versus EC of groundwater in the Luohui Irrigation District. The mean values of EC and δ^{18}O of groundwater from third terrace to first terrace are 0.27 S m^{-1} and −7.52 ‰, 0.33 S m^{-1} and −7.84 ‰, 0.56 S m^{-1} and −8.10 ‰, respectively. The results show that the δ^{18}O values along the flow direction enriched as the EC of groundwater declined except Wells 37 (second terrace) and 42 (first terrace). The groundwater of Well 37 is mixed brine from deep groundwater and precipitation because the location of Well 37 around the settlement; the recharge source of groundwater in Well 42 is very complicated because frequently pumping irrigation.

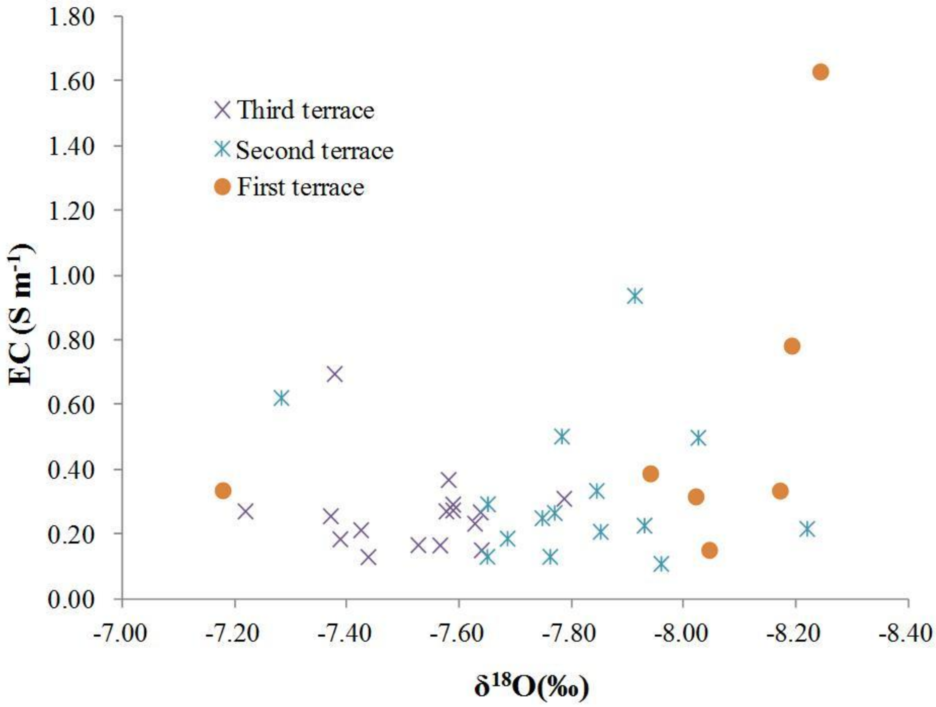


Fig. 4-14 Variations of δ^{18}O values versus EC of groundwater in the Luohui Irrigation District

4.4.2.2 Stable isotope analysis of groundwater

The eastern block of the Luohui Irrigation District are three canal systems (**Fig. 4-1**), including canal system in east Luohui Irrigation District, canal system in middle Luohui Irrigation District, and canal system in west Luohui Irrigation District

4.4.2.2.1 Canal system of west Luohui Irrigation District

The groundwater samples from 2 to 7 March 2010 were collected for stable isotope analysis in spring irrigation period (from 21 February to 20 May 2010) in the Luohui Irrigation District. According to the LMWL and the LRWL, I make the relation of δ^{18}O and δ^{2}H for groundwater. **Fig. 4-15** shows that the mean isotopic value of groundwater samples from the third terrace to the second terrace are −7.43 ‰ and −71.17 ‰, −7.72 ‰ and −75.24 ‰ for δ^{18}O and δ^{2}H, respectively. The results indicate that isotopic enrichment of groundwater from the second terrace to the third terrace with the groundwater flow direction is gradually increasing.

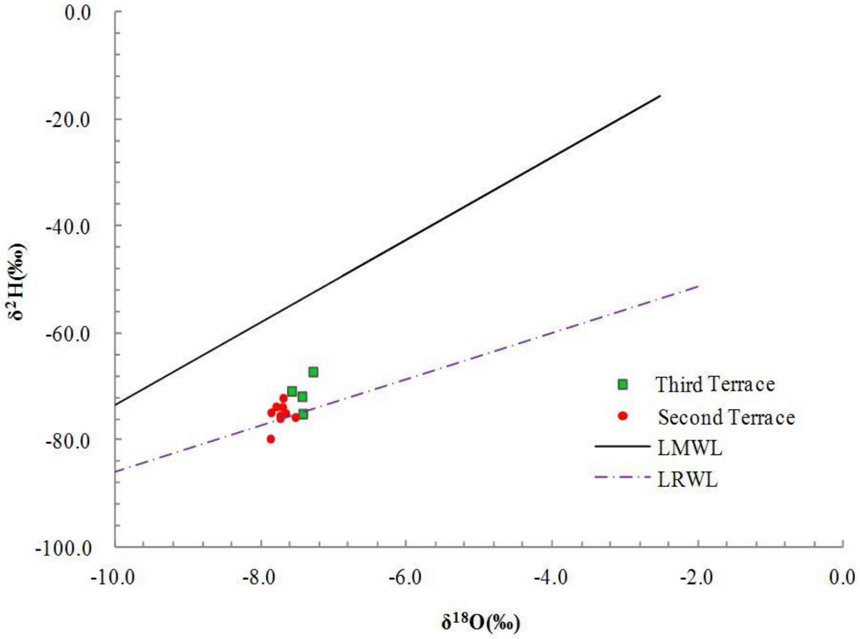


Fig. 4-15 Relation of δ^{18}O and δ^2H in canal system of west Luohui Irrigation District on March 2010

Seen from **Figs. 4-13, 4-14,** and 4-**15**, most all samples for recharge source in the third terrace were come from rainfall except the Well 12 come from the Luo River water, because Luo River water is very easy to take lateral flow into the Well 12. Afterward I are using two-component mixing model based on mass balance, groundwater in the third terrace was isotopically separated in to precipitation and Luo River water, the mean percentage of Luo River water in groundwater is evaluated at 88.7% (using the average δ^{18}O and δ^2H value to calculation are 91.1% and 86.2%, respectively), and precipitation to groundwater is 11.3% in the Luohui Irrigation District. The high percentage of precipitation in the groundwater is probably due to the location of Well 35 around the settlement caused it is easy to accept the supply of precipitation. Moreover, in the second terrace, the recharge source of groundwater of most all well comes from rainfall except the Well 10 from deep groundwater (deep groundwater, Luo River water to groundwater is 22.2%, 87.8%, respectively). **Fig. 4-16** shows the detail for the groundwater components of each well in the canal system of west Luohui Irrigation District.

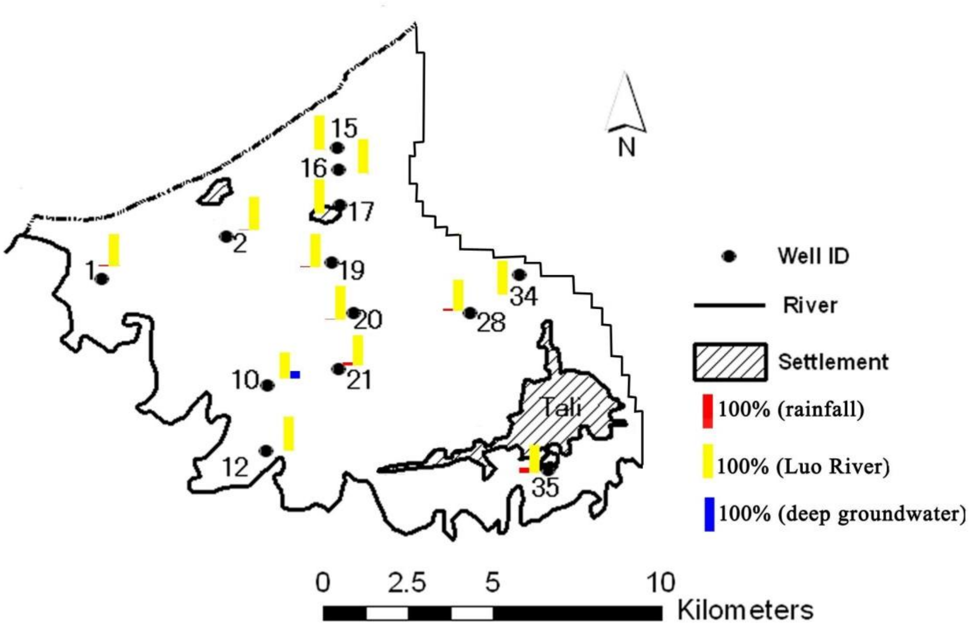


Fig. 4-16 Groundwater components of each well in the canal system of west Luohui Irrigation District

4.4.2.2.2 Canal system of middle Luohui Irrigation District

I used the same way with last part to set up the relationship of groundwater isotopes between $\delta^{18}O$ and $\delta^{2}H$ in the canal system of middle Luohui Irrigation District on March 2010 based on the LMWL and the LRWL. **Fig. 4-17** shows that the mean isotopic value of groundwater samples in the third terrace, second terrace, and first terrace, are −7.47‰ and −73.91‰, −7.65‰ and −74.59‰, −7.95‰ and −78.22 ‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively. The results indicate that isotopic enrichment of groundwater from the first terrace to the third terrace with the groundwater flow direction is gradually increasing.

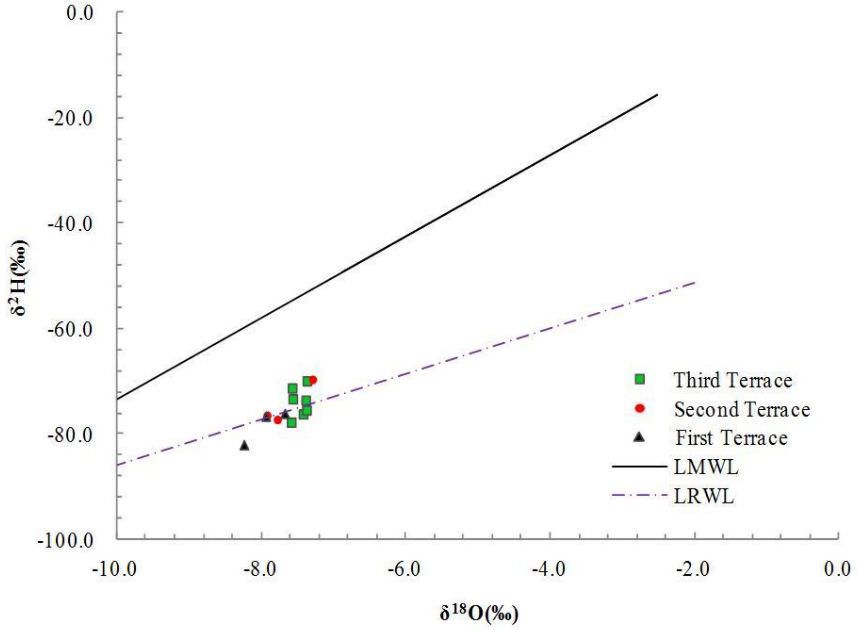


Fig. 4-17 Relation of $\delta^{18}O$ and $\delta^{2}H$ in canal system of middle Luohui Irrigation District on March 2010

Moreover, in the first terrace, the recharge source of Well 36 are come from the Luo River because the plots of groundwater isotope are located on the LRWL except the Well 42 which the recharge source come from the deep groundwater, Luo River water and rainfall (**Figs. 4-13, 4-14,** and **4-17**) because the human activity (pumping irrigation).

However, the content of isotopes of Well 45 ($\delta^{18}O = -8.25‰$, $\delta^{2}H = -82.00‰$) was very dilution, it means that the recharge source is mainly from deep groundwater. This is due to the high elevation and no canal near around the Well 45. So the Well 45 was isotopically separated in to Luo River water and deep groundwater, the mean percentage of Luo River water in groundwater is evaluated at 48.3%, and precipitation to groundwater is 51.7% in the Luohui Irrigation District. In the second terrace, the content of isotopes of Well 37 (**Figs. 4-13, 4-14,** and **4-17**) was very enrichment ($\delta^{18}O = -7.28‰$, $\delta^{2}H = -69.78‰$), it means that the recharge source is mainly from deep groundwater and rainfall (deep groundwater, precipitation to groundwater is 65.9%, 34.1%, respectively) because the location of Well 37 around the settlement, and the recharge source of Wells 33 and 39 are come from the Luo River.

Meanwhile, in the third terrace, the recharge source is very complex, including rainfall, Luo River water, and deep groundwater. But the mean isotopic value of groundwater samples is the most enrichment in the canal system of middle Luohui Irrigation District, the groundwater accept directly (or indirectly) precipitation supply. **Fig. 4-18** shows the detail for the groundwater components of each well in the canal system of middle Luohui Irrigation District.

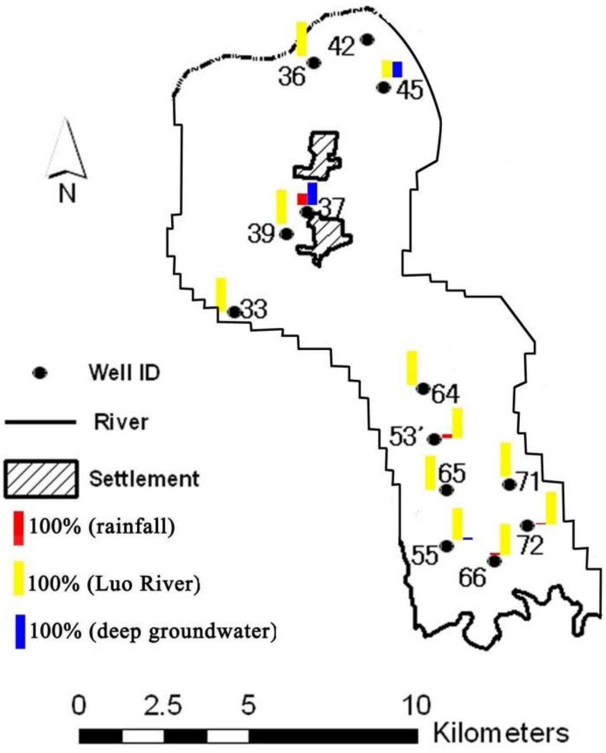


Fig. 4-18 Groundwater components of each well in the canal system of middle Luohui Irrigation District

4.4.2.2.3 Canal system of east Luohui Irrigation District

Fig. 4-19 shows that the relationship of groundwater isotopes between $\delta^{18}O$ and $\delta^{2}H$ in the canal system of east Luohui Irrigation District on March 2010 based on the LMWL and the LRWL. The mean isotopic value of groundwater samples in the third terrace, second terrace, and first terrace, are −7.54‰ and −72.31‰, −7.77‰ and −77.88‰, −8.21‰ and −81.98‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively. The results indicate that isotopic enrichment of groundwater from the first terrace to the third terrace with the groundwater flow direction is gradually increasing.

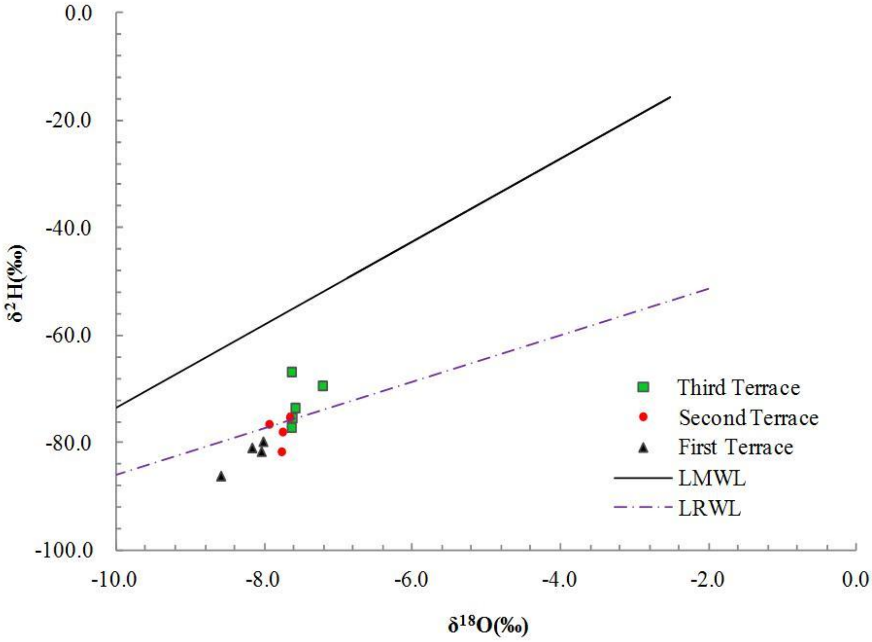


Fig. 4-19 Relation of $\delta^{18}O$ and $\delta^{2}H$ in canal system of east Luohui Irrigation District on March 2010

In the first terrace (**Fig. 4-19**), the recharge source of all the wells are come from the deep groundwater because the isotopic value of groundwater is very depleted, and the plots of groundwater isotope are located below the LRWL. However, the content of isotopes of Well 76 ($\delta^{18}O = -8.59‰$, $\delta^{2}H = -86.03‰$) was very dilution, the mean percentage of Luo River water in groundwater is evaluated at 19.3%, and deep groundwater to groundwater is 80.7% in canal system of east Luohui Irrigation District. In the second terrace, the plots of Wells 78 and 80 are located on the LRWL, the recharge source are mainly Luo River water.

However, in the third terrace, most all plots are located between the LMWL and the LRWL, and the mean isotopic value of groundwater is the most enriched in the canal system of east Luohui Irrigation District. The results indicate that the main recharge source of groundwater is rainfall. Meanwhile, **Fig. 4-20** shows the detail for the groundwater components of each well in the canal system of east Luohui Irrigation District.

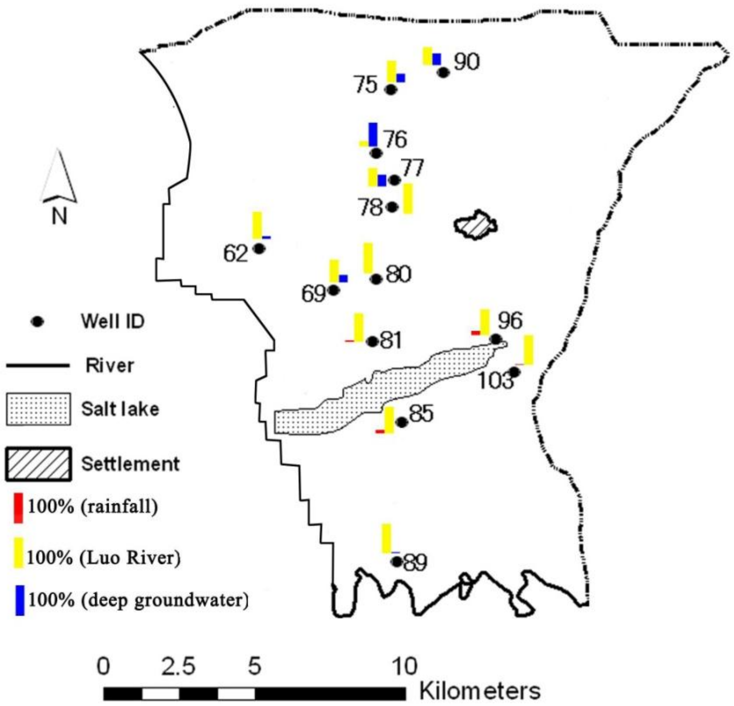


Fig. 4-20 Groundwater components of each well in the canal system of east Luohui Irrigation District

4.5 Conclusions

The Luohui Irrigation District is the important food base in Middle Shaanxi, but many serious eco-environmental problems increased in recent years, such as soil secondary salinization, groundwater level rising, and groundwater quality deterioration, caused by the unreasonable exploitation and utilization mode and insufficient management pattern of water resources in the Luohui Irrigation District. Therefore, it is of great importance to consider how to reasonably exploit the groundwater and to prevent the soil salinization. In this paper, I used the piper tri-linear graphic representation method, the descriptive statistics, the ion ratio coefficient method and the stable isotope technology to study the chemical and stable isotopic characteristics of groundwater and salt in the Luohui Irrigation District, China. The results are concluded as following:

(1) Well 34 in the Luohui Irrigation District, the contents of Cl^-, SO_4^{2-}, and EC of groundwater grown as the depth from the groundwater level increased, and the concentrations abruptly rose in 15 m from the groundwater level. In contrast, the contents

of NO_3^- of groundwater decreased as the depth, and the concentration abruptly declined in 15 m. The results show that the salt of groundwater come from the deep groundwater (below 15 m depth from the groundwater level) because the bottom of the Luohui Irrigation District has the massive soluble salts at 40−50 m in depth from ground surface.

(2) The chemical characteristics of groundwater in Well 34 relate to the brine invasion effect. The effect of evaporation and condensation is not the control elements of chemical characteristics formation of groundwater in the saturation zone, but the brine invasion from the deep groundwater and human activity is the main formation reason.

(3) The chemical type of groundwater in the eastern block of the Luohui Irrigation District is relatively single and mainly $Cl^- \cdot SO_4^{2-}$–Na^+, then is $Cl^- \cdot SO_4^{2-}$–$Na^+ \cdot Mg^{2+}$. And the chemical characteristics of Na^+、Mg^{2+}、SO_4^{2-} are linear with Cl^- in groundwater. The result shows that the source of salt is the same.

(4) According to the results of chemical and stable isotopes (^{18}O, ^{2}H) analysis of groundwater (Depth > 15 m from groundwater level), I established the deep groundwater water line (DGWL) and expressed as follow: $\delta^2H = 1.04\delta^{18}O - 97.21$.

(5) The mean values of EC and $\delta^{18}O$ of groundwater from the third terrace to first terrace are 0.27 S m^{-1} and −7.52 ‰, 0.33 S m^{-1} and −7.84 ‰, 0.56 S m^{-1} and −8.10 ‰, respectively. The results show that the $\delta^{18}O$ values along the flow direction enriched as the EC of groundwater declined except Wells 37 (second terrace) and 42 (first terrace).

(6) According to the LMWL and the LRWL, I analyzed the stable isotope and chemical characteristic of groundwater in the Luohui Irrigation District, and then I found the recharge source of groundwater and salt. Meanwhile, using two-component mixing model based on the water and tracer (oxygen isotope) mass balace, I calculated the proportion of recharge source in groundwater for each well. Moreover, the recharge source of groundwater in west and middle Luohui Irrigation District is mainly Luo River water (irrigation water), then is precipitation. However, the recharge source of groundwater in east Luohui Irrigation District is mainly brine, and then is Luo River water.

5 Tracing infiltration and recharge using stable isotopes in unsaturated zone

5.1 Introduction

Salts are neutral ionic compounds composed of metal cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and radical anions (Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-). Saline soils are soils consists of a variety of saltierra and solonetz. Alkaline soil is the sodium predominates (over 20%) in the soil colloids. Its main feature is a strongly alkaline reaction (pH 8.5 ~ 11), poor permeability, and low salt content. Therefore, alkaline soil has very poor structure which limits or prevents water infiltration and drainage. Saltierra is a kind of soil, a soluble salt content in the soil to achieve a significant hazard for crop growth. Saltierra are therefore also alkaline soils, there may be alkaline that are not saline. In arid and semiarid regions salts may accumulate, leading to naturally saline soils. Human activities can increase the saline soil by irrigation system. Proper irrigation management can prevent salt accumulation in the soil surface by providing adequate drainage canal. Meanwhile, damage and imperfections of the drainage canal can also lead to salt accumulation. (Howard and Mullings, 1996; Northey *et al*., 2006; Moore *et al*., 2008; Zhang, 2008).

Salinization, the build-up of salinity in the soil, is a worldwide problem mainly in arid and semiarid regions. It can occur when the water table is between two to three meters from the surface of the soil. The salts from the groundwater are raised by capillary action to the surface of the soil. This occurs when groundwater is saline (which is true in many areas), and is favored by land use practices allowing more rainwater to enter the aquifer than it could accommodate. For example, the clearing of plants for agriculture is a major reason for salinity in arid and semiarid regions, since deep rooting of plants has been replaced by shallow rooting of annual crops (Xu *et al*., 2006; Yamanaka and Shimizu, 2007; Cui *et al*., 2011).

In recent years, with a growing world population, there has been an increase in magnitude and intensity of salt-affected soils due to unreasonable irrigation methods, overuse of chemical fertilizer, severe deforestation, etc. it is estimated that tens of millions of hectares of land are degraded every year (Li *et al.*, 2006; Yu and Rui, 2007; Yu *et al.*, 2009).

The stable isotope technology has a number of functions, such as tracer, integration, and instructions. Currently, the stable isotope technology has been widely applied to various fields of ecological and environmental sciences. For example, plant physiology, animal ecology, and microbial ecology, and so on. And gradually became one of the most effective tools used in the modern ecological and environmental science (Graves and Romanek, 2009; Lin, 2010).

Luohui Irrigation District, the study area, was established 70 years ago as the cotton production center of Shaanxi province, China. This area has been facing salinization problem through time, which demands remedies by preventing new salinization processes and rehabilitating salinized areas. Saline soils are an environmental problem in the Luihui Irrigation District, they have poor or low crop production. Salinization may occur on surface soil when the groundwater levels is very high, caused by a lack of natural subsurface drainage. However, human activities can cause the subsurface drainage and transport capacity is poor in the aquifer. Therefore, the primary cause of the artificial saline soil is irrigation water, because all irrigation water from river and groundwater contains salts. The main reason is that the salts remain behind in the soil after the irrigation water has evaporated (Li, 1995; Du *et al*., 2008).

Meanwhile, applying soil conditioners and much amount of water to leach down the salt, installing surface or subsurface drainage structures, cultivating salt-tolerant crop are among the typical measures implemented to mitigate salinization problems. This paper selects typical soil sections to do soil water-salt experiment of stable isotope and chemical analysis, and analyze soil water-salt dynamic feature and its influencing factors based on analyzing the geological properties of unsaturated zone. Consequently, the aim of the study is prevent soil degradation by salinization and reclaim already salty soils, it is crucial to understand the regulation of salt movement through water in unsaturated zone.

5.2 Materials and methods

5.2.1 Introduction of irrigation area

Luohui Irrigation District located in the lower stream of the Luo River, east part of middle Shaanxi Province, concerning Dali, Pucheng and Chengcheng counties, with the area of 750 km^2. The terrain goes down from north to south, with the altitude between 329 to 400 m, and is a part of the terrace of the Wei-Luo River. This area has a long history, acclaimed as the granary for the ancient capital. The area belongs to warm-temperate, semiarid, continental, monsoon climate zone, with distinct seasons. The rainfall in this area is not sufficient and the rainfall distribution varies in time and in space. Drought and flood disasters occurred frequently, especially the droughts. Luo River, the source of irrigation water, originates from Baiyu Mountain in Dingbian County, North Shaanxi Province (**Fig. 5-1**).

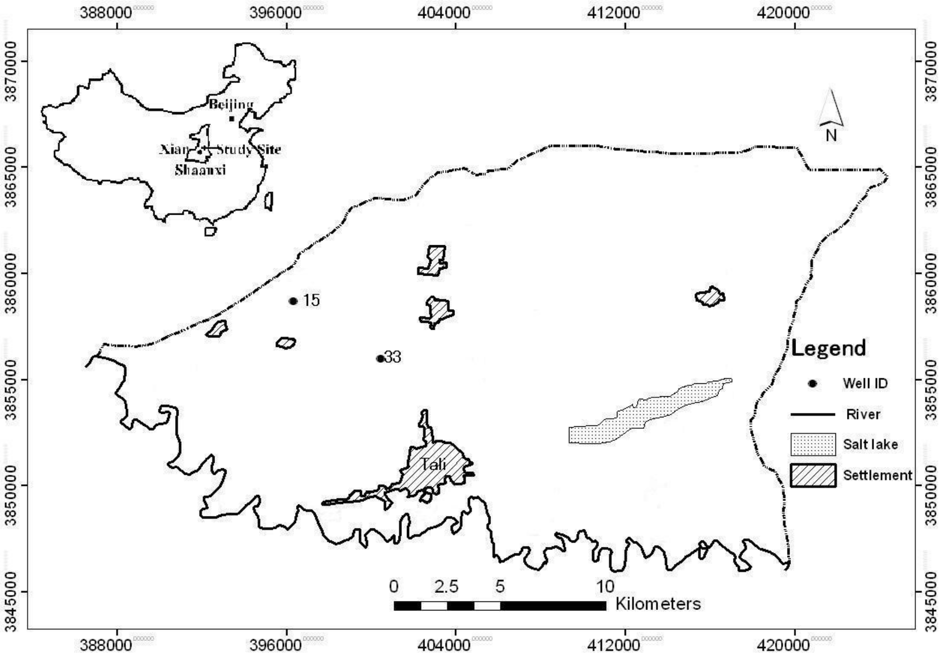


Fig. 5-1 Location of the eastern block of the Luohui Irrigation District, China

The climatic condition of the area is a semiarid type with average annual precipitation of 484.2 mm, which is too low for rainfed agriculture. The rainy season is typically from July to September, and the average annual temperature is around 13.5˚C **(Fig. 5-2)**. The average potential evaporation (1690.3 mm) is about three times the annual precipitation.

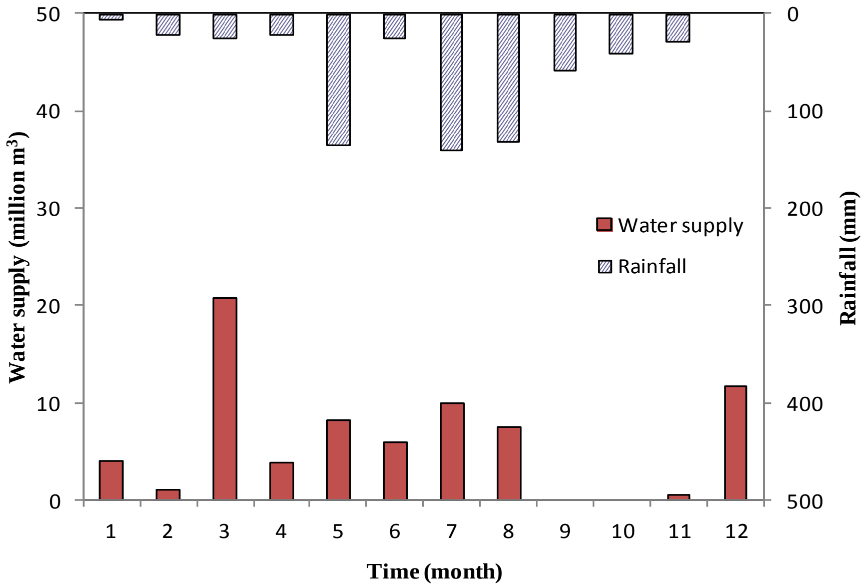


Fig. 5-2 Variation of irrigation water supply and rainfall in 2009

5.2.2 Samples

Six soil samples from Well 33 and eight soil samples from Well 15 for each 50 cm in depth from topsoil were collected for further measurements in the laboratory on 20, 21, and 22 December 2009 (**Fig. 5-3**). The sampling site around each well is about 50 m. Besides, groundwater samples from each well were collected. **Fig. 5-1** shows the location of each well in the eastern block of the Luohui Irrigation District, China. All samples were stored in polypropylene bags (1 kg) which were carefully filled without any air entrapment for stable isotopes analysis. After taking all samples were stored at 4˚C to prevent evaporation.

Pore water salinity of soil (ECp) for each 50 cm in depth from topsoil and moisture content (MC) were measured directly at field (around Wells 15 and 33) in 2009, using a device called water content, electrical conductivity and temperature (WET) sensor Delta-T. It was done by inserting the rods of the sensor to a depth of about 6 cm and through which an electric current is released to the soil.

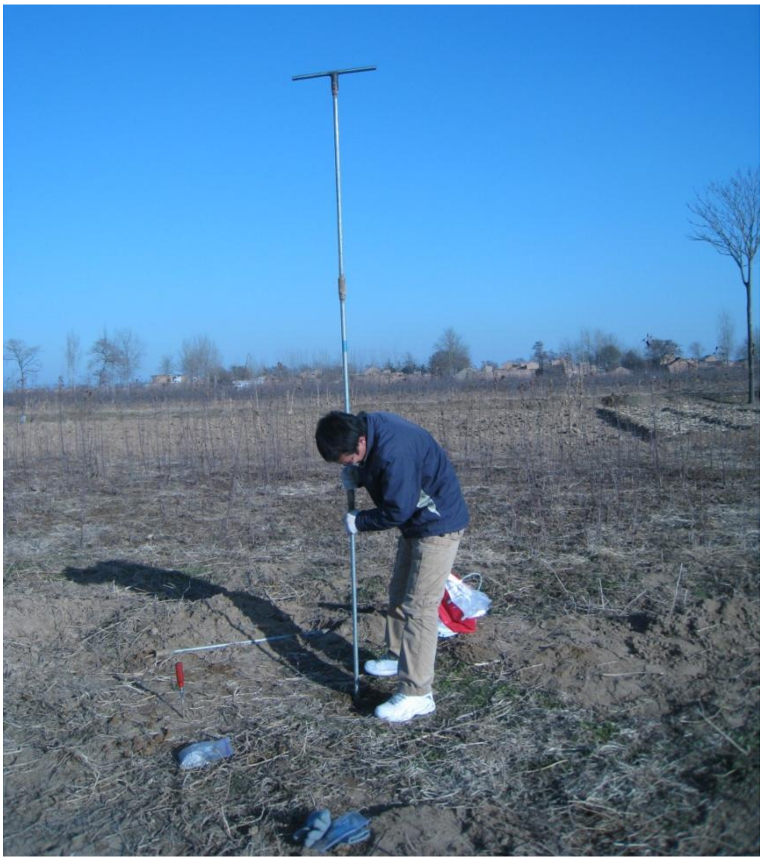


Fig. 5-3 Soil sampling around Well 33 in the eastern block of the Luohui Irrigation District on 20 December 2009

5.2.3 Experimental set-up

In the laboratory, I divided soil samples into two equal shares: one part that all soil samples were air-dried and sieved to < 2 mm. Then I used the kind of soil samples to make soil water samples in May 2010, the ratio is 1:5 (1 for soil sample and 5 for distilled water). Finally, the soil water samples were collected in 250 ml sterilized polythene bottles, and, immediately preserved in a refrigerated room (T below 5˚C) until the time of analysis for major ion. In July 2010, the water samples were analyzed at the Laboratory of Environmental Soil Science and Global Arid Land Science at the Tottori University, Japan. In addition, in the case that the chemical analysis of groundwater and soil water samples are major (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}) ion analysis.

On the other hand, I extracted soil water from all soil samples by a CR-21G high speed refrigerated centrifuge (**Fig. 5-4**), and all water samples were stored in polypropylene bottles (5 ml.) with watertight caps which were carefully filled without any air entrapment for stable isotopes analysis in June 2010. After sampling all samples were stored at 5˚C to prevent evaporation. The stable isotopes (^{18}O, ^{2}H) analyses were carried out at Xi’an University of Technology in China using a common equilibration technique with a MAT-253 Mass Spectrograph in July 2010. Measurement accuracy for δ^{18}O and δ^{2}H are ±0.1‰ and ±1.0‰ versus VSMOW, respectively.

Fig. 5-4 CR-21G high speed refrigerated centrifuge in Yangling, China

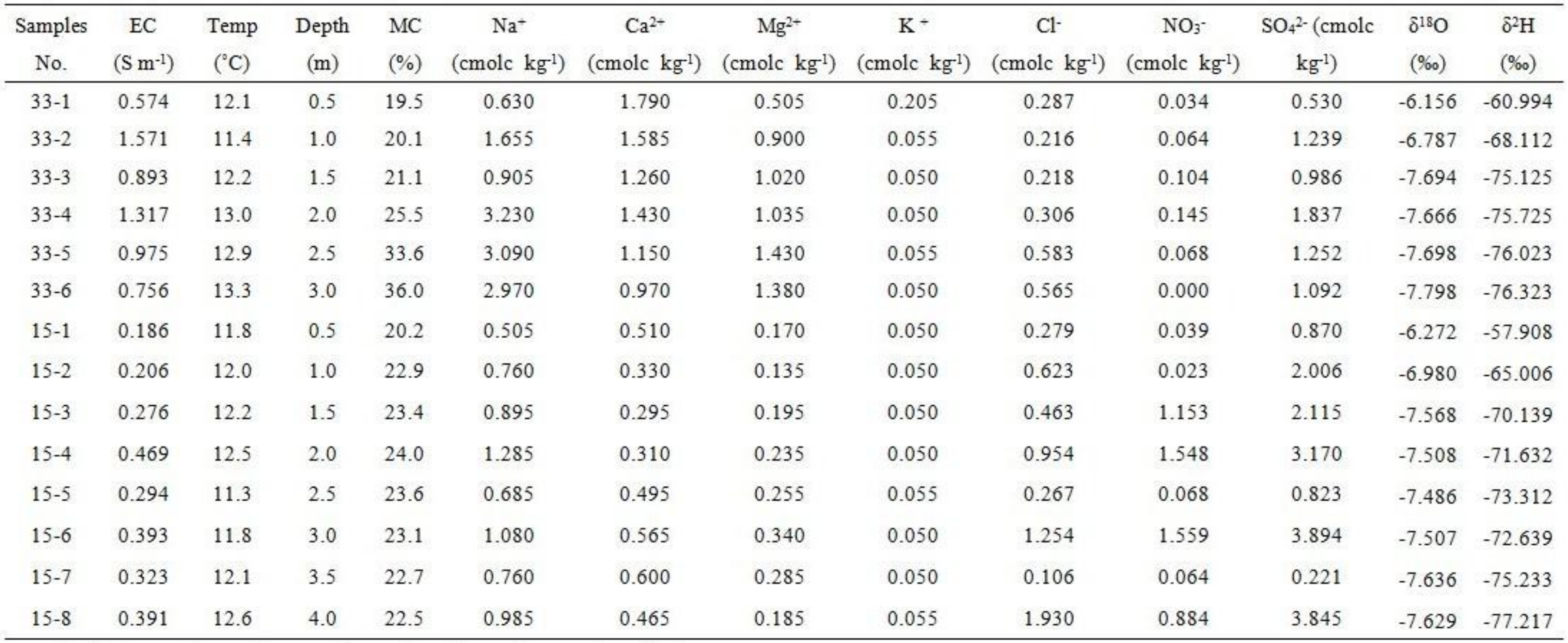
5.3 Results and discussion

General characteristics and isotopic data of Wells 15 and 33 are given in **Table 5-1**. **Tables 5-2** show that the chemical compositions and general characteristics of isotopic composition of soil water around Wells 15 and 33 in the eastern block of the Luohui Irrigation District.

Table 5-1 General characteristics and isotopic data of Wells 15 and 33 in the Luohui Irrigation District on December 2009

Well No.	Terrace	Altitude (m)	Canal System	T (˚C)	Depth (m)	EC (S m^{-1})	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
15	2	373.6	West	11.8	8.05	0.222	-7.716	-76.204
33	2	359.8	West	12.1	5.08	0.941	-7.892	-77.322

Table 5-2 Chemical compositions and stable isotopic data of soil water in the Luohui Irrigation Dirstrict on December 2009



Samples No.	EC (S m^{-1})	Temp (°C)	Depth (m)	MC (%)	Na$^+$ (cmolc kg^{-1})	Ca^{2+} (cmolc kg^{-1})	Mg^{2+} (cmolc kg^{-1})	K$^+$ (cmolc kg^{-1})	Cl$^-$ (cmolc kg^{-1})	NO$_3^-$ (cmolc kg^{-1})	SO$_4^{2-}$ (cmolc kg^{-1})	$\delta^{18}O$ (‰)	δ^2H (‰)
33-1	0.574	12.1	0.5	19.5	0.630	1.790	0.505	0.205	0.287	0.034	0.530	-6.156	-60.994
33-2	1.571	11.4	1.0	20.1	1.655	1.585	0.900	0.055	0.216	0.064	1.239	-6.787	-68.112
33-3	0.893	12.2	1.5	21.1	0.905	1.260	1.020	0.050	0.218	0.104	0.986	-7.694	-75.125
33-4	1.317	13.0	2.0	25.5	3.230	1.430	1.035	0.050	0.306	0.145	1.837	-7.666	-75.725
33-5	0.975	12.9	2.5	33.6	3.090	1.150	1.430	0.055	0.583	0.068	1.252	-7.698	-76.023
33-6	0.756	13.3	3.0	36.0	2.970	0.970	1.380	0.050	0.565	0.000	1.092	-7.798	-76.323
15-1	0.186	11.8	0.5	20.2	0.505	0.510	0.170	0.050	0.279	0.039	0.870	-6.272	-57.908
15-2	0.206	12.0	1.0	22.9	0.760	0.330	0.135	0.050	0.623	0.023	2.006	-6.980	-65.006
15-3	0.276	12.2	1.5	23.4	0.895	0.295	0.195	0.050	0.463	1.153	2.115	-7.568	-70.139
15-4	0.469	12.5	2.0	24.0	1.285	0.310	0.235	0.050	0.954	1.548	3.170	-7.508	-71.632
15-5	0.294	11.3	2.5	23.6	0.685	0.495	0.255	0.055	0.267	0.068	0.823	-7.486	-73.312
15-6	0.393	11.8	3.0	23.1	1.080	0.565	0.340	0.050	1.254	1.559	3.894	-7.507	-72.639
15-7	0.323	12.1	3.5	22.7	0.760	0.600	0.285	0.050	0.106	0.064	0.221	-7.636	-75.233
15-8	0.391	12.6	4.0	22.5	0.985	0.465	0.185	0.055	1.930	0.884	3.845	-7.629	-77.217

Note: depth from surface soil to sampling point. All samples near the well about 50 meters.

5.3.1 Chemical characteristics of soil water

For the sampling sites present the linear distribution along Wells 15 and 33 from the surface in depth, it is difficult to allsidedly control the irrigation district. So, the research mainly analyzed the rule of chemical components of soil water along the depth variation from the surface.

Fig. 5-5 shows that the variations of Na^+, SO_4^{2-} and ECp with the depth from the surface in Well 33 in the Luohui Irrigation District. The contents of Na^+, SO_4^{2-}, and ECp of soil water grown as the depth of 50 cm and 150 cm from the surface increased, and the concentrations abruptly declined in 100 cm and 200 cm from the surface. It indicated that the salinity from the soil water stay temporarily in 100 cm and 200 cm. The saline water is possible come from the groundwater without the human activity because the groundwater level is very shallow in Well 33.

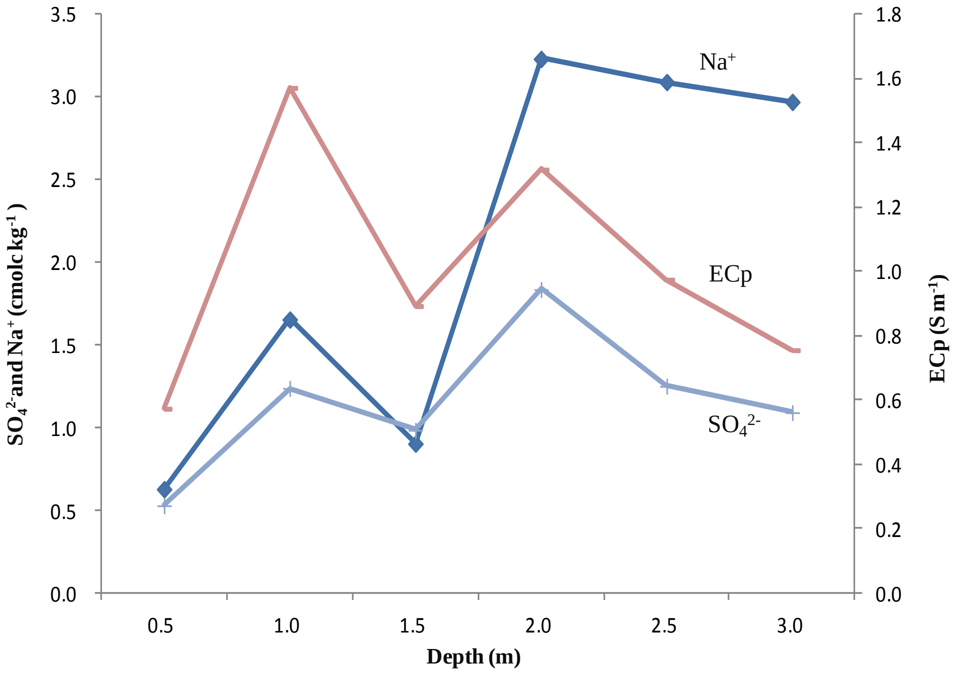


Fig. 5-5 Variations of Na^+, SO_4^{2-} and ECp with the depth from the surface in Well 33 in the Luohui Irrigation District

However, the contents of some major ion components such as Mg^{2+}, Ca^{2+}, NO_3^-, K^+ and Cl^- presented the fluctuation variation as the depth from the surface had not the abruptly rise or decline trend (**Fig. 5-6**). The results shown that the human activity (agricultural irrigation from groundwater) wasn't the main element which affected the chemical characteristics of soil water, and the sources of salinity were not same and might come from the groundwater through capillary water rise or Luo River water (irrigation water) through infiltration.

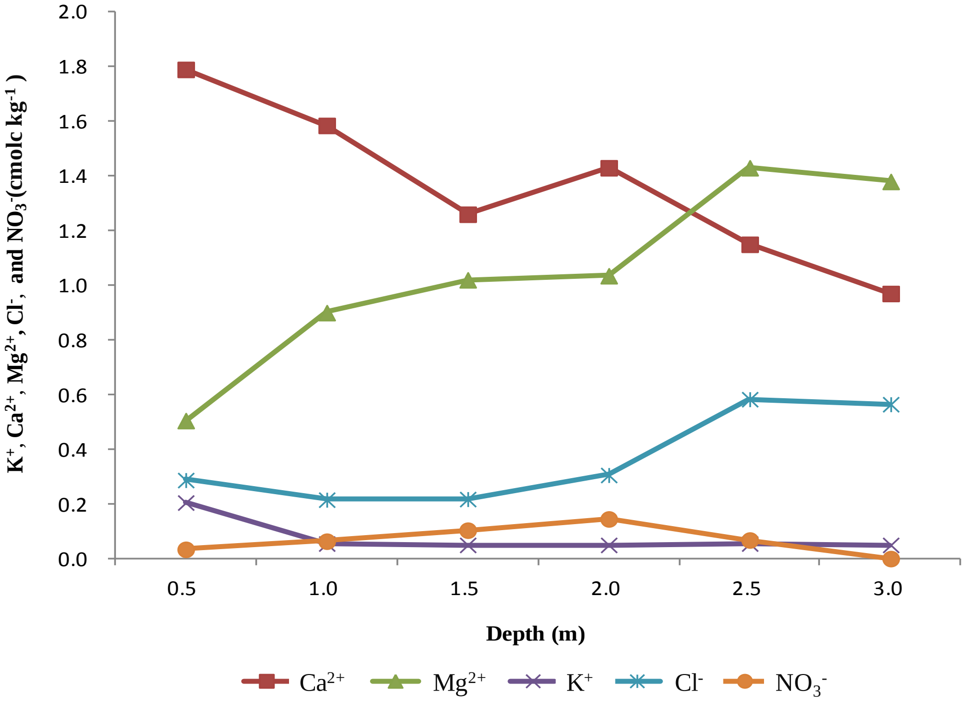


Fig. 5-6 Variations of Mg^{2+}, Ca^{2+}, NO_3^-, K^+, and Cl^- with the depth from the surface in Well 33 in the Luohui Irrigation District

Fig. 5-7 shows that the variations of Na^+, SO_4^{2-} and ECp with the depth from the surface in Well 15 in the Luohui Irrigation District. The contents of Na^+, SO_4^{2-}, and ECp of soil water grown as the depth of 50 cm, 250 cm and 350 cm from the surface increased, and the concentrations abruptly declined in 200 cm and 300 cm from the surface. The contents of Na^+ and SO_4^{2-} with depth from surface indicated that the salinity from the soil water stay temporarily in 200 cm and 300 cm. The saline water is possible come from the groundwater and Luo River water which such practice in longer period of time causes for accumulation of salinity in the soil.

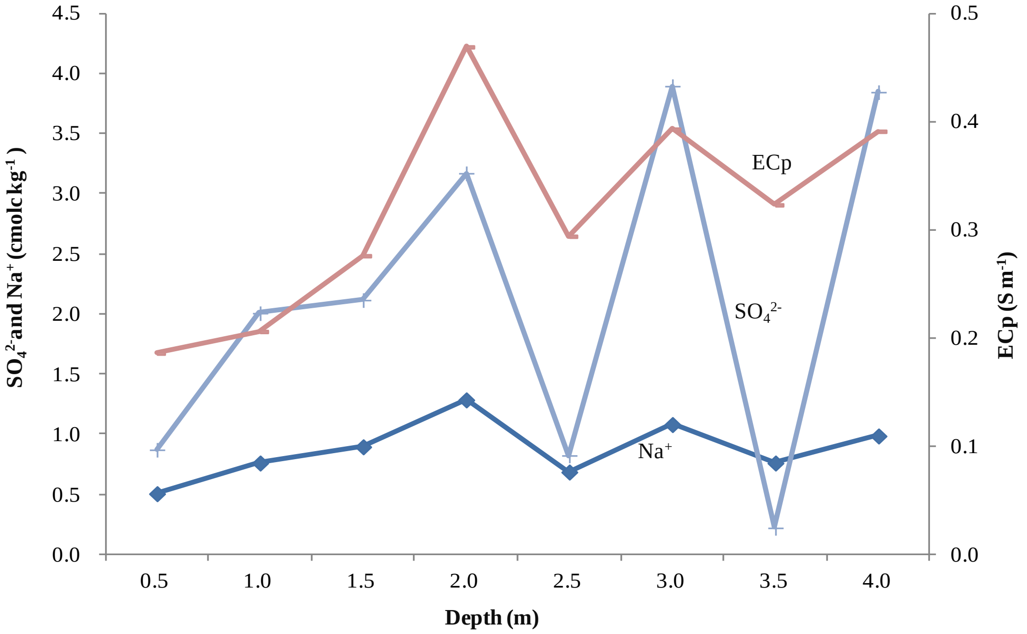


Fig. 5-7 Variations of Na^+, SO_4^{2-} and ECp with the depth from the surface in Well 15 in the Luohui Irrigation District

Fig. 5-8 shows that the variations of Mg^{2+}, Ca^{2+}, NO_3^-, K^+ and Cl^- with the depth from the surface in Well 15 in the Luohui Irrigation District. But the contents of NO_3^- and Cl^- of soil water grown as the depth of 50 cm, 250 cm and 350 cm from the surface increased, and the concentrations abruptly declined in 200 cm and 300 cm from the surface. And it indicated that the human activity (agricultural irrigation from groundwater) was the main element which affected the chemical characteristics of soil water, and the sources of salinity were same and might come from the groundwater due to Na^+ and SO_4^{2-} presented the strong correlation relationship with Cl^-, and they all abruptly changed with the abruptly variation of Cl^- concentration.

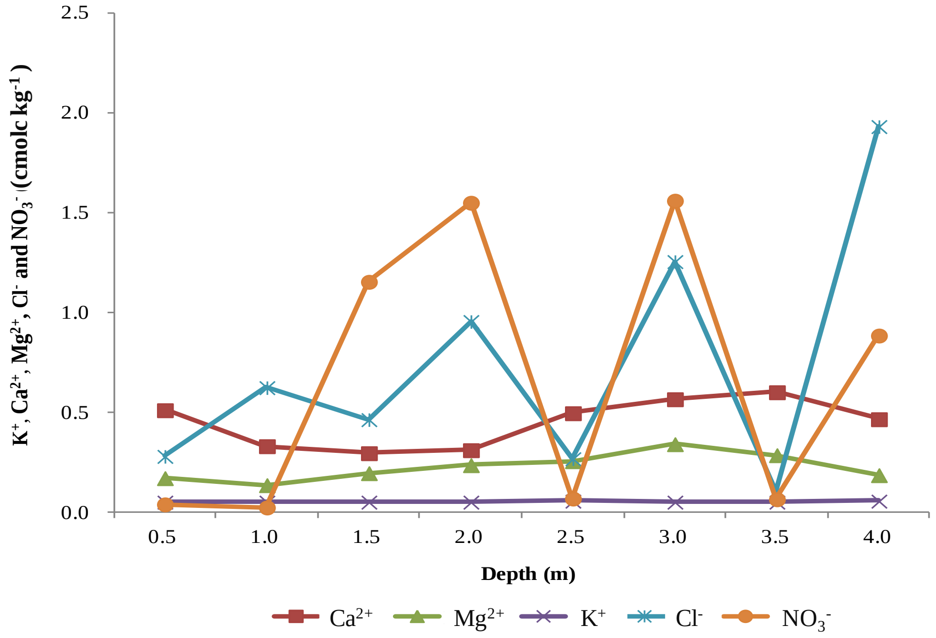


Fig. 5-8 Variations of Mg^{2+}, Ca^{2+}, NO_3^-, K^+ and Cl^- with the depth from the surface in Well 15 in the Luohui Irrigation District

5.3.2 Stable isotopic composition in soil water

The soil samples from 20 to 22 December 2009 were collected for stable isotope analysis in winter irrigation period (from 27 November 2009 to 20 February 2010) in the Luohui Irrigation District. According to the LMWL and the LRWL, I make the relation of $\delta^{18}O$ and δ^2H for soil water.

Fig. 5-9 shows the stable isotope relationship based on 14 samples of soil water and 2 samples of groundwater. The results indicate that all isotope dots of soil water fall on or along the right-side of the LMWL. Most of oxygen-18 compositions were higher than −7‰ at 100 cm, whereas those at the depths from 150 cm were lighter than −7.5‰. Generally, the values of $\delta^{18}O$ and δ^2H in soil water decrease with depth at the top layer above 100 cm at both sites, because the vapour-dominant transport is near the surface controlling the isotopic composition. In contrast, below 100 cm in depth isotope value had the unobvious enrichment or depletion trend.

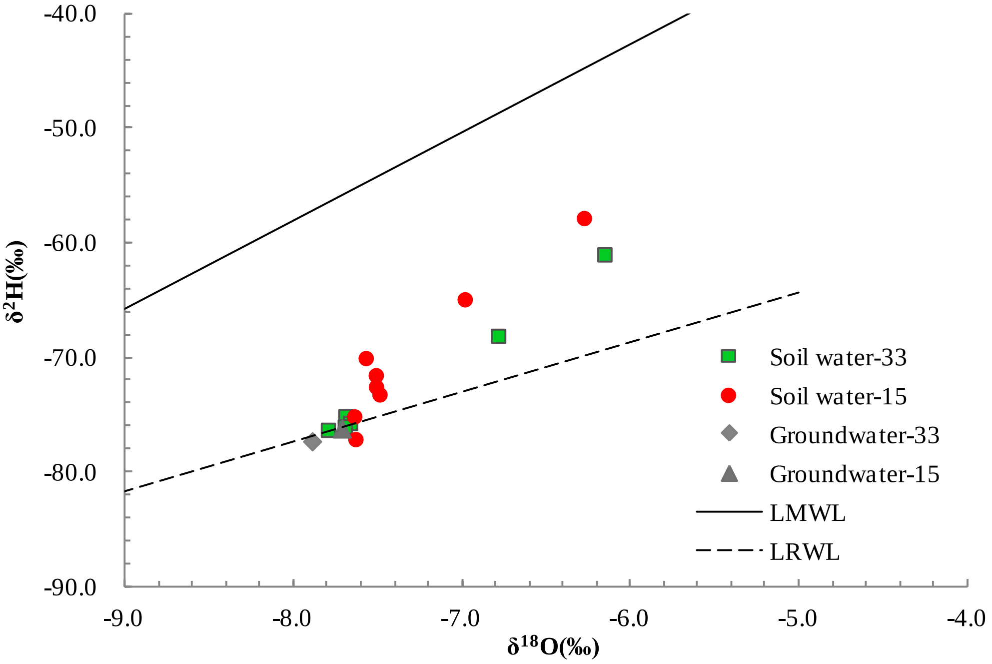


Fig. 5-9 δ^{18}O−δ^{2}H relationship of soil water at different depths of Wells 15 and 33 in the Luohui Irrigation District

The isotopic composition at both sites shows that the values of δ^{18}O and δ^{2}H declined with depth in the vertical profiles from surface. And the concentration of isotope abruptly declined in 50 cm from surface. It was considered as more effects of evaporation on the topsoil, which was similar at low rainfall sites in semiarid area.

The variations of isotopic values in Well 33 were smaller than Well 15. Because the groundwater table (from surface to the groundwater level) of Well 33 is only 5.08 m, it is easy to affect the isotopic values though capillary water rise. However, the soil water from precipitation has limited at 3–3.5 m in depth by infiltration caused the values of δ^{18}O and δ^{2}H depleted (**Fig. 5-9**).

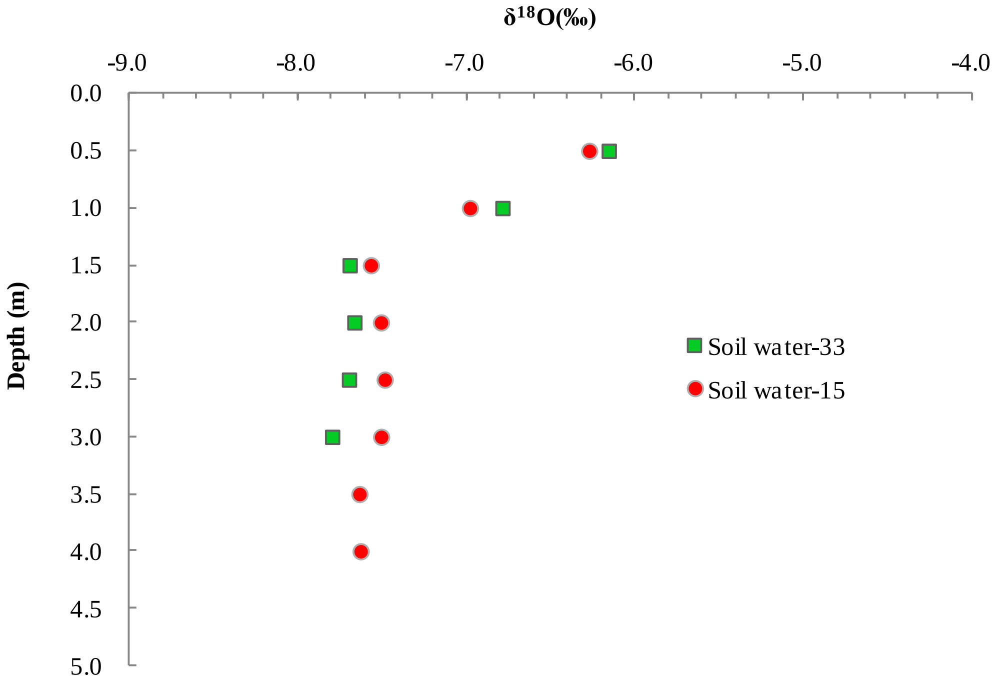


Fig. 5-10 Variation of δ^{18}O along soil profile at Wells 15 and 33 in the Luohui Irrigation District

5.3.2.1 Movement of soil water traced by stable isotope

Precipitation and irrigation water are the only source for soil water in the Luohui Irrigation District. Evaporation is the major factor for enrichment of isotopes at topsoil. Moreover, the isotope composition is also influenced by its composition in precipitation. By comparing soil water isotope composition at 50 cm and 100 cm in **Fig. 5-10**, the trend of isotope values suggests that the soil water originated from precipitation and the fractionation controlled by evaporation during the infiltration caused the values of δ^{18}O above 100 cm are different with the values below 100 cm. it is further evidence that the infiltration of precipitation can be traced by changes of stable isotope values with depth. From 150 cm to 300 or 400 cm in depth, all isotope values of δ^{18}O from −7.486‰ to −7.636 ‰ in Well 15 and from −7.666 ‰ to −7.798 ‰ in Well 33, the variation range was smaller. They indicated the evaporation effect was mainly to the upper 100 cm of water soil in the Luohui Irrigation District.

5.3.2.2 Recharge composition in soil water

Below 100 cm in depth, the isotope fractionation becomes very weak and can be ignored. Therefore, the isotopic compositions of soil water in Wells 15 and 33 strongly suggest that there are near relationship between the local groundwater and soil water below 100 cm depth for Wells 15 and 33 in the Luohui Irrigation District (**Fig. 5-10**). **Fig. 5-9** show that the isotopic compositions of groundwater are close to Well 33 of soil water at 300 cm in depth. The results indicate that the recharge source of soil water in depth 300 cm come from the groundwater because the groundwater level of Well 33 is only 5.08 m. Thus, the amount of recharge at 300 cm in depth of Well 33 is 33.2 % for groundwater, and 66.8% for Luo River water. Meanwhile, other soil water is very stable in the soil layer above depths of 300 cm in Well 33 and 400 cm in Well 15 will not recharge by capillary rise water. **Table 5-3** shows that the soil water composition were precipitation and Luo River water.

Table 5-3 Soil water composition of Wells 15 and 33 in the Luohui Irrigation District

Samples No.	The percentage of precipitation in soil water (%)	The percentage of Luo River water in soil water (%)
33-3	1.4	98.6
33-4	1.1	98.9
33-5	0.3	99.7
15-3	8.9	91.1
15-4	8.2	91.8
15-5	6.6	93.4
15-6	7.1	92.9
15-7	2.2	97.8
15-8	0.1	99.9

Note: The groundwater table of Well 33 is only 5.08 m, the capillary water rise and infiltration have a strong effect on soil water isotope. These caused the percentage of precipitation in soil water of Well 33 is smaller.

5.4 Conclusions

In recent years, Luohui Irrigation District has many serious eco-environmental problems, such as soil secondary salinization, groundwater level rising, and groundwater quality deterioration, caused by the unreasonable exploitation and utilization mode and insufficient management pattern of water resources. Therefore, it is of great importance to understand the regulation of salt movement through water in unsaturated zone. In this paper, I used the stable isotope technology to study the chemical and stable isotopic characteristics of Wells 15 and 33. The results are summarized as following:

(1) I taken some soil water from soil samples by the high speed refrigerated centrifuge when the moisture content of soil sample > 20%. And used chemical characteristics of soil water to confirm that capillary water rise is one of the major ways of salinization processes in shallow depth (depth < 6 m from ground surface) in the Luohui Irrigation District.

(2) Comparison of δ^{18}O and δ^{2}H profiles for Wells 15 and 33 in the Luohui Irrigation District shows that the δ^{18}O and δ^{2}H of soil water in depth (depth ≤ 100 cm) from ground surface is strongly dependent on those values of precipitation and isotopically enriched by evaporation effect.

(3) In Well 33, the salinity from the soil water stays temporarily in soil layers between 100 and 200 cm. And the sources of salinity were not same and might come from the groundwater through capillary water rise and Luo River water (irrigation water) through infiltration. However, the proportion of recharge at 300 cm in depth of Well 33 is 33.2 % for groundwater, and 66.8% for Luo River water. Due to the groundwater move 2−2.5 m in vertical depth by capillary water rise, the soil water from 100 to 250 cm in depth is mainly composed of Luo River water and precipitation.

(4) In Well 15, the salinity from the soil water stays temporarily in 200, 300 and 400 cm. The sources of salinity were same and might come from Luo River water (irrigation water) which such practice in longer period of time causes for accumulation of salinity in the soil. By comparing soil water isotope composition between 100 cm and 400 cm in depth, it indicates that the soil water main composition is Luo River water and precipitation. And the soil water originated from precipitation during the infiltration effect declines up to 300 cm in depth, but the soil water below a depth of 300 cm main composition is only Luo River water.

6 Effect of desalination of salinized farmland by warp soil dressing in the Loess Plateau

6.1 Introduction

Human activities affect the interaction between groundwater and surface water, can be observed as a result, such as irrigation systems, surface drainage, reservoirs construction, and removal of natural vegetation (Zhang, 2007). At the same time, many natural processes also affect the interactions of groundwater and surface water. In order to understanding the natural processes of interaction between groundwater and surface water, it is necessary to know as follow: (1) Hydrological cycle, including groundwater interaction and receiving water; (2) Chemical interactions of groundwater and surface water (Na^+, Ca^{2+}, Mg^{2+}, and K^+); (3) Groundwater and surface water interaction in different environments, such as temperature.

Warp soil dressing is process which occurs when fine particles from the Loess Plateau region, transported by precipitation in rainy season, are dammed in gaps of skeleton. These particles produce less porosity and permeability of porous medium while the density of the material sedimentation increases. Meanwhile, the water infiltration down into the groundwater with salt because the salt movement can be controlled by water. Thereby, warp soil dressing can improve soil salinization. And warp soil dressing is introduced as one of measures against the problem (Guo, 2009).

Warp soil dressing, is oldest agricultural muddy irrigation technology in China. It is carried out extensively in the northern arid and semiarid area where water and soil has lost a lot. By muddy irrigation and comprehensive utilization of water, soil and fertilizer, product increases very obviously, effectively promote the development of agricultural production, making this technology welcomed by the famers. After New China was founded, warp soil dressing, in theory and practice has achieved a great development and improvement. With the necessity of construction, this work should be taken seriously in water and soil conservation. First of all, it is closely related to the improvement of the ecological environment and comprehensive management of watersheds in soil erosion areas, it is an important means of land improvement. Secondly, it will expand the water source, then ease the summer drought and water shortage resulting from the “extremely drought”, and the soil can be improved through creating farmland on a large scale, thus, expanding the area of basic farmland. Thirdly, it can block and use substantial lost soil and water, also reduce the river flood peak and sediment concentration, thereby, reducing river siltation, in order to cure the Yellow River and other sand rivers.

In Luohui Irrigation District, through the research of warp soil dressing, I tried to clarify changes in soil physical and chemical characteristics after conducting warp soil dressing in order to evaluate the sustainability and effects of saline soil improvement by warp soil dressing.

6.2 Materials and methods

6.2.1 Study area

Luohui Irrigation District is located in Dali County of Shaanxi Province, China. It is separated into the eastern block and western block by the Luo River (**Fig. 6-1**). Luo River, the source of irrigation water, originates from Baiyu Mountain in Dingbian County. The rainy season occurs only from July to September where as the annual temperature an average around 13.3˚C and annual precipitation is 480 mm in the site. The climate is semiarid area.

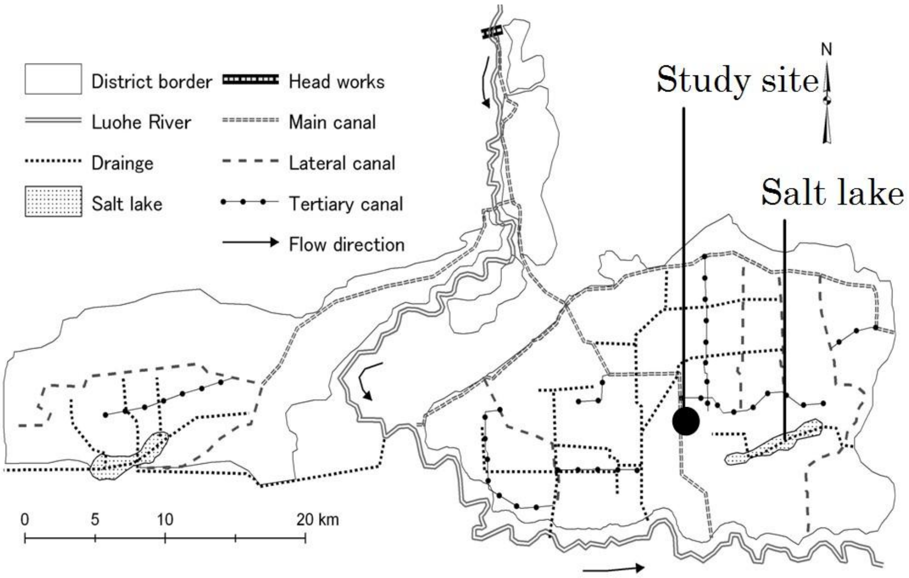


Fig. 6-1 Outline of the Luohui Irrigation District

6.2.2 Experimental set-up

The plot of the study area (34^{o}49'36.9" N, 110^{o}00'23.7" E) is a cotton field which is located northwest from the salt lake in the east block of the Luohui Irrigation District, and warp soil dressing was conducted in 2002. Five sampling points are indicated in **Fig. 6-2**. The object region around the drainage canal which long 300 m, wide 130 m, and the area is about 4 ha. The east side has the main canal; the intake for irrigation water is located at the northeast of the study area.

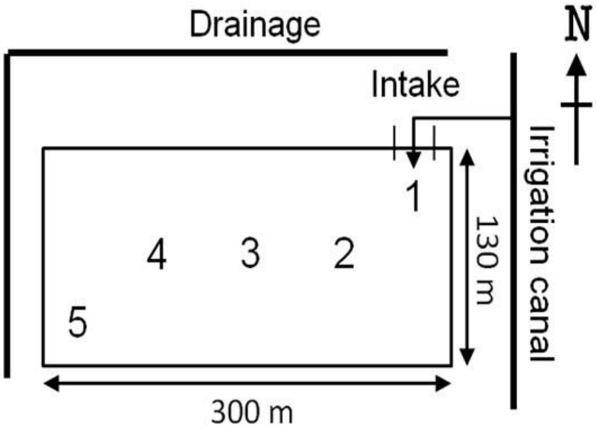


Fig. 6-2 Soil sampling points in the study area

In the survey in September 2008, I specified the thickness of dressed soil by soil profile survey at No. 3, the center of the study area as the representative point. I directly measured the moisture content, temperature, and ECe of soils in depth from surface to 1 m, where I used the WET sensor to measure at 5 mm of each layer in No. 3. Meanwhile, I used a soil sampling auger to collect some soil samples at 20 cm each until 100 cm in depth for permeability test and chemical analysis (Na^+, Ca^{2+}, Mg^{2+}, and K^+). In addition, other 4 sampling point only collected some soil sampling with the No. 3. Then I investigated the grain size and color of soil, and rhizome distribution of crop in depth for each layer (**Fig. 6-3**).

Horizon	Depth (cm)
Ap	16
C1	26
C2	36
2Apb	48
2C1	65
2C2	80
3C	100+

Fig. 6-3 Soil profile at No. 3 in the eastern block of the Luohui Irrigation District

6.2.3 Methods

The sodium adsorption ratio (SAR) of groundwater was computed using the equation (Solomon, *et al.*, 2005; Song, *et al.*, 2010):

$$SAR = Na^+ \Big/ \sqrt{(Ca^{2+} + Mg^{2+})/2} \tag{6.1}$$

Then I can get the ESP from the Eq. (6.2):

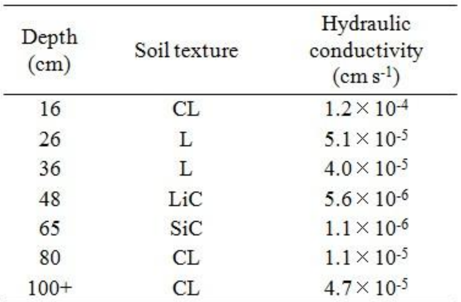
$$ESP(\%) = \frac{100(-0.0126 + 0.01475 \cdot SAR)}{1 + (-0.0126 + 0.01475 \cdot SAR)} \tag{6.2}$$

where Na^+, Ca^{2+}, Mg^{2+} are sodium, calcium and magnesium in milliequivalent per liter (meq L^{-1}), respectively.

6.3 Results and discussion

In No. 3, grain size distribution was analyzed for all soil samples. And hydraulic conductivity for each layer from surface to 1 m was measured by permeability test (**Table 6-1**). Chemical characteristics (Na^+, Ca^{2+}, Mg^{2+}, and K^+), electrical conductivity (ECe), and pHe were measured by saturated extraction method for all samples, the main equipment for analysis are atomic absorption spectrophotometer AA6700F, 3200 conductivity instrument, and pH meter HM-25G. Besides the water samples from soil samples were analyzed at the Laboratory of Water Use and Management and Global Arid Land Science at the Tottori University, Japan. In the survey in March 2009, the groundwater level was measured and groundwater was sampled at No. 3. Level survey was conducted to examine the slope and undulation of the study area.

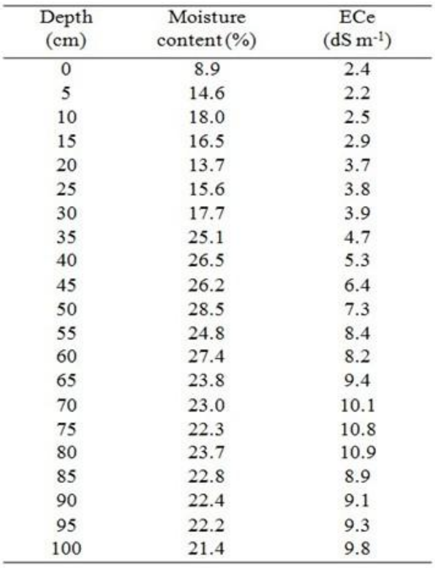
Table 6-1 Soil profile and permeability at No. 3 in the Luohui Irrigation District



Depth (cm)	Soil texture	Hydraulic conductivity (cm s^{-1})
16	CL	1.2×10^{-4}
26	L	5.1×10^{-5}
36	L	4.0×10^{-5}
48	LiC	5.6×10^{-6}
65	SiC	1.1×10^{-6}
80	CL	1.1×10^{-5}
100+	CL	4.7×10^{-5}

*Soil texture is classified based on International system (Japanese Society of Pedology, 1997)

Table 6-2 General characteristics in soil profile at No. 3 in the Luohui Irrigation District

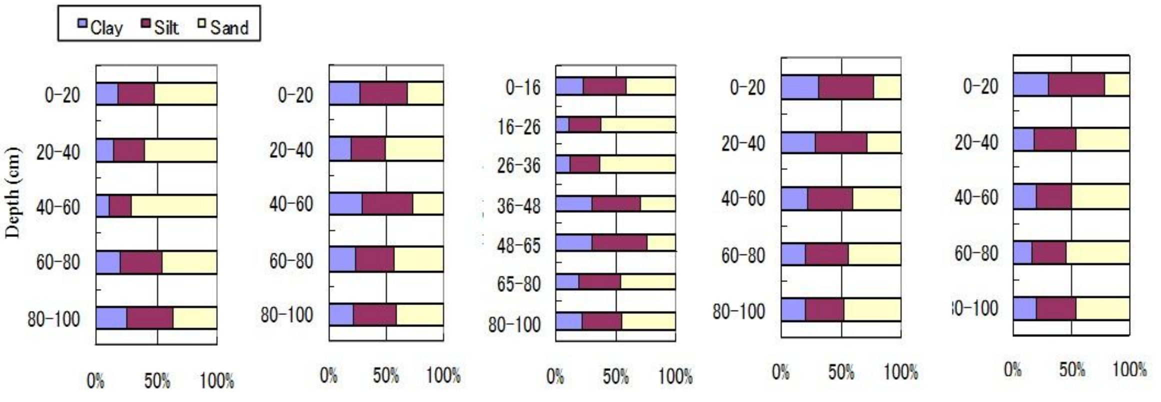


Depth (cm)	Moisture content (%)	ECe (dS m^{-1})
0	8.9	2.4
5	14.6	2.2
10	18.0	2.5
15	16.5	2.9
20	13.7	3.7
25	15.6	3.8
30	17.7	3.9
35	25.1	4.7
40	26.5	5.3
45	26.2	6.4
50	28.5	7.3
55	24.8	8.4
60	27.4	8.2
65	23.8	9.4
70	23.0	10.1
75	22.3	10.8
80	23.7	10.9
85	22.8	8.9
90	22.4	9.1
95	22.2	9.3
100	21.4	9.8

The significant difference of soil texture from sandy to clayish soil is observed at the boundary between C2 and 2Apb layers under 36 cm from the ground surface as shown in **Table 6-1**. In addition, the result of permeability test showed the same tendency; therefore the thickness of dressed soil is estimated as 36 cm at No. 3. Additionally, the grain size distribution of all sampling points showed that the thickness of dressed soil gradually becomes thinner and grain size becomes smaller as the distance is increased away from the intake.

Seen from **Table 6-2**, EC at 0−15 cm less than 3 dS m^{-1}, but EC grown as the depth increased from 15 cm, and the maximum value of EC is 10.9 dS m^{-1} at 80 cm. On the other hand, the maximum mean value of moisture content is 26.4% in depth from 35 to 60 cm. The results show that the water is very difficult to infiltration through the soil layer because the characteristic of soil layer is heavy clay soils.

According to **Fig. 6-2** and **6-4**, the results show that the amount of muddy soil and grain size of soil decreased as the distance from intake increased. It indicated that the warp soil dressing brought muddy soil from intake at the study area, and the flow speed and distance is main factor for the warp soil dressing.



(a) Sampling point No.1 (b) Sampling point No.2 (c) Sampling point No.3 (d) Sampling point No.4 (e) Sampling point No.5

Fig. 6-4 Grain size distribution in the eastern block of the Luohui Irrigation District

Chemical properties of the soil are summarized in **Fig. 6-5**. ECe values of soil layers from the ground surface to 65 cm depth at No. 3 and all layers up to 100 cm depth at No. 2 do not reach to the threshold of the ECe value of 4.0 dS m^{-1} (**Fig. 6-5 (a)**), which is generally defined as saline soil (USDA, 1954). However, ECe values of all other layers exceed 4.0 dS m^{-1}. It indicates the progress of salinization in the study area. On the other hand, pHe value 8.5 and Exchangeable Sodium Percentage (ESP) 15% is the threshold of the values, which are generally defined as sodic soil (USDA, 1954). As shown in the **Figs.**

6-5 (b) and **(c)**, the results of most layers are under the values, except the ESP value of 21.9% in the layer 80 to 100 cm depth at No. 5. Moreover, the groundwater level of the study area is 2.4 m that is higher than 3.0 m, which indicates that salt accumulation easily occurs, besides ECw of ground water is 8.2 dS m^{-1}. As these results, drainage is not functioning sufficiently at the study area. The values of ECe for No. 1 layers are relatively high, even though No. 1 is located at higher position than others, and there are no apparent depressions where salt accumulation easily occurs. The slope of the study field is 1/1000 in the direction from north to south as water flows during irrigation. This result is almost same as the design criteria of the irrigation district.

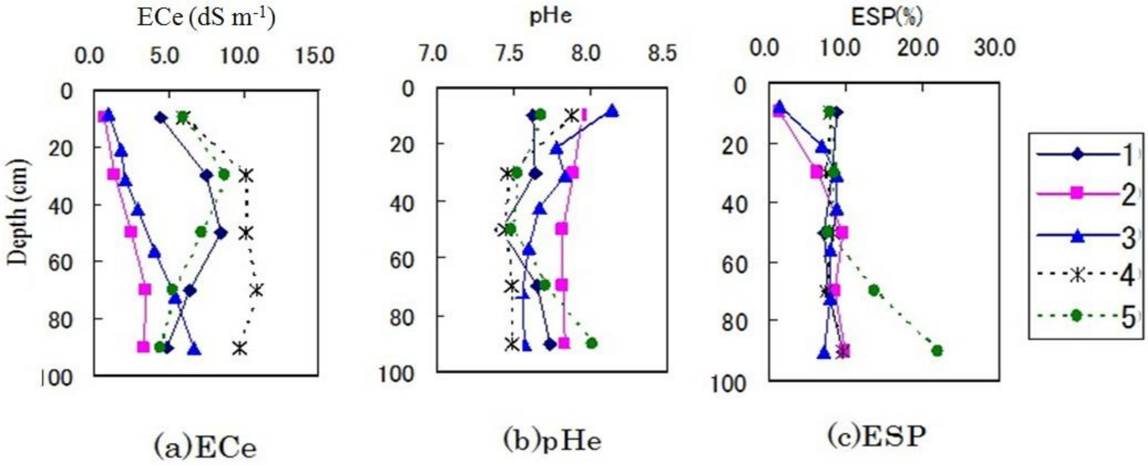


Fig. 6-5 Chemical properties of soil in the eastern block of the Luohui Irrigation District

6.6 Conclusion

Luohui Irrigation District is facing to more serious salinity problem. Salinity problem has occurred since irrigation was launched in 1950. Warp soil dressing has been introduced as one of measures against the problem since 1970s. In the chapter, I found the thickness of dressed soil is approximately 36 cm, and the thickness of dressed soil gradually becomes thinner and grain size becomes smaller as the distance is increased away from the intake. Also the process of soil salinization in the study area was indicated. However, the process of sodication was not found.

Since cotton cultivation has been practiced without significant loss of the yield after the operation of warp soil dressing at the study area, certain effects of the operation on sustainability in agricultural practice was confirmed. However, as drainage was not functioning sufficiently at the study area, the long-term effects of saline soil improvement using warp soil dressing were not observed. Therefore more appropriate management of drainage (groundwater) is essential to sustain the effect of the saline soil improvement after warp soil dressing.

7 Soil salinization in check dam farmland in the Loess Plateau

7.1 Introduction

The Loess Plateau is the largest silt deposition area in all over the world and is located in the middle reaches of the Yellow River Basin. It has an area of about 635,000 km^2 including some parts of Shanxi, Shaanxi, and Gansu, Qinghai, Ningxia, Inner Mongolia, Henan Province. Meanwhile, the ecological environment of the Loess Plateau is the most vulnerable area in China. The region is a core part of China, and it is the cradle of Chinese political, economical and cultural center in history. However, the main constraint is serious water loss and soil erosion due to fragile environment, shortage of arable land, lower grain yield, nature disasters and poverty in the region. The Loess Plateau by soil erosion is the source of flood calamity of the Yellow River by silt deposition. Therefore, the problem of soil erosion and water conservation has been paid great attention in the Loess Plateau, China (Xu *et al.*, 2002; Jia *et al.*, 2002).

In north central China, soil erosion, flooding, and desertification have all become more severe, not only causing ecological damage but also posing a threat to economic growth and ecological security. However, check dam project was very effective for improving the local natural environment and living conditions, prevention soil erosion, and interception silt deposition. Therefore, check dam project is feasible and sustainable in the Loess Plateau. However, check dam farmland has serious problem of soil salinization, and its generating mechanism is still not clear in the Loess Plateau.

The previous study showed that in the farmland at the Caomao check dam in Zizhou County, Shaanxi province, China, the soil salinization is influenced by the groundwater level more than the soil texture. In the study area, I clarify that the situation of the soil salinization in the farmland of the Caomao check dam, and revealed the variation characteristics of the groundwater level and its cause (Iwabuchi *et al.*, 2010).

7.2 Materials and methods

7.2.1 Study area

The Caomao check dam is located at Xiaohegou of Zizhou County, Shaanxi Province, China. The climatic condition of the study area is semiarid climate zone, the annual average temperature is 9.3˚C and the annual precipitation is 427.5 mm. The Caomao check dam is a big one among check dam system with 48 m height, 220 m dike length, 6 m dike width, 53 km^2 catchments area (**Fig. 7-1**), and 8.49 million m^3 water storage capacity. The farmland area of check dam is 36 ha, the main plants are corn and sunflower which are the dry farming material. The special area which is 1.6 km away from the Caomao check dam is not used for agricultural production due to the most serious salinization of the soil.

Fig. 7-1 Location of Caomao check dam in Zizhou County, Shaanxi province, China

7.2.2 Field survey

To clarify the variation characteristics of the groundwater level in the study area, I installed a group of the rain collector for collecting the precipitation data and the water gauge with logger for observing the groundwater level in the local wells during in September 2009 and September 2010. **Fig. 7-2** showed the investigated wells and the installed position in the study area.

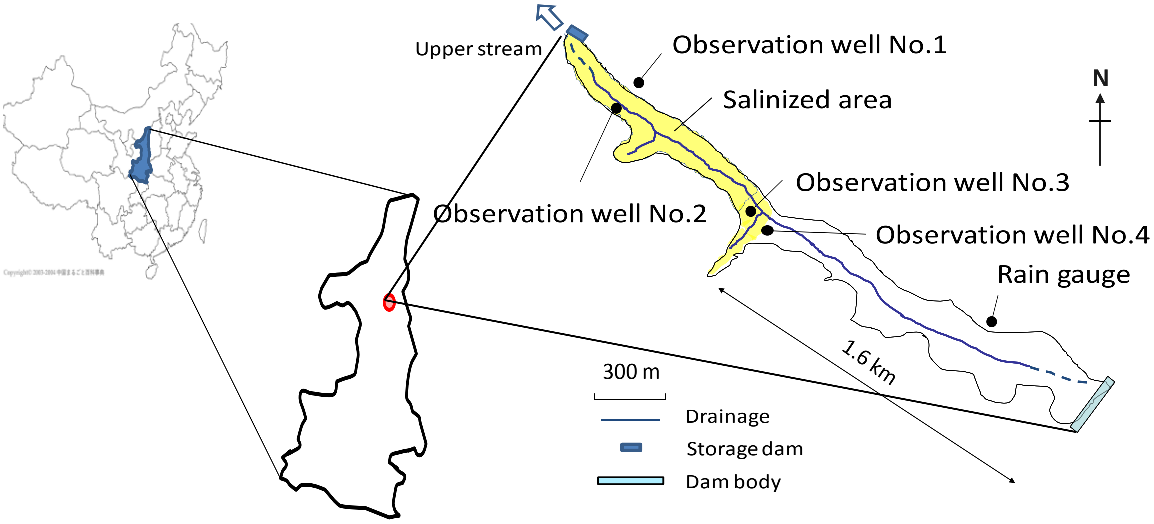


Fig. 7-2 Location of observation wells at the Caomao check dam of Zizhou County, Shaanxi province, China

To investigate the relationship between the salt accumulation and seasonal variation in the study area. The special area is located at 1.6 km upstream from check dam body. The topsoil was sampled at 40 points around the border line between abandoned land and cultivated land, which is 1.9−1.3 km upstream of check dam were collected and investigated (**Fig. 7-3**). The soil samples were measured for the electrical conductivity (ECe) by the saturated extracted liquid in the laboratory. After this, according to the variation characteristics of groundwater level and the results of soil analysis, I can find the cause of the salt accumulation.

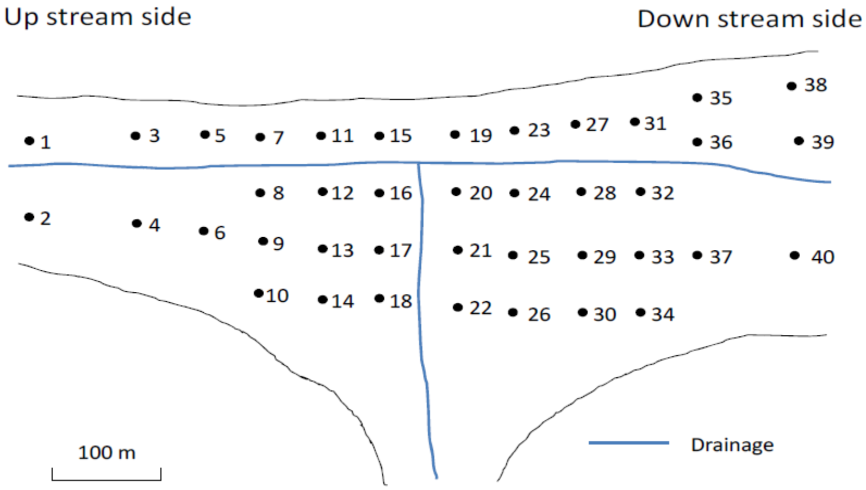


Fig. 7-3 Location of soil samples in the study area

7.3 Results and discussion

7.3.1 Variation characteristics of groundwater level

Fig. 7-4 showed the precipitation between September 2009 and September 2010, groundwater level and temperature change at the Caomao check dam in the study area. The data of precipitation was collected by rain collector between 7 September 2009 and 13 December 2009 and by record of local meteorological observatory between 14 December 2009 and 30 April 2010. In addition, the data of precipitation after 1 May 2010 was lacked. The lacking data of groundwater level was due to the fluctuation of groundwater level lower the measure range of water gauge. The measure of observation Well No 4 was started from 5 June 2010.

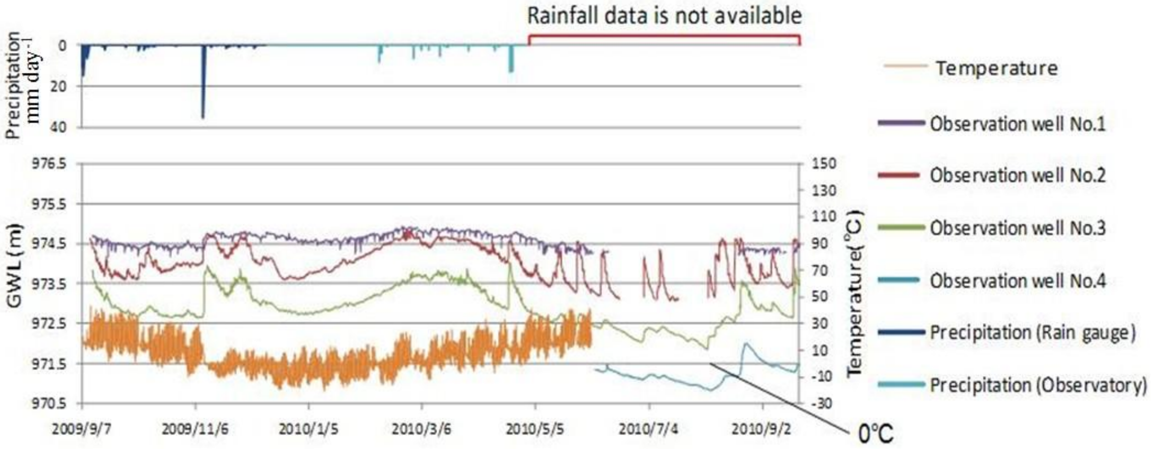


Fig. 7-4 Fluctuations of groundwater level, precipitation, and temperature

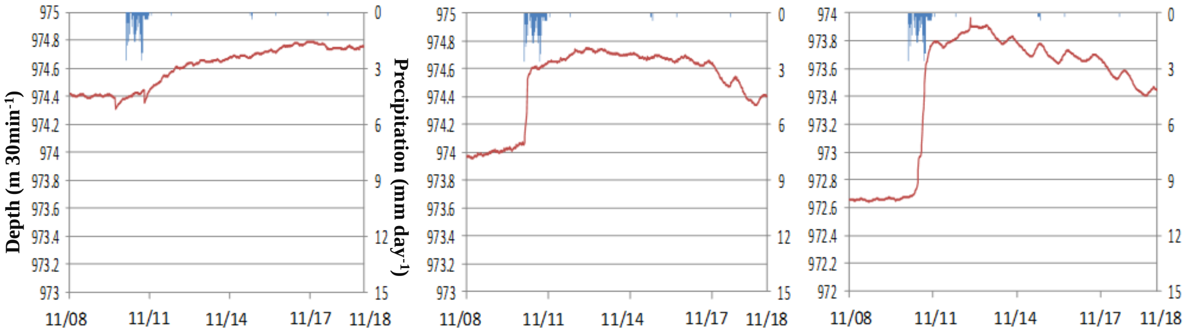
7.3.1.1 Characteristics of groundwater level and seasonal variation

As shown in **Fig. 7-4**, when the lowest temperature closed to −20˚C during late December 2009, the groundwater level has the tendency to rise. Also, when the temperature was above 0˚C, the groundwater level showed the tendency to decline. This phenomenon shown that the low temperature in winter, the topsoil became freezing, so the soil around the drainage canal was frozen. These causes the unfrozen groundwater cannot drain and raise of groundwater level. Afterwards when the spring came, the frozen soil around the drainage canal started to melt with the rise of temperature, so the groundwater level showed the tendency to decline. In addition, the rainy season between May and

September, 2010 causes the raise and decline of groundwater level frequently. About this phenomenon, due to the lacking data of precipitation, I hope to collect more detail data especially in rainy season in the future.

On the other hand, the fluctuation of groundwater level in short term was investigated. In 10 November 2009, the precipitation was 35.4 mm d^{-1}. The relation of groundwater level and precipitation of every 30 minutes at the rainfall event was showed in **Fig. 7-5**. To reach the peak of groundwater level, observation Well No 1 needed 164.5 hours, Well No 2 needed 55.0 hours and Well No 3 needed 53 hours. Also, the groundwater level of Well No 1 raised 0.40 m, Well No 2 raised 0.67 m and Well No 3 raised 1.29 m. In the observation Well No 2 and 3, the groundwater level almost raised to ground surface. According to these data, I can know in check dam farmland, the groundwater level reach to ground surface needs about 2 days when meeting the heavy rain. Furthermore, Well No 1 which slow raise of groundwater level, the reason may be due to the depth is 13 m from ground surface to groundwater level which substantially increases the time of groundwater level reaching to ground surface.

From above analysis, I can conclude that the raise of groundwater level in the farmland of Caomao check dam caused by the precipitation which is influenced by vertical infiltration from surface to groundwater. In Well No 2 located at upper stream and Well No 3 at downstream, the groundwater level raised simultaneously during raining. The results have the very big relationship with the surface runoff from the lateral slope in the farmland of Caomao check dam.



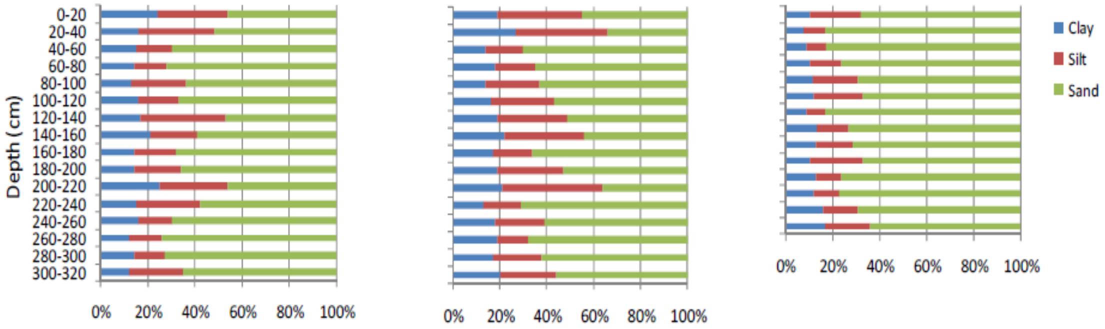
(a) Well No. 1 (a) Well No. 2 (a) Well No. 3

Fig. 7-5 Fluctuations of groundwater level and precipitation for each well

7.3.1.2 Characteristics of groundwater level and spatiality

As seen from **Fig. 7-4**, the precipitation data after 1 May 2010 was lacked, but I found that the temporary raise of groundwater level is related with precipitation. In Wells No 2, 3, and 4, the difference of groundwater level was observed. Among them, the change amount of groundwater level in Well No 2 was bigger than Wells No 3 and 4. During 5–20 August 2010, In Well No 3 it rose 1.5 m while in Well No 3 rose 1.0 m. From this comparison, it was sure that the raise tendency of groundwater level in Well No 3 around abandoned land is higher than Well No 4 around cultivated land.

It's well known that the soil texture is one of main reasons causing the fluctuation of groundwater level. Comparison of grain size of soil between Wells No 3, 4 and Well No 1 was shown in **Fig. 7-6**. International rules were used for measure the grain size of soil. The grain size of soil in Well No 1 was much larger than in Wells No 3 and 4. (the soil texture in Well No 1 was the same with Well No 2.) So I can conclude that the variation of groundwater level corresponding to the precipitation is influenced by the soil texture of large-grained and high penetrability in Wells No 1 and 2. On the other hand, the soil texture of Wells No 3 and 4 has no large difference. So except the soil texture, the terrain is the main factor causing the easier rise of groundwater level in Well No 3 than Well No 4.

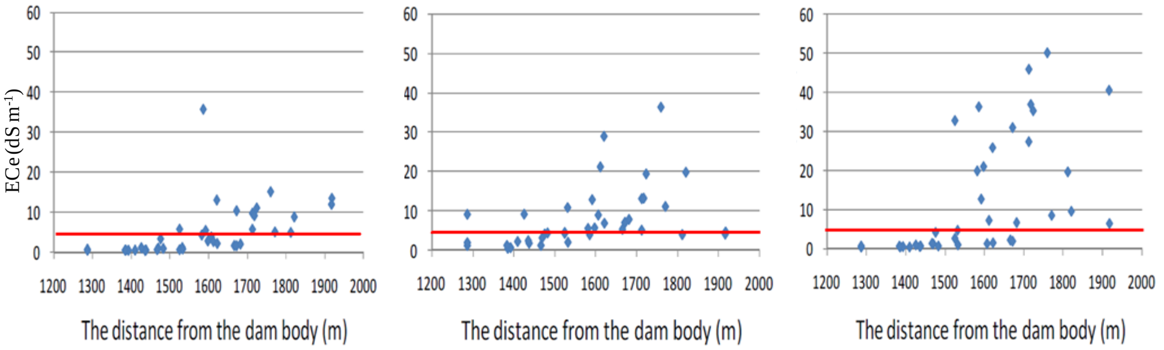


(a) Well No. 3 (b) Well No. 4 (c) Well No. 1

Fig. 7-6 Grain size distribution in the farmland of Caomao check dam

7.3.2 Soil salinization and seasonal variation

To investigate the accumulation situation of salt, the soil samples were analyzed. ECe of topsoil in March, June, and September 2010 (**Fig. 7-7)** and the soil samples collected sites away from dam body were shown in **Fig. 7-3**. The red line indicated the threshold limit value of soil salinization is 4 ds m^{-1}. The results showed that the value of ECe in the farmland of Caomao check dam within 1.6 km away from dam body was less than the threshold limit value of soil salinization in any month. But the value of ECe in the abandoned land which was 1.6 km away from dam body was always above the threshold limit value and showed the increasing tendency on June, September after March.



(a) Mar. 2010 (b) Jun. 2010 (c) Sep. 2010

Fig. 7-7 ECe values of the soil samples on ground surface

7.3.3 Mechanism of salinization

According to the fluctuations of groundwater level in the farmland of Caomao check dam at Zizhou County, Shaanxi province, China. The results show that the groundwater level raise in the winter and declines in spring, and the seasonal variation is influenced by temperature. Combined the variation characteristics of groundwater level with ECe of topsoil, I could consider the following mechanism:

First, in winter when the temperature is greatly lower than 0˚C, the soil around the drainage canal is frozen, and it causes the unfrozen groundwater cannot drain. So the groundwater level rises. Moreover, in spring when the temperature raises, the frozen soil starts to melt and the amount of evaporation increases with temperature. So the groundwater moves to topsoil by capillary water rise. Consequently, the salt is accumulated on the topsoil.

7.4 Conclusion

Using Caomao check dam in Zizhou County, Shaanxi Province, China, as the study area, I investigated the fluctuation of groundwater level and soil salinization in check dam farmland, and the results are concluded as following:

(1) The groundwater level is greatly influenced by precipitation. It is caused by infiltration of surface runoff from the lateral slope into groundwater in the farmland of Caomao check dam.

(2) The groundwater level has a tendency to rise in winter and to decline in spring. The tendency has close relationship with temperature. Consequently, the soil salinization is caused by the frozen soil start to melt, the amount of evaporation increase, and the high groundwater level.

(3) The process of soil salinization is mainly due to the frozen soil melt in spring which is frozen in winter, and high groundwater level combined with capillary water rise which is caused by the high amount of evaporation in summer.

8 Conclusions and recommendations

8.1 Conclusions

In this thesis the research conducted in two case studies are mainly presented. The first one discussed about the recharge source and movement of water and salt in the eastern block of the Luohui Irrigation District, China, and would find the best way to prevent salinization of soil. The second on discussed about the soil salinization in check dam farmland in the Loess Plateau, China.

With regard to the first case study, precipitation, Luo River water, groundwater and soil samples were collected at field in the eastern block of the Luohui Irrigation District located in Dali County, Shaanxi Province of China at latitude of 34°45'23" to 34°56'05" N and longitude 109°45'22" to 110°10'23" E. The irrigation district consists of about 60 groundwater wells, which serve as measurement points and used for agricultural and non-agricultural purposes. The measured field data at each groundwater well or around groundwater well were EC, MC, T, groundwater depth, surface elevation and geographic coordinates. Water samples from groundwater level (depth of 0 to 20 m) and soil samples from topsoil (depth of 0 to 400 cm) were also collected for laboratory analysis. Then major ion (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, HCO_3^{-}) and stable isotope (^{18}O, ^{2}H) of water and soil samples were measured using the chemical and stable isotope technology. All results were interrelated and analyzed. Consequently, the main conclusions were the following in this part:

(1) I established the local meteoric water line (LMWL) and the Luo River water line (LRWL), characterized by $\delta^2H = 7.71\delta^{18}O + 3.71$ and $\delta^2H = 4.34\delta^{18}O - 42.61$, respectively; In summer, the influence of groundwater level on the recharge source is very significant: GD < 3 m, all the recharge source of groundwater come from rainwater except the Well 45

which come from deep groundwater; GD > 3m, mainly received the irrigation water from Luo River that infiltrated into groundwater by canal system and field irrigation; meanwhile, isotopic enrichment of the groundwater in the shallow due to the evaporation processes is very strong. On the other hand, in winter, the recharge source of groundwater was mainly controlled by the terraces: most of wells in the third terrace and the second terrace were recharged by irrigation water from Luo River, apart from Wells 89, 35, 53', and 17 from precipitation; but in the first terrace, the groundwater recharge was mainly from deep groundwater except Wells 14, 36, and 57 from Luo River water; furthermore, $\delta^{18}O$ and $\delta^{2}H$ isotopes of groundwater in the study area have spatial characteristics, which isotopic enrichment of groundwater from the first terrace to the third terrace along with the groundwater flow direction is gradually increasing. Meanwhile, the $\delta^{18}O$ and $\delta^{2}H$ isotopes of groundwater in the study area had the obvious seasonal variation characteristic, and have received certain evaporation effects when the groundwater accepted recharge from precipitation and the Luo River. Finally, I used two-component mixing model based on mass balance, groundwater was isotopically separated in to precipitation and Luo River water. The results which using only oxygen isotope shown that, in summer, the mean percentage of Luo River water in groundwater is evaluated at 93.0% using the average $\delta^{18}O$ value of 29 groundwater samples, apart from Well 45; in winter, the mean percentage of the Luo River water in groundwater is evaluated at 98.1%, and precipitation to groundwater is 1.9%.

(2) The chemical type in the eastern block of the Luohui Irrigation District is relatively single and mainly $Cl^{-}\cdot SO_4^{2-}-Na^{+}$, followed by $Cl^{-}\cdot SO_4^{2-}-Na^{+}\cdot Mg^{2+}$. And the chemical characteristics of Na^{+}, Mg^{2+}, SO_4^{2-} are linear with Cl^{-} in groundwater. The result shows that the source of salt is the same.

According to the contents of Cl^{-}, SO_4^{2-}, and EC of groundwater grown as the depth from the groundwater level increased, and the concentrations abruptly rose in 15 m from the groundwater level. In contrast, the contents of NO_3^{-} of groundwater decreased as the depth, and the concentration abruptly declined in 15 m. The results show that the salt of groundwater come from the deep groundwater (below 15 m depth from the groundwater level) because the bottom of the Luohui Irrigation District has the massive soluble salts at 40−50 m in depth from ground surface. The evaporation condensation effect isn’t the control elements of chemical characteristics formation of groundwater in the saturation zone, but the brine invasion from the deep groundwater and human activity is the main formation reason.

Afterwards, I used the chemical and stable isotopes (^{18}O, ^{2}H) characteristics of groundwater (Depth > 15 m from groundwater level) of Well 34 in the Luohui Irrigation District to get the deep groundwater water line (DGWL) and expressed as follow: $\delta^2H = 1.04\delta^{18}O - 97.21$. Meanwhile, combine the LMWL and the LRWL with the two-component mixing model based on the water and tracer mass balance, I calculated the proportion of recharge source in groundwater for each well.

(3) Using the high speed refrigerated centrifuge is one of the most effective methods for taking soil water from soil samples and providing feasible water samples when the soil moisture content > 20% for making stable isotope analysis. According to the chemical and stable isotope (^{18}O, ^{2}H) characteristics of soil water, the results show that the soil water in depth (depth ≤ 100 cm) from ground surface is strongly dependent on those values of precipitation and isotopically enriched by evaporation effect.

In Well 33, the salinity from the soil water stays temporarily in 100 cm and 200 cm. The sources of salinity were not same and might come from the groundwater through capillary water rise and Luo River water (irrigation water) through infiltration. However, the proportion of recharge at 300 cm in depth of Well 33 is 33.2% for groundwater, and 66.8% for Luo River water. Due to the groundwater move 2−2.5 m in vertical depth by capillary water rise, the soil water from 100 cm to 250 cm in depth is mainly composed of Luo River water and precipitation.

In Well 15, the salt from the soil water stays temporarily in 200 cm and 300 cm. The sources of salinity were same and might come from Luo River water (irrigation water) which such practice in longer period of time causes for accumulation of salinity in the soil. By comparing soil water isotope composition between 100 cm and 400 cm in depth, it indicates that the soil water main composition is Luo River water and precipitation. And the soil water originated from precipitation during the infiltration effect declines up to 300 cm in depth, but the soil water below a depth of 300 cm main composition is only Luo River water.

(4) Warp soil dressing can improve soil from salinization, and is introduced as one of measures against the problem. I observed and found the thickness of dressed soil is

approximately 36 cm, and the thickness of dressed soil gradually becomes thinner and grain size becomes smaller as the distance is increased away from the intake. Also the process of soil salinization in the study area was indicated. However, the process of sodication was not found.

Since cotton cultivation has been practiced without significant loss of the yield after the operation of warp soil dressing at the study area, certain effects of the operation on sustainability in agricultural practice was confirmed. However, as drainage was not functioning sufficiently at the study area, the long-term effects of saline soil improvement using warp soil dressing were not observed. Therefore more appropriate management of drainage (groundwater) is essential to sustain the effect of the saline soil improvement after warp soil dressing.

With regard to the second case study, soil samples were collected at field in Caomao check dam of Zizhou County, Shaanxi Province, China. The topsoil in Caomao check dam was sampled at 40 points around the border line between abandoned land and cultivated land, which is 1.9−1.3 km upstream of check dam were collected and investigated. The soil samples were measured for the electrical conductivity (ECe) by the saturated extracted liquid in the laboratory. Then major ion (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) of water samples from soil were measured using the chemical analysis. Moreover, I installed a group of the rain collector for collecting the precipitation data and the water gauge with logger for observing the groundwater level in the local wells during in September 2009 and September 2010. All results were interrelated and analyzed. Consequently, the main conclusions were the following in this part:

(1) The groundwater level is greatly influenced by precipitation. It is caused by infiltration and the lateral runoff from slope into groundwater in the farmland of Caomao check dam.

(2) The groundwater level has a tendency to rise in winter and to decline in spring. The tendency has close relationship with temperature. Consequently, the soil salinization is caused by the frozen soil start to melt, the amount of evaporation increase, and the high groundwater level.

(3) The process of soil salinization is mainly due to the frozen soil melt in spring which

is frozen in winter, and high groundwater level combined with capillary water rise which is caused by the high amount of evaporation in summer.

8.2 Recommendations

8.2.1 Luohui Irrigation District

(1) Lowering the groundwater depth by installing effective drainage canal which the design of canal depth must be more than 3 m.

(2) Controlling exploitation groundwater or reducing pumping time for irrigation in the fields and managing the use of saline irrigation water.

(3) Improving the irrigation and drainage structures especial the east area in the Luohui Irrigation District and avoiding the deep groundwater (depth more than 15 m from the groundwater level) moving up.

(4) Continuing to collect water and soil samples for stable isotope (^{18}O, ^{2}H) analysis in order to the further study and finding the salt in the Luohui Irrigation District where it is stay.

(5) Using the stable isotope (^{13}C) technology to analyze the relationship between the plants and the soil salinization, then breeding salt-tolerant plants

(6) Warp soil dressing is an effective measure by comprehensively improving the soil texture and preventing the soil salinization. The use of the technology and promotion is required to promising.

(7) In the future research, I hope to further clarify the relationship between the groundwater level and desalination effect, and continues to observe the desalination effect by warp soil dressing.

8.2.2 Caomao check dam

Due to the main cause of the groundwater level rise in the farmland of Caomao check dam is infiltration of surface runoff from the lateral slope into groundwater in summer. The following suggestions are forwarded:

(1) The most efficient way to decline the groundwater level is to build drainage canal around check dam farmland. Also, it is necessary to take some strategy to control the high groundwater level in winter.

(2) In the future research, I hope to further investigate the infiltration capacity of surface runoff from the lateral slope at the Caomao check dam, which mainly causes the rise of groundwater level, and continues to observe the groundwater level to clarify the relationship between precipitation in rainy season and the groundwater level variation.

Reference

Allison, G.B., Barnes, C.J., Hughes, M.W. and Leaney, F.W.J. (1984): Effect of climate and vegetation on oxygen-18 and deuterium profiles in soils. *Isotope Hydrology, IAEA, Vienna,* 105-122.

Andrew, E.M., Blair, O.W. and Carlos, M.R. (2004): Deuterium stable isotope ratios as tracers of water resource use: an experimental test with rock doves. *Oecologia*, 140(2): 191-200.

Appelo, C.A.J. and Postma, D. (1993): *Geochemistry, groundwater and pollution*. Rotterdam: A. A. Balkema Publisher.

Banoeng-Yakubo, B., Yidana, S.M. and Nti, E. (2009): an evaluation of the genesis and suitability of groundwater for irrigation in the Volta Region, Ghana. *Environmental Geology*, 57: 1005-1010.

Barnes, C.J. and Allison, G.B. (1988): Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. *Journal of hydrology,* 100: 143-176.

Bohn, H., Mcneal, B. and O’Connor, G. (1985): *Soil chemistry*. John Wiley & Sons, Inc., 2nd edition.

Bouchaou, L., Michelot, J.L., Qurtobi, M., Zine, N., Gaye, C.B., Aggarwal, P.K., Marah, H., Zerouali, A., Taleb, H. and Vengosh, A. (2009): Origin and residence time of groundwater in the Tadla basin using multiple isotopic and geochemical tools. *Journal of Hydrology*, 379: 323-338.

Cheikh, B.G. (2001): Isotope techniques for monitoring groundwater salinization. *Hydrogeology Journal,* 9: 217-218.

Chen, H.S., Shao, M.G. and Li, Y.Y. (2007): Soil desiccation in the Loess Plateau of China. *Geoderma*, 143: 91-100.

Chen, J.Y., Tang, C.Y. and Yu, J.J. (2006): Use of ^{18}O, ^{2}H and ^{15}N to identify nitrate contamination of groundwater in a wastewater irrigated field near the city of Shijiazhuang, China. *Journal of Hydrology*, 326 (1-4).

Craig, H. (1961): Isotopic variations in meteoric waters. *Science*, 133: 1702-1703.

Carol, E., Kruse, E. and Mas-Pla, J. (2009): Hydrochemical and isotopical evidence of ground water salinization processes on the coastal plain of Samborombon Bay, Argentina. *Journal of Hydrology*, 365: 335-345.

Criss, R.E. and Davisson, M.L. (1996): Isotopic imaging of surface water/groundwater interactions, Sacramento Vally, California. *Journal of Hydrology*, 178: 205-222.

Cui, Y.Q., Ma, J.Y. and Sun, W. (2011): Application of stable isotope techniques to the study of soil salinization. *Journal of Arid Land*, 3(4): 285-291.

Davisson, M.L. and Criss, R.E. (1993): Stable isotope imaging of a dynamic groundwater system in the southwestern Sacramento Valley, California, USA. *Journal of Hydrology*, 144: 213-246.

Dochartaigh, B.E., Macdonald, A.M., Darling, W.G., Hughes, A.G., Li, J.X. and Shi, L.A. (2010): Determining groundwater degradation from irrigation in desert-marginal northern China. *Hydrogeology Journal*, 18: 1939-1952.

Du, Z. (2009): *Tracing groundwater and salt transport and health evaluation in Luohui irrigation district*. Xi’an University of Technology, 75p. (In Chinese).

Du, Z., Li, Z.B., Li, P., Ning, Y.F., Lu, K.X., Zou, B.H., Yu, G.Q., Zhang, X. and Liu, H.B. (2008): Study on the transfer of groundwater and salt by stable isotope in Luohui irrigation district. *Acta Agriculturae Boreali-occidentalis Sinica*, 17(6): 343-347. (In Chinese).

Duan, L. and Wang, W.K. (2006): Water isotope technology for tracing groundwater movement. Ground Water, 28(2): 33-36. (In Chinese).

Gonfiantini, R., Dincer, T. and Derekoy, A.M. (1974): Isotope hydrology in the Hodna region, Algeria. *Isotope Techniques in Groundwater Hydrology*, 1: 293-316.

Graves, G.R. and Romanek, C.S. (2009): Mesoscale patterns of altitudinal tenancy in migratory wood warblers inferred from stable carbon isotopes. *Ecological Applications*, 19(5): 1264–1273.

Guo, Y.P. (2009): *Study on the modern technology of warping irrigation in Guanzhong Area*. Shaanxi Normal University, 66p. (In Chinese).

Harvey, F.E. and Sibray, S.S. (2001): Delineating ground water recharge from Leaking irrigation canals using water chemistry and isotopes. *Ground water,* 39(3): 408-421.

Howard, K.W.F. and Mullings, E. (1996): Hydrochemical analysis of ground-water flow and saline incursion in the Clarendon Basin, Jamaica. *Ground Water*, 34(5): 801-810.

Hsieh, J.C.C., Chadwick, O.A., Kelly, E.F. and Savin, S.M. (1998): Oxygen isotopic composition of soil water: quantifying evaporation and transpiration. *Geoderma*，82: 269-293.

Hu, C.H., Wu, D.Y., Jayakumar, R. and Shingo, A. (2004): Warping dams – Construction and its effects on environment, economy, and society in Loess Plateau region of China. *International Hydrological Programme (IHP), UNESCO Office Beijing&The International Research and Training Center on Erosion and Sedimentation (IRTCES), Beijing*, 32p.

Iwabuchi, N., Tojo, M., Kitamura, Y. and Shimizu, K. (2010): A study on the actual condition of soil salinization in the check dam farmland in Loess Plateau, China. *Proceedings of 65th The Japanese Society of Irrigation, Drainage and Rural Engineering Conference.*

Japanese Society of Pedology (1997): Soil profile survey Hand book. Hakuyu-sha, 51-56, 72-75.

Jia, Z.X., Wang, D.X. and Wang, B. (2002): Effect Analysis of Soil Erosion Prevention of the Loess Plateau on Developing and Utilizing Water Resources. *Proceedings of 12th ISCO Conference*, 2: 425-428.

Junge, C.E. and Werby, R.T. (1958): The Concentration of chloride, sodium, potassium, calium and sulfate in rain water over the United States. *J. Meteor*, 15:417-425.

Kattan, K. (2008): Estimation of evaporation and irrigation return flow in arid zones using stable isotope ratios and chloride mass-balance analysis: Case of the Euphrates River, Syria. *Journal of Arid Environments*, 72: 730-747.

Kohfahl, C., Sprenger, C., Herrera, J.B., Meyer, H., Franzisca, F.C. and Pekdeger, A. (2008): Recharge sources and hydrochemical evolution of groundwater in semiarid and karstic environments: A field study in the Granada Basin. *Applied Geochemistry*, 23: 846-862.

Levy, R. (1984): *Chemistry of irrigated soils*. Benchmark papers in Soil Science, Van Nostrand Reinhold Company Inc., 2, 418p.

Li, D.M. (1995): *Luo hui qu zhi*. Shaanxi people's publishing company, 378p. (In Chinese).

Li, F.D., Song, X.F., Tang, C.Y., Liu, C.M., Yu, J.J. and Zhang, W.J. (2007): Tracing infiltration recharge using stable isotope in Taihang Mt., North China. *Environmental Geology*, 53: 687-696.

Li, Q.S., Wu, L.Z. and Liu, C.J. (2006): Amelioration model of medium saline—alkali soil by leaching with mildly saline groundwater. *Agricultural Research in the Arid Areas,* 24(4): 164–167.

Li, L. (2008): Study on the Transport of Soil Water and Salt between Irrigation Land and Saline Land in Hetao Irrgation District. Inner Mongolia Agricultural University, 95p. (In Chinese).

Li, X.Q., Hou, X.W., Zhang, H.D. and Zhang, L. (2006): Study on the Geochemistry-isotope Characteristics of the Groundwater Systems in Taiyuan Basin. *Journal of Arid Land Resources and Environment*, 20(5): 109-114.

Lin, G.H. (2010): Stable isotope ecology: a new branch of ecology resulted from technology advances. *Chinese Journal of Plant Ecology*, 34(2): 119–122.

Lin, X.B. (2007): *Study on the groundwater environmental isotopes in the Hangjiahu Region*. Chinese Academy of Geological Sciences, 66p. (In Chinese).

Liu, G.C., Chen, H., Han, M. and Song, T. (2007): Features of hydrogen and oxygen isotopes in groundwater of irrigation area of Luanjing, Inner Mongolia. *China Water Transport*, 5(5): 118-120. (In Chinese).

Lu, Y.T., Tang, C.Y., Chen, J.Y., Song, X.F., Li, F.D. and Sakura, Y. (2008): Spatial characteristics of water quality, stable isotopes and tritium associated with groundwater flow in the Hutuo River alluvial fan plain of the North China Plain. *Hydrogeology Journal*, 16: 1003-1015.

Melayah, A., Bruckler, L. and Bariac, T. (1996): Modelling the transport of water stable isotopes in unsaturated soils under natural conditions. *Water Resour*, 32: 2047-2054.

Moore, S.J., Bassett, R.L., Liu, B.L., Wolf, C.P. and Doremus, D. (2008): Geochemical tracers to evaluate hydrogeologic controls on river salinization. *Ground water*, 46(3): 489-501.

Northey, J.E., Christen, E.W., Ayars, J.E. and Jankowski, J. (2006): Occurrence and measurement of salinity stratification in shallow groundwater in the Murrumbidgee irrigation area, south-eastern Australia. *Agricultural Water Management*, 81: 23-40.

Peace, A.J., Stewart, M.K. and Sklash, M.G. (1986): Storm runoff generation in humid headwater catchments, 1, where does the water come from? *Water Resources Research*, 22: 1263-1271.

Tang, C., Chen, J., Shindo, S., Sakura, Y., Zhang, W. and Shen, Y. (2004): Assessment of groundwater contamination by nitrates associated with wastewater irrigation: a case study in Shijiazhuang region, China. *Hydrological Processes*, 18: 2303-2312.

Sharma, P. and Gupta, S.K. (1985): Soil water movement in semi-arid climate-an isotope investigation. *IAEA*, 357: 55-69.

Solomon, H., Kitamura, Y., Li, Z.B., Yamamoto, S., Li, S.Y., Li, P., Abou, E.W. and Otagaki, K. (2005): Classification of salinization processes in Luohui irrigation district, China. *Journal of Arid Land Studies*, 15(2): 89-105.

Song, X.M., Gao, C.P., Basher, H.M. and Yang, Y.S. (2010): analysis on the hydrochemical characteristics of groundwater and the formation reason in Wadi Bay area of Libya. *Agricultural Science & Technology*, 11(11-12): 28-32.

USDA. (1954): *Diagnosis and improvement of Saline and Alkali Soils*. Agriculture Hand book, 60: 29-30.

Vimeux, F., Masson, V., Jouzel, J., Petit, J.R., Steig, E.J., Stievenard, M., Vaikmae, R. and White, J.W.C. (2001): Holocene hydrological cycle changes in the Southern Hemisphere documented in East Antarctic deuterium excess records. *Climate Dynamics*, 17(7): 503-513.

Wu, P., Tang, C.Y., Zhu, L.J., Liu, C.Q., Cha, X.F. and Tao, X.Z. (2009): Hydrogeochemical characteristics of surface water and groundwater in the karst basin, southwest China. *Hydrological Processes*, 23: 2012-2022.

Xu, S.G., Liu, Y.F. and Sun, W.G. (2006): Research on the stable isotope for soil water vertical transporting in unsaturated zone of Zhalong Wetland. *Journal of China Hydrology*, 26(5): 1-6. (In Chinese).

Xu, X.Z., Zhang, H.W., Feng, S.X., Dong, Z.D. and Gan, Z.G. (2002): Check dam System in Gullies--The Most Effective Measure to Conserve Soil and Water in Chinese Loess Plateau. *Proceedings of 12th ISCO Conference*, 2: 503-509.

Yamanaka, M. and Kumagai, Y. (2006): Sulfur isotope constraint on the provenance of salinity in a confined aquifer system of the southweatern Nobi Plain, central Japan. *Journal of Hydrology*, 325: 35-5.

Yamanaka, T. and Shimizu, R. (2007): Spatial distribution of deuterium in atmospheric water vapor: Diagnosing sources and the mixing of atmospheric moisture. *Geochimica et Cosmochimica Acta*, 71: 3162-3169.

Yidana, S.M. and Yidana, A. (2010): An assessment of the origin and variation of groundwater salinity in southeastern Ghana. *Environmental Earth Science*, 61: 1259-1273.

Yu, M. and Rui, X.F. (2007): Study on integrated management model of groundwater and surface water for prevention of soil salinization. *Water Resources Protection*, 23(4): 6–9.

Yu, S.P., Yang, J.S. and Yang, X.Y. (2009): Impacts of different adjustment measures on quality dynamics of crop and soil in salinization blocked farm land in Huang-Huai-Hai Plain. *Journal of Arid Land Resources and Environment*, 23(8): 150–154.

Zhang, B.Y. (2008): *Study on Dynamic of Soil Water under Different Landuses in Small Watershed of Loess Hilly Region*. University of Chinese Academy of Sciences, 136p. (In Chinese).

Zhang, X. (2007): *Study on rules of groundwater and salt dynamic change in Luohui canal irrigation district*. Xi'an University of Technology, 63p. (In Chinese).

Zhang, X., Li, Z.B. and Li, P. (2007): Investigation on dynamical rules of groundwater in Luohui trench irrigation district. *Journal of Northwest A & F University*, 35(8): 223-226. (In Chinese).

Zhang, Y.H. and Wu, Y.Q. (2009): Analysis of groundwater replenishment in the middle reaches of Heihe River. *Journal of Desert Research*, 29(2): 370-375. (In Chinese).

Zhang, Y.H., Song, X.F. and Wu, Y.Q. (2009): Use of oxygen-18 isotope to quantify flows in the upriver and middle reaches of the Heihe River, Northwestern China. *Environmental Geology*, 58: 645-653.

Zimmerman, U., Ehhalt, D. and Münnich, K.O. (1967): Soil-water movement and evapotranspiration: changes in the isotopic composition of the water. *Proc. IAEA Symp. Isotopes Hydrol*, 567-585.

Zuppi, G.M., Fontes, J.Ch. and Letolle, R. (1974): Isotopes du milieu et circulaton d'eaux sulfurée dans le LATIUM - Isotope techniques in groundwater hydrology. *IAEA*, 1: 341-361.

List of Publications

Major Publications

1. Li Hong, Kitamura Yoshinobu, Shimizu Katsuyuki, and Ichiro Kita (2012): Identification of Recharge Sources and Groundwater Movement in a Semiarid Region by Stable Isotope Analysis: A Case Study in the Eastern Block of the Luohui Irrigation District, China. *Journal of Arid Land Studies*, 21(4), 181-189

2. Li Hong, Shimizu Katsuyuki, Kitamura Yoshinobu, and Tojo Masayuki (2012): Soil Salinization and Groundwater Level Fluctuation of a Check-dam Farmland. *Water, Land and Environmental Engineering*, 80(2), 87-90

Sub-Publications

1. Kitamura Yoshinobu, Li Hong, Shimizu Katsuyuki, and Tojo Masayuki (2012): Salination of Farmlands and Its Remedial Measures in the Lower Basin of Loess Plateau, China. *Water, Land and Environmental Engineering*, 80(2), 95-98

Summary of the doctoral thesis

In this thesis the research conducted in two case studies are mainly presented. The first one discussed about the recharge source and movement of water and salt by the chemical analysis and stable isotope technology in the eastern block of the Luohui Irrigation District, China, and would find the best way to prevent soil salinization. The second one discussed about the soil salinization by soil texture and chemical analysis in check dam farmland in the Loess Plateau, China. This research laid a scientific foundation for studying salt and water movement, preventing salinization and allocating the utilization of canal systems and wells for reasonable water resources management.

The source and movement regularity of water and salt in the eastern block of the Luohui Irrigation District (32,000 ha) of the Loess plateau, China, have been studied, with an emphasis on relating geographical characteristics (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, HCO_3^{-}) and stable isotopes factors ($\delta^{18}O$, $\delta^{2}H$). Subsequently, I evaluated the sustainability and effects of saline soil improvement by warp soil dressing. The followings were some main results of our study:

(1) I established the local meteoric water line (LMWL) and the Luo River water line (LRWL). In summer, the recharge source of groundwater was mainly controlled by the groundwater depth (vertical distance between ground surface and groundwater level; GD): GD < 3m, the recharge source of groundwater come mainly from precipitation, but GD > 3m, mainly received the irrigation water from Luo River; In winter, the recharge source of groundwater was mainly controlled by the existence of fluvial terraces: in the third terrace and the second terrace, the recharge source of groundwater was mainly from Luo River water, but in the area of the first terrace come mainly from deep groundwater which was isotopic depletion. Moreover, the $\delta^{18}O$ and $\delta^{2}H$ isotopes of groundwater in the study area

had obvious seasonal variation characteristics, and had received certain evaporation effects when the groundwater accepted recharge from precipitation and the Luo River. Finally, I used a two-component separation model based on the water and tracer (oxygen isotope) mass balance to determine the relative contribution of precipitation and Luo River water to groundwater.

(2) The chemical type of groundwater in the eastern block of the Luohui Irrigation District was relatively single and mainly $Cl^- \cdot SO_4^{2-}–Na^+$, then was $Cl^- \cdot SO_4^{2-}–Na^+ \cdot Mg^{2+}$. According to the relationship between the chemical characteristics of groundwater and the depth, I found the salt of groundwater come from the deep groundwater (below 15 m depth from the groundwater level) because the bottom of the Luohui Irrigation District has the massive soluble salts at 40–50 m in depth from ground surface. The effect of evaporation and condensation was not the control elements of chemical characteristics formation of groundwater in the saturation zone, but the brine invasion from the deep groundwater and human activity was the main reason for the formation. Subsequently, I used the chemical and stable isotope ($\delta^{18}O$, δ^2H) characteristics of groundwater (Depth > 15 m depth from groundwater level) in the Luohui Irrigation District to get the deep groundwater water line (DGWL). Meanwhile, combining the LMWL and the LRWL with the two-component separation model, I calculated the proportion of recharge source in groundwater for each well.

(3) I taken some soil water from soil samples by the high speed refrigerated centrifuge when the moisture content of soil sample > 20%. According to the chemical and stable isotope ($\delta^{18}O$, δ^2H) characteristics of soil water, the stable isotope of the soil water in depth (depth ≤ 100 cm) from ground surface was enriched by evaporation effect. In the shallow depth (depth ≤ 5 m), the salinity from the soil water stay temporarily in soil layers between 100 and 200 cm. Meanwhile, the soil water above 300 cm in depth was composed of precipitation and Luo River water, the sources of salinity come from Luo River water (irrigation water) through infiltration. However, soil water below 300 cm was composed of groundwater and Luo River water, the sources of salinity mainly come from the groundwater through capillary water rise. In the deep depth (depth ≥ 5 m), the salinity from the soil water stays temporarily at 200 and 300 cm. The sources of salinity might come from Luo River water (irrigation water) which such practice in longer period of time causes for accumulation of salinity in the soil. The soil water below 300 cm was only Luo River water. Finally, according to the two-component mixing model, I calculated the

composition of the soil water.

(4) The warp soil dressing was an effective method to rehabilitate saline land and improve soil chemical and physical properties from salinization. It not only could effectively prevent soil salinization, but also formed the cultivated land. Consequently, the short-term effect of saline soil improvement using warp soil dressing was feasible, but not sustainable.

Using Caomao check dam in Zizhou County, Shaanxi Province, China, as the study area, I investigated the fluctuation of groundwater level and soil salinization in check dam farmland, and the results are concluded as following:

(1) The groundwater level is greatly influenced by precipitation. It is caused by infiltration of surface runoff from the lateral slope into groundwater in the farmland of Caomao check dam.

(2) The groundwater level has a tendency to rise in winter and to decline in spring. The tendency has close relationship with temperature. Consequently, the soil salinization is caused by the frozen soil start to melt, the amount of evaporation increase, and the high groundwater level.

(3) The process of soil salinization is mainly due to the frozen soil melt in spring which is frozen in winter, and high groundwater level combined with capillary water rise which is caused by the high amount of evaporation in summer.

学位論文要旨

本学位論文では、半乾燥地域の農地で問題となる塩類集積に焦点を当て、中国陝西省の黄土高原でこの問題に悩む２地区を対象に調査・試験研究を実施し、その詳細を論じた。まず、灌漑農地である洛恵渠灌区を対象に、土壌化学的分析と安定同位体分析を適用した地下水涵養源と土壌中における水・塩動態、土壌の塩性化を防ぐための方策について論じた。次いで、降雨依存農地である子洲県の曹峁（Caomao）チェックダム農地*を対象に、地下水変動の長期モニタリングおよび土性分析と土壌化学分析に基づき土壌の塩性化について論じた。

洛恵渠灌区洛東区（32,000ha）においては、水・塩の源とその動態について、化学特性（Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, HCO_3^{-}）と安定同位体（$\delta^{18}O$, $\delta^{2}H$）の関連性の解明に焦点を当てて研究を行った。主な研究成果は以下の通りである。

(1) 対象地域の天水および洛河の河川水の安定同位体（$\delta^{18}O$ と $\delta^{2}H$）の関係式である天水線（LMWL）と河水線（LRWL）を求めた。夏季の地下水涵養源は主に地下水位によって決まる。地下水位（地表面からの垂直距離）が３m以下と高い場合、地下水涵養源は主に雨水であり、^{18}O と ^{2}H の安定同位体を多く含むのは蒸発の影響と考えられる。地下水位が３m以上と深い場合には、洛河から取水した灌漑水が主な地下水涵養源である。冬季の地下水涵養源は主に河成段丘の存在によって決まる。低位・中位段丘では、地下水涵養源は主に洛河の水であり、高位段丘では主に同位体減損の進んだ深い地下水である。対象地域の地下水の安定同位体は、雨水や河川水などの涵養源と蒸発の影響により、明瞭な季節変動特性を有する。水収支と物質収支に基づき、地下水中に占める洛河の水と雨水の割合を試算した。

(2)対象地域の地下水の化学形態は、比較的単純で主に Cl^{-}・SO_4^{2-}－Na^{+}、次いで

Cl^-・SO_4^{2-}－Na^+・Mg^{2+} である。また、地下水中の塩は深部（地下水面から 15m以下）の地下水に由来し、それは地表面から 40－50m深付近に存在する可溶性塩類の集積層によることを明らかにした。さらに、地下水面から 15m以深の地下水の化学特性と安定同位体（$\delta^{18}O$ と δ^2H）の特徴を用いて、深層地下水の $\delta^{18}O$ と δ^2H の関係式である深層地下水線（DGWL）を求めた。加えて、２つの安定同位体の分離モデルに LMWL と LRWL を結合させせて、各井戸の地下水の涵養源の割合を算定した。

(3)土壌水の化学特性と安定同位体（$\delta^{18}O$ と δ^2H）の特徴から、地表面から１m以浅の土壌水の安定同位体は蒸発効果により濃縮されていること、５m深までの浅い層では、土壌水の塩類は一時的に１、２m周辺に留まることが分かった。一方、３m以浅の土壌水は、降水と洛河の水で構成され、塩類は洛河の水（灌漑水）に由来し、浸透を通して集積したものである。しかしながら、３m以深の土壌水は地下水と洛河の水からなり、塩類の源は主に毛管上昇した地下水である。５m以深では、土壌水の塩類は一時的に２、３、４m付近に留まる。土壌水の塩類は灌漑水に起因しており、長年にわたる灌漑の実施が土壌の塩性化の原因である。３m以深の土壌水の起源は、洛河の水だけである。２つの安定同位体の混合モデルにより、土壌水の涵養源の割合を算定した。

(4) 流水客土は塩性化した農地を修復し、その土壌の物理・化学特性を改善する上で、有効な方法である。この方法は、塩性化した農地を修復し塩類化を防ぐだけでなく、耕地の造成を可能にする。本研究では、流水客土による塩性化農地の改良効果について評価を行い、短期的効果は高いことを確認したが、長期的効果については確認できなかった。

曹峁チェックダム（36ha）においては、ダム農地の塩類集積状況と地下水位変動特性を分析し、以下の知見を得た。

(1)ダム農地上流部（堤体から 1.6 km 上流）では、塩類集積が起こり、土壌の塩類濃度は３月と比較して６月に、６月と比較して９月に高くなる傾向がみられた。

(2) ダム農地における塩類集積の発生は、ダム農地の原地盤標高に起因するダム農地上流域での高い地下水位（１～２m程度）と、４月から９月頃の高い蒸発散能による毛管上昇が主な要因である。

(3)ダム農地の地下水位上昇の主要因が、ダム農地側面の山腹斜面からの表面流出の浸透および中間流出であるため、地下水位を下げる対策としてダム農地周囲への承水路設置が有効と考えられる。

(4)地下水位は冬季に排水路周辺土壌の凍結に伴って上昇し、春季に凍結土壌の融解によって生ずる過湿状態が塩類化の一因となり得るので、冬季の地下水位上昇を抑制する対策が必要である。

一連の調査・試験研究により、黄土高原における灌漑農地および降雨依存農地の塩性化とその発生メカニズムについて明らかにした。

本研究は、黄土高原における農地土壌の塩性化と発生メカニズムを解明しており、土壌塩性化の防止と適正な水資源管理に向けての科学的礎となり得ると考えられる。