

The impacts of human activities on the groundwater system in the middle reaches, Heihe River basin

Wang Genxu

Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou

Part 1: Changes of hydro-geological system under the influence of human activities in the middle reaches (Zhangye city), Heihe River basin

Introduction

The Heihe River basin, the second largest inland river basin in the arid region of northwest China, is located between 96°42' E - 102°00' E. The middle reaches of the Heihe River watershed, where the study was undertaken, were located in the central portion of the Hexi Corridor, Gansu province, including the counties of Minle, Linze and Goatai, and Zhangye city. The middle reaches of the Heihe River watershed, totalling $4.08 \times 10^4 \text{ km}^2$ in area (Fig.1), receive between 250 mm yr^{-1} in the mountainous areas of the south, to less than 100 mm yr^{-1} in the northern high plains area. Under the influences of landforms, climate and vegetation, zonal soils are formed from the south (Qilian Mountain) to the north plain area: black soil, mountain chestnut soil, sierozem, grey desert soil, grey brown desert soil and blown sand soil, in addition to zonal soil types including meadow soil and aquisoils occurring in the Zhangye and Linze regions. Land types in the study area can be divided into: mountain meadow grassland, piedmont desert steppe grassland, agricultural land (includes cropland, forested land and garden land), plain swamp meadow grassland (including tree and shrub grasslands), and gobi and desert sandy land.

In hypsography, it is slanted from southeast to northwest with the elevation ranged between 1414-3616m asl. In large scale, the physiognomy of the study area can be divided into south corridor plain and north Longshou Mountain. The south plain area is slanted from southeast to northwest with a slight gradient of 25-4‰, and have a complanate land surface. From south mountain side to plain center, the corridor plain was divided to two sub-grade physiognomy types, i.e. alluvial and diluvial gravel plain and alluvial granule soil plain. At present, the granule soil plain was the main agriculture area of Zhangye city.

Due to the large-scale land reclamation and water resources development, many rivers have been reduced to oases, the water distribution status of the river system has changed greatly since the 1970s in the study area, and the ground water system was disturbed heavily. In recent 20 years, groundwater table changed greatly and the spring water declined by more than 50%. For recognizing the hydrological cycle and its change under human activities, rational utilization of water resources and efficaciously protecting the eco-environment of the study area, it is urgently demanded to research the dynamic changes of groundwater system.

1. Conditions of ground water formation and movement

1.1 Groundwater types and spatial distribution

Based on the geological materials and some hydrological characteristics of aquifer, the groundwater in the Zhangye city can be divided into unconsolidated sand and gravel aquifers groundwater, semiconsolidated sand and sandstone aquifers groundwater, carbonate-rock aquifers groundwater and Pre-Miocene old indurated rocks aquifers. Each of the four categories occupies a different hydrogeologic setting, and is characterized by water storage, aquifer recharge conditions and distributing area.

1.1.1 Unconsolidated Sand And Gravel Aquifers Groundwater

Unconsolidated sand and gravel aquifers groundwater was the main type of groundwater in the corridor plain where Zhangye city located. At present, it was also the only utilization aquifer in the study area. According to the aquifers matter composition and forming way, the unconsolidated sand and gravel aquifers can be grouped into the following three categories: basin-fill aquifers, referred to as valley-fill aquifers in many reports; blanket sand and gravel aquifers; and stream-valley aquifers.

Basin-Fill Aquifers

These aquifers are also commonly called valley-fill aquifers because the basins that they occupy are topographic valleys. Fine-grained deposits of silt and clay, where interbedded with the porous sand and gravel, form confining units that retard the movement of ground water. The sediments that comprise the basin-fill aquifers mostly are alluvial deposits, but locally include windblown sand, and fluvial sediments deposited by streams that flow through the basins. The alluvial deposits consist of sediments eroded by streams from the rocks in the mountains adjacent to the basins. The sediments eroded, transported, and deposited by the streams are the principal material of basin-fill aquifers. The streams transported the sediments into the basins and deposited them primarily as alluvial fans at the base of the mountains. The coarser sediment (boulders, gravel, and sand) was deposited near the basin margins and finer sediment (silt and clay) was deposited in the central parts of the basins (Fig.1).

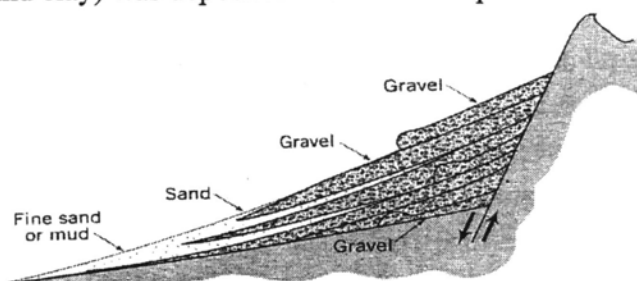


Figure 1. Diagrammatic cross section of the sediments in an alluvial fan from mountain adjacent to basin centre

In the study area, this type aquifer distribute widely in Zhangye basin and Shandan basin as the main type of unconsolidated sand and gravel aquifers, and it occupied the most area of corridor plain. Two geomorphic landforms can be distinguished on the basis of the gradient of the land surface in study area. Alluvial fans border the mountains and have the steepest

surface slopes and the coarsest sediments. Basinward, alluvial fans flatten, and form alluvial slopes of moderate gradient or with a flat surface. Controlled by the geological tectonic and topographic conditions, from south mountains adjacent to the basins center, the aquifers become thick and complex, the sediments finer and water table shallow, and the aquifer become from single and under unconfined, or water-table aquifer to multi and confined complex aquifer system (Fig.2). The depth of groundwater table is generally more than 200m in upper alluvial fans near the mountain adjacent, 50-150m in middle alluvial fans south side of Zhangye city, and 10-20m in lower part of alluvial fans and fine soil plain around Zhangye city area. In northwest area of Zhangye city and near the valley of Shandan river and Heihe river, the depth of groundwater become less than 5m.

The unconsolidated sand and gravel aquifers fill consists mostly of unconsolidated deposits of Miocene and Pliocene through Holocene age. There are the largest of sediments thickness in basin center near Zhangye city with a deposit of 300-500m. Mountains adjacent ward both south and north side, the sediments thickness becomes thinner with general thickness of 50-100m (Fig.2). Generally, the groundwater storage capacity and the degree of groundwater resources abundance are scaled by single well water yields per day or minute. The unconsolidated sand and gravel aquifers have the well water yields ranged between 1000-5000m³/d in most study area. The largest storage was located in the lower part of Heihe river and Liyuan river alluvial fans with the well water yields more than 5300 m³/d. In north and south mountains adjacent area, however, the well water yields was less than 800m³/d.

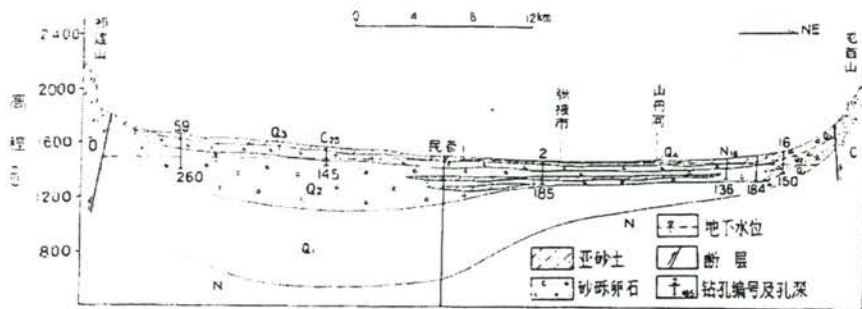


Figure 2 Cross section showing the aquifer system in Zhangye corridor plain

Stream-Valley Aquifers

Stream-valley aquifers, is located beneath channels, floodplains, and terraces in the valleys of major streams. The sediments deposit in Quaternary, and the thickness varied in large scale at different stream valley. There are 17 streams formed from Qilian Mountains and delivered to the corridor plain in the study area, and 4 larger rivers such as Heihe river, Suyoukou river, Dayekou river and Daciyao river. In these stream-valleys, the unconfined aquifers, consists of coarse sand and gravel, was formed in valley sediments. The aquifer have 2-20m thickness and less than 5m water table depth. The groundwater storage capacity and the degree of groundwater resources abundance are indigent in the Qilian Mountains' stream-valley aquifers with the well yields less than 100m³/d.

In the Longshou Mountains area, there are about 9 streams delivered to the corridor area. The stream-valley aquifers consist mostly of coarser sediment (such as boulders, gravel and coarse sand), and the thickness is generally ranged 2-10m. Due to the folium aquifer and largely varied precipitation, the well yields were ranged between 4.32-348.2m³/d with the groundwater table varied from 1m to 6m.

Blanket Sand And Gravel Aquifers

Widespread sheet-like aquifers that consist mostly of medium to coarse sand and gravel are collectively called blanket sand and gravel aquifers. These aquifers mostly located in both south and north side of the corridor plain, and contain water under unconfined. Locally, where stream-valley alluvial aquifers, which also consist of sand and gravel, cross the blanket sand and gravel aquifers, the two types of aquifers are hydraulically connected. As mentioned above, both south and north corridor plain side, there are about 26 streams with short river way and formed many little alluvial fans allied each other. The blanket sand and gravel aquifers largely consist of those allied little alluvial deposits, however, there are large areas of windblown sand and water erosion or both along the adjacent mountains.

The aquifer thickness varied spatially, and ranged between 20-150m. The groundwater tables unconfined have depth of mostly larger than 100m, with a sharp slope slanted to basin center. Blanket sand and gravel aquifers have a middle groundwater storage capacity, generally, the well water yields was about 1000-3000m³/d per 5m water table decrease.

1.1.2 Semiconsolidated Sand And Sandstone Aquifers Groundwater

Sediments that primarily consist of semiconsolidated sand, silt, and clay, interbedded with some carbonate rocks, consist sequences of Mesozoic and Paleozoic semi-consolidated sand and sandstone layer. The aquifer was comprised of both porous media and fracture media aquifer, extent along the Qilian Mountains and north Longshou Mountains(Fig.3). The semiconsolidated sand and sandstone aquifers have been grouped into three aquifer systems that were distinguished with sediments types and water storage conditions.

Carboniferous and Triassic Aquifer

The aquifer consists of sediments deposited in sea and terrestrial alternation environment, such as limestone, sandstone, mudstone and shale in Carboniferous and Triassic age, and mainly distribute in some local parts of Qilian Mountains' north side. Including both porous and fracture water content media, the aquifers have a less spatial extent area and were broken up to pieces by fault fractured zone, therefore, the aquifers have a very indigent water storage capacity. In the study area, the aquifer was mostly comprised of Carboniferous and Triassic sandstone with a single spring water yields of 0.05-0.1l/s. In some mountain parts of Shandan county, well water yields can reached to 0.07-0.16l/s with water table declined 5-8m in Carboniferous aquifer.

Jurassic and Cretaceous Aquifer

Sediments that primarily consist of coarse sandstone or gravel sandstone and sandstone

interbedded with mudstone and shale, were deposited in lake and mountain environment during Jurassic and Cretaceous age. The Cretaceous aquifers are mainly distributed in the upper reach of Liyuan river and Daciya stream at the north slope of Qilian Mountains and in Pingyi and Yangtai village of south Longshou Mountains. The Jurassic aquifer was distributed only in some parts of north Longshou Mountains.

Jurassic and Cretaceous aquifer retains mainly the sand porous water content media, and have a lower porosity and permeability. The water storage capacity and water resources abundant degree were varied with the various sediments, and the well water yields ranged between 0.5-256.5m³/d for water table declined to 5-8m. In Qilian Mountain area, the well water yields mostly ranged 22-256.5m³/d, and it changed to 2-12.4m³/d in north Longshou Mountain area.

Pleistocene and Tertiary age Aquifer

Sediments that primarily consist of semiconsolidated sand, gravel and coarse sand, silt interbedded with mudstone. The aquifer was distributed extensively in the both side of corridor plain near pro-mountains. At present, the thickness has not being confirmed, but its' porosity and permeability was better than the other two types of semiconsolidated sand and sandstone aquifers. The water storage capacity varies greatly with the varied sediments from place to place. In south side of Zhangye basin, the well water yields ranged between 10-100m³/d for no water table decline, and when the water table declined to 5m, the single well water yields could reach to more than 2000m³/d.

1.1.3 Carbonate-Rock Aquifers And Pre-Miocene Old Indurated Rocks Aquifers Groundwater *Pre-Miocene bedrock aquifer*

The rocks of the aquifer system, exposed in large areas of Qilian and Longshou Mountains (Fig.3), are the basal rock in the study area. The aquifer system consists of layered rocks, such as sandstone, shale, quartzite, pegmatite, et al., deposited in Cambrian, Ordovician, Carboniferous and Silurian age. Those old bedrocks, undertaken folding and faulting of geological construction movement following lithification and erosion, formed greatly construct cranny and fracture. The geological construction action type and sediments texture complicate the movement of water through these rocks and controlled the water storage capacity.

In Qilian Mountain area, the aquifers have a runoff modulus ranged from 0.1-20.0l/s per square kilometers, and the single spring water yields ranged between 0.001-3.7l/s. In Longshou Mountain area, the groundwater runoff modulus is about 0.05-1.0 l/s per square kilometers, and the single spring water yields are generally less than 1.0 l/s.

Carbonate-Rock Aquifers

Aquifers in carbonate rocks are most prominent in the Longshou Mountain area in the study area. Most of the carbonate-rock aquifers consist of limestone, but locally have dolomite and marble deposited in Paleozoic and Upper-middle Carboniferous age. Carbonate

rocks develop connective fractures and faults, and even locally develop some dissolution pore space. Such pore and fractures enhance the permeability and water storage capacity in the aquifer. However, due to the greatly variation of the sediments texture, geological construction actions and local precipitation conditions, the aquifer permeability and water storage capacity varied from place to place, and the single well water yields ranged between 0.5-256.6m³/d.

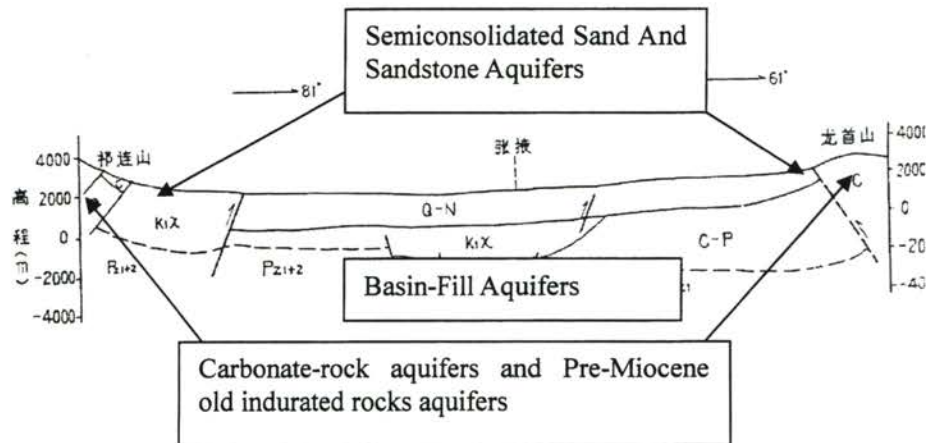


Figure 3 Cross section showing the sediments and groundwater types distribution

1.2 Conditions of groundwater recharge and discharge

1.2.1 Groundwater recharge and discharge in corridor plain

In arid inland river basin, Each basin has essentially the same characteristics-the impermeable rocks of the mountain ranges serve as boundaries to the groundwater flow system, and have a individual unit of groundwater system, including the mountain recharge, flow in plain and discharge in fine earth plain and terminal lake or area. In Zhangye city, most recharge to the basin-fill deposits originates in the Qilian mountains as rainfall and snowmelt, and, where the mountain streams emerge from bedrock channels, which form rivers and streams outflow from mountains, the surface river water infiltrates into the upper alluvial fans, where the sediments consist mostly of gravel and coarse sand, and have great permeability. The infiltrating river water replenishes the basin-fill aquifer. Such way is the dominating recharge of groundwater in the Zhangye basin (Fig.4). Intense thunderstorms may provide some direct recharge to the basin-fill deposits in local groundwater table buried less than 4 meters, but, in most cases, any rainfall that infiltrates the soil is either immediately evaporated or taken up as soil moisture; little water percolates downward through the unsaturated zone to reach the water table in the basins.

Another source of groundwater replenishment in the corridor plain aquifer system is

interflow from mountain aquifers, which was called as basin side interflow recharge. The bedrock is sufficiently permeable to allow all recharge to flow through it and out of the mountain area, and then traverse through the pre-mountain fault and flow into deep basin-fill aquifers. The Zhangye basin is surrounded by bedrock from south and north side that is sufficiently permeable to conduct flow into the basin. The recharge volume could reach to 13% of total replenishment in the corridor plain. At present, the average volume of recharge by interflow was about $0.445 \times 10^8 \text{ m}^3/\text{a}$ (Table 1), between that, $0.436 \times 10^8 \text{ m}^3/\text{a}$ was from Qilian Mountain area and $0.009 \times 10^8 \text{ m}^3/\text{a}$ was from Longshou area.

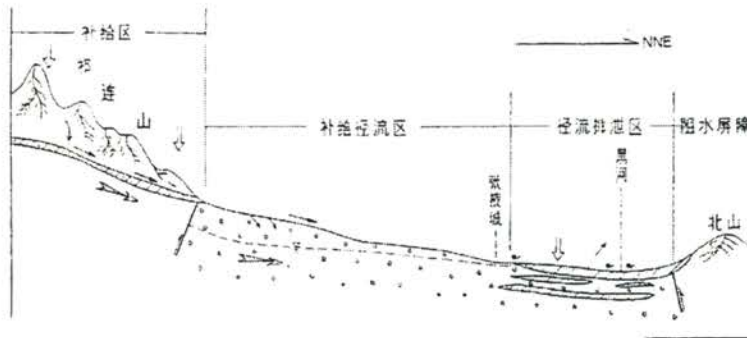


Figure. 4 Cross section showing the groundwater recharge, flow and discharge in Zhangye basin

The return water recharge from irrigation is the third source of groundwater replenishment, which was called “no-point infiltrating”. At present, the infiltrating replenishment by irrigation canals and fields is calculated approximatively to $1.99 \times 10^8 \text{ m}^3/\text{a}$ (Table 1). But the replenishment occurred in the area of groundwater table less than 10m.

Table 1 Recharge of groundwater in Zangye basin at present (1997)

Infiltrating way	River water	Flood runoff	Irrigation canal	Irrigation field	Inter flow	Condensation and rainfall
Replenishment volume ($10^8 \text{ m}^3/\text{a}$)	2.916	0.124	1.836	0.163	0.445	0.067

The direction of groundwater is almost same as river, warding to basin center with the hydraulic gradient of 5‰-6‰, and then flow to northwest with the hydraulic gradient of 1‰-2‰. At the fine earth belt of alluvial fans in corridor plain or basin center, due to the lower transmissivity and declined landsurface in topographic, the groundwater table rises. Such aquifer conditions provide groundwater outflow from aquifer to landsurface by spring. In the points, groundwater discharged by evapotranspiration and spring. The volume of groundwater discharged by evapotranspiration and spring occupied about 70% of total groundwater discharge in Zhangye basin at present (1997).

1.2.2 Groundwater recharge and discharge in mountain area

In mountain area, relatively heavy precipitation forms the surface runoff, at same time, there are some rainfall replenishes the semiconsolidated sand and sandstone aquifers and

bedrock fracture aquifers. The steep canyons and gulches, incised by hydraulic net, discharged the aquifer. However, some groundwater locally emerged from bedrock aquifer and reforms the Stream-valley aquifers and delivered to Zhangye basin ultimately.

1.3 Unconfined groundwater and confined groundwater

Unconfined aquifer, extensively distributes in every type aquifer and the whole study area, is the fundamental elements of Zhangye city groundwater system. Near the both south and north mountains area, called pro-mountain adjacent high plain, the unconfined aquifer has a single layer and simple sediments texture consisted primarily of coarse sand, gravel and boulders. The depth of free groundwater table ranged 100-250m in south Qilian mountain adjacent area, and 50-150m in north Longshou adjacent area. In tail of alluvial fans marched with fine earth plain, unconfined aquifers changed from single layer to multi-layer, where the confined aquifers therefore were formed, and sediments consist mostly of fine-grained sand, interbedded with silt. The single aquifer has an average 20-30 thicknesses. As showed in Figure 5, the unconfined aquifer distributes primarily in south of Zhangye basin, i.e. Xiaoman, Daman, Shigangdong, Xiaohe and Ganjun villages, et al.. From south mountain adjacent area to basin center, the unconfined aquifer water table rise, and the depth changed from more than 200m to 5-10m. Even around Zhangye city, such as Sangqi and Wujiang villages, the unconfined aquifer water table depth is less than 3m and overflow to surface by spring.

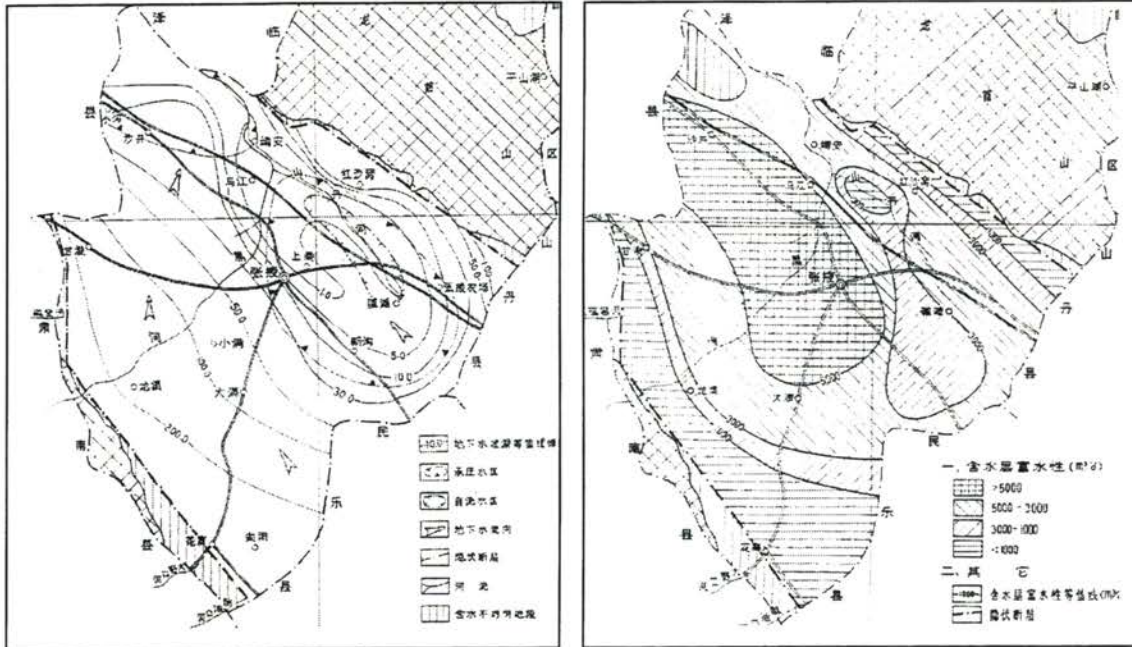


Figure 5 (Left) Diagrammatic map of unconfined and confined aquifer distribution and the unconfined water table depth isoline.

Figure 6 (Right) Diagrammatic map of the groundwater yields capacity isoline.

Generally, there are abundant groundwater resources in Zhangye basin. As showed in

Figure 6, the unconfined aquifer has a water yields capacity more than $3000\text{m}^3/\text{d}$ in most area of Zhangye basin. As same as the groundwater hydraulic gradient distributes spatially, the groundwater yields capacity of unconfined aquifer is increased from south mountain adjacent area to basin center, and there are maximum water yields around the central part with well water yields more than $5000\text{m}^3/\text{d}$, however, the water yields capacity is generally less than $500\text{m}^3/\text{d}$ near the adjacent mountain area.

There are two main area of confined aquifer distribution in Zhangye basin (Fig.5). One is just in east north area of Zhangye city town, including Shangqing, Wujiang and Pingyuanbu villages, et al., another in Linze county, including Liaoquan village, Xiaotong village and Xinhua Farm. Where the confined aquifer distributes primarily there are complex aquifer texture and relationship between more than 3 layers of aquifers. The confined water head are generally out of the surface and support first unconfined groundwater outflow to surface with together by spring. The confined aquifer consists primarily of sand and gravel with little silt. The overlying and underlying low-permeability confining beds are composite of clay and silt with a greatly varied thickness. The water abundance degree or water storage capacity was nearly same in confined aquifer distribution area with mostly the well water yields more than $5000\text{m}^3/\text{d}$.

PART 2: The temporal-spatial variations of groundwater table in the middle reach of Heihe River Basin.

1. Introduction to analysis of groundwater table variation

The temporal-spatial variations of groundwater table, which reflect the forming and varying regulation of groundwater system, are controlled by precipitation, surface runoff and human activities. As an information output of groundwater system responding to outer influence factors, the groundwater table variation is an important way to understand the human influence degree on groundwater system, the changing trend and rate of groundwater system. There fore, the regulation of groundwater table variation is the essential bases to groundwater management, catchment development plan and eco-environment protection.

Since 1980, there were about 54 sites for groundwater table observation set up along the Heihe river in Zhangye basin. Those observation sites distributed in different hydrogeological unites. Controlled by geographical type, sediment characteristics and geological construction conditions, the aquifer system varied from single unconfined aquifer in south pro-mountain to multi-layer and confined aquifer system in north basin center area, and the groundwater table depth become shallower. According to topography, aquifer structure, groundwater recharge and discharge conditions and irrigation water source, the study area, middle reach of Heihe river basin, is divided into four sub-regions. For each sub-region, some basic information, such as the spatial distribution, natural characteristics, hydrogeological features, irrigation water source and observation points distribution, are listed in Table 1.

Table 1 Sub-regions and their some basic information

Sub-region	Distribution scope and nature term	Hydro-geology and irrigation condition	Distribution of observation points
Upper-middle of the alluvial and diluvial fan	Located in south pro-mountain alluvial and diluvial Gobi plain with the elevation between 1500-2800m and precipitation of 120-300mm.	Single unconfined aquifer, groundwater table depth > 30m; mainly used river water to irrigation.	Zhangye 6#, 8#, 14#
Lower part of the alluvial and diluvial fan	Intersection of alluvial and diluvial Gobi plain with the fine-grained soil plain with elevation between 1400-1800m and precipitation of 100-250mm.	Conversion from single unconfined aquifer to multi layer confined aquifer with the water table depth between 8-30m; ground water mixed with river water for irrigation	Zhangye 3#, 4#, 5#, 11#, 13#, 21#
Fine-grained soil plain	Located in Zhangye city area of the fine-grained soil plain with elevation between 1300-1600m and precipitation of 100-150mm.	Multi layer confined aquifer with water table depth less than 10m, ground water, spring and river water mixed for irrigation	Zhangye 1#, 2#, 18#, 15#, 25#, 28#, 29#
River valley plain of Linze and Gaotai county	Located along the river in Linze and Gaotai county with elevation between 1270-1500m and precipitation of 60-130mm.	Multi layer confined aquifer with water table depth less than 10m, ground water, spring and river water mixed for irrigation	Linze: 11#-23#; Gaotai: 1#-16#

2. The spatial variation types of groundwater table with long-term annual series

2.1 The trend of groundwater table variations in the upper-middle part of the alluvial-diluvial fan

In the upper-middle part of the alluvial-diluvial fan, which is located in the south of Zhangye Basin, including most Minle irrigated areas, the groundwater table depth are over 30m, most of which are more than 50m, and the groundwater is simple unconfined. Based on the recorded data of variations of groundwater from 1981-2000, an apparent decreasing trend is observed in some typical observed wells (Fig. 1). There into, annual decrease of the groundwater levels of Daman and Shigangdun Village, located in the center of fans, vary from 0.32m to 0.43m, adding up to 6.5-8.6m in 20 years. And in No. 65 observed well, located in Minle County, accumulative decrease of groundwater level is up to 12.91m, averagely 1m per year. These variations of the observed wells belong to markedly continuous decreasing types, which indicate that the groundwater levels of upper-middle areas of alluvial and diluvial fan in the southern basin keep on declining , and the higher the areas are located, the more the groundwater levels decline.

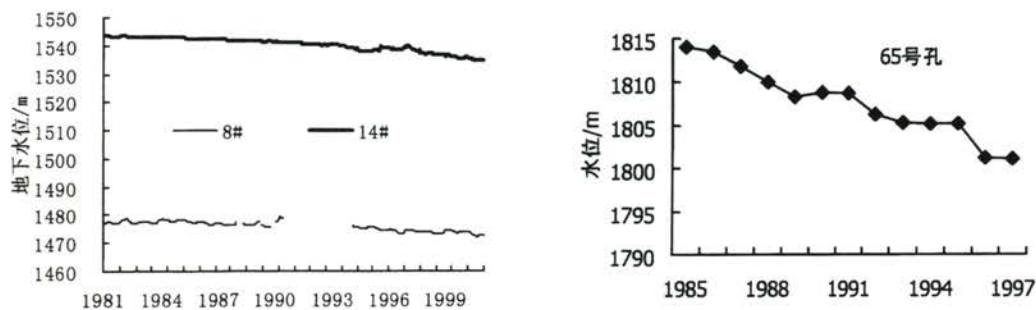


Figure 1 The long-term variations of groundwater levels in the upper-middle part of the alluvial and diluvial fan in Zhangye Basin

2.2 The trend of the long-term variations of groundwater levels in the lower part of alluvial fan

Most aquifers of the lower part of alluvial fan, located in the south and eastern Zhangye Basin, are simple unconfined, but in the north areas next to fine-grained-soil plain, there are multi-layer and confined aquifers. Generally, the groundwater level varied from 5m to 20m, mainly from 8m to 15m. Due to sufficient and easily exploited, groundwater was largely exploited and mixed with river water to irrigate in this area. In general, the groundwater levels show a two phases variation trend (Fig.2A) in temporal distribution. In the decade of the 1980s the groundwater levels declined slowly with averagely 0.07-0.15m per year, even some parts had no change. In the 1990s, however, the groundwater levels in every part declined rapidly. In Yingke irrigated areas and Yangjia Village, for example, the groundwater table declined 4.2-6.5m. Long-term variations of groundwater in this area show the conversion from slow decrease to rapid decrease, which manifest a slow-rapid decreasing conversion type.

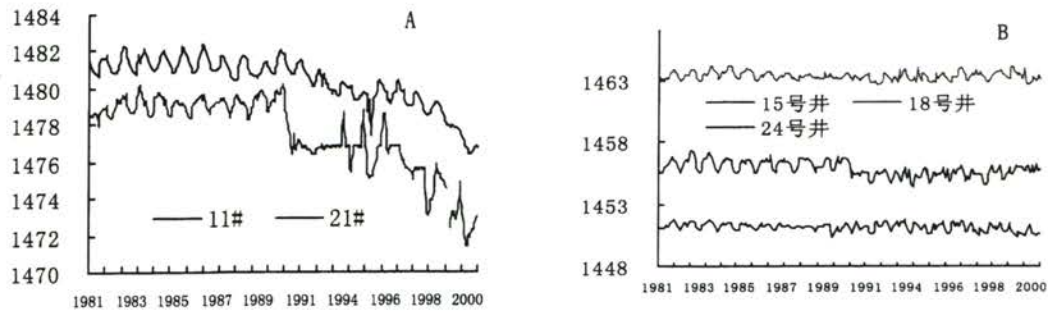


Figure 2 The long-term variations of groundwater levels in the lower part of alluvial fan and fine-grained soil plain

2.3 In the fine-grained soil plain in the centre of basin

The aquifers in the northern and northwestern Zhangye city, which are located in the center of Zhangye Basin, composed of multi-layers, are confined aquifers. Before the 1970s, this area was the main area where springs emerged, and local heads of confined groundwater were higher than the ground surface. Affected by the setup of confined groundwater the upper unconfined groundwater levels were relatively higher, part of which overflowed as spring water. At present, the groundwater table depths are usually lower than 2m in most of the area. The variations of groundwater levels are relatively stable (Fig. 2B) in this area, and in such local parts as the area from Xiaqin to Shandanhe Bridge they show an increasing trend after the 1998. Therefore, the groundwater level variation belongs to a stable type.

2.4 The trend of the long-term variations of groundwater levels in river valley plain of Linze and Gaotai county

In the alluvial valley along Heihe river in Linze and Gaotai County, main irrigated water comes from the river. In this area, the aquifer structure is complicated: the groundwater system is composed of multi-layer aquifers and the groundwater levels are usually less than 5m, most of them lower than 3m. According to the data of typical observed wells along the river, long-term variation characteristics of groundwater levels in this valley plain are shown in Figure 3. Similar to Zhangye fine-grained soil plain, the groundwater levels in this valley plain generally keep stable. In some local areas, such as the intersection of Liyuan River alluvial fan with Heihe river valley in Linze county, lower parts of Heihe river valley in Gaotai county, the groundwater level increase gradually from 1995-1997. Therefore, the groundwater levels variation in this area belongs to a stable-increasing type.

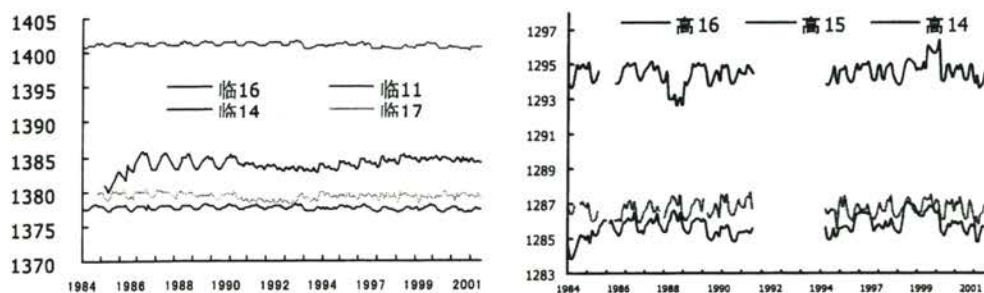


Figure3 The long-term variations of groundwater levels in Linze-Gaotai river valley plain

3. Spatial inter-annual variation characteristics of groundwater table

Inter-annual variations of groundwater tables are controlled by the type and structure of aquifers, the recharge and discharge of groundwater. The long-term variation type of groundwater table are formed and influenced by the inter-annual variation characteristics within regions share the similar types and structures of aquifers. Therefore, inter-annual variation characteristics of groundwater table are discussed according to the distributed areas of long-term groundwater table variations.

3.1 Inner-annual variations of groundwater tables in the continuous declining areas

Because of the deep storage, the recharge of groundwater comes from lots of infiltration of river water, so it is weakly affected by irrigated water but strongly affected by river water. Commonly, the higher groundwater levels appeared between August and next January, and the lower ones appear between March and July inner year before 1992, and compared to river flow the groundwater levels fluctuation have some time delayed (Fig.4 No.34 observed well). With the distance away from the river, the moments when the higher groundwater levels appear differ: the longer the distance is the longer it delays. Originally, the characteristics of groundwater table fluctuation are controlled by the hydrological process of river. However, the types of groundwater table variation inner annual changed from river hydrological process controlled to exploitations controlled types after 1992 (Fig.4 No.34 observed well). Since 1992, the higher groundwater levels appear between October and next March while non-exploitation period, and the lower ones appear between April and September during exploitation.

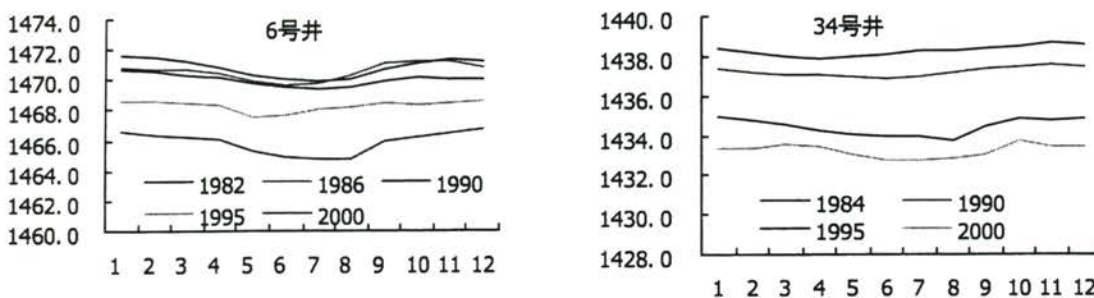


Figure4 Curves of annual exploitative and hydrological-runoff variations of groundwater

In the center of alluvial and diluvial fan, which is the main historically cultivated lands due to that the groundwater levels are low and easily exploited. In the area far away from the river, such as Daman irrigated areas, river water is the main source of irrigation but complemented by lots of groundwater. Therefore, there exists the groundwater table dynamic exploited state controlled by the exploitation, and during the exploitative period between April and September there is a low-groundwater-level while the non-exploitation period between October and next February there is a high-groundwater-level (Fig.4 No.6 observed well). The variations of groundwater in this area are uniform, and the variation range is within

0.44-1.97m. Annual variations of various typical years in this area as shown in Figure 4 (No.6 observed well) indicate that their characteristics have few change but the range of groundwater levels increases in two decades.

3.2 Variations of inner-annual groundwater table fluctuation in the slowly-rapidly decreasing conversion areas.

Inner-annual groundwater table fluctuation was complicated due to the infiltration of the river and irrigative water. Before and in the 1980s, regional inner annual variations of groundwater table were mainly controlled by the river hydrological and river water irrigative processes. Thereinto, hydrological-runoff type was mainly distributed in southern and western area near to Heihe riverbanks (Fig. 5, No. 11). In the 1990s, however, annual high groundwater levels appeared in October to next February, and the low groundwater levels were in April to September. These characteristics of groundwater table fluctuation belong to exploitation process controlled type (Fig. 5, No. 11).

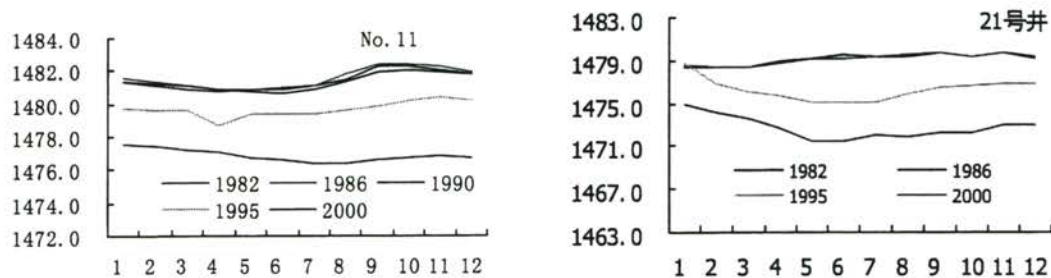


Figure 5 Curves of annual hydrological-runoff and irrigative variations of groundwater

The latter type, river water irrigative processes controlled the groundwater table fluctuation, was distributed in the most parts of lower alluvial fan. Before 1990, the variations of groundwater table, which were controlled by surface water irrigation, corresponded to the irrigative periods. In the irrigative period from April to November the groundwater kept high level, and in the non-irrigative period from December to March the groundwater kept low level (Fig. 5, No. 21). After the 1990, especially after 1995, the regional inner annual dynamic state of groundwater table changes remarkably. In the exploitative period from April to September regional groundwater levels commonly decline, and in the non-exploitative period from November to February higher groundwater levels emerge. The variation creates the relatively uniform exploitative type. Particularly, the original irrigative areas become the exploitative types after 1995.

3.3 Variations of inner-annual groundwater table fluctuation in the relative stable areas

On the background of long-term stable variations, this region contains the complicated inner annual variations of groundwater table. Deduced from inner annual variations in three representative observed wells (Fig. 6), it is clear that, before 1990, the groundwater table fluctuation type controlled by the river hydrological process is added to the basic irrigative one that is controlled by the irrigative factors of surface water. In the irrigative period from April to October groundwater levels are higher, at the same time, groundwater level peaks

relating to the hydrological process of river appear in August to October. In addition, in some areas the variations of groundwater table show the exploitative characteristics in the irrigative period. In No. 25 and NO. 29 (Fig. 6), for example, the curves of variations of groundwater table fluctuation in June to August are apparently concave, the typical saddles. In general, the variation of groundwater table is irrigative-exploitative, partly irrigative-runoff. Since the 1990, however, with the exploitative factors augmenting, annual variations have invisible change. In NO. 29 well, for example, in the exploitative period from April to August the groundwater levels decline, and annual high groundwater levels appear in the non-exploitative period from November to February. The area represented by No. 25 and No.30 wells have still some characteristics of the irrigative-runoff type after 1990.

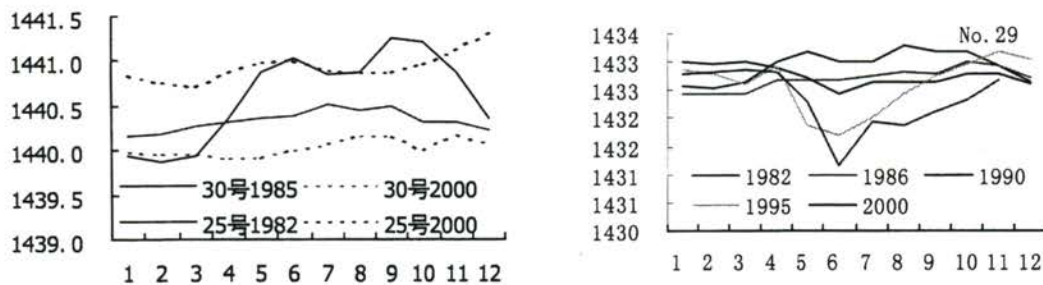


Figure 6 Mixed variations of groundwater

3.4 Variations of inner-annual groundwater table fluctuation in the stable-increasing areas

In the areas of valley plain along the river in Linze and Gaotai County, inner annual variations of groundwater are apparently controlled by the irrigative factors and hydrological factors of river together. From the beginning of irrigation in April, the groundwater levels keep on increasing, and attain the highest points in September to November (Fig.7). In the 1990s, the dynamic state of groundwater has such changes as the apparent return of groundwater levels in June to November since 1995, and annual high groundwater levels in December to February, which may be related to regional exploitation of groundwater. Generally, the groundwater table fluctuation in the river valley plain mainly exhibited irrigation factor controlled type together with some river hydrological process influence, and the fluctuation model has not obviously change through recent 20 years.

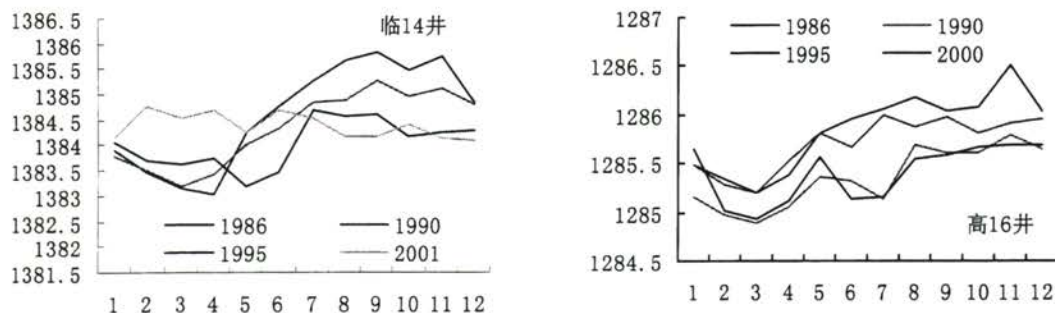


Figure 7 Inner annual variations of groundwater table in the river valley plain of Linze and Gaotai County

4. General variation of groundwater table depth in recent 20 years

Groundwater table depth is an important factor for the groundwater dependent plant, soil quality and groundwater irrigation and drinking conditions. Under the groundwater table variation, the depth varied with temporal-spatial series (Table 2). In the area of upper-middle of the alluvial-diluvial fan, the total groundwater table depth decreased by 5.5-12.9m in recent 20 years, which is the largest decrease of groundwater table in middle reach of Heihe river basin with decrease of 9.37m in average. Among that, however, the groundwater table deceased less in 1980s by average 2.6m, and another 6.7m decrease was taken place in 1990s. Inner annual fluctuation of groundwater table is about 1.37m, and keeps relatively stable during the recent 20 years in the upper-middle of the alluvial-diluvial fan (Table2).

Table 2 The temporal-spatial variations of groundwater table depth in recent 20 years

	Upper-middle of the alluvial-diluvial fan		Lower part of alluvial fan		Fine-grained soil plain		River valley plain	
	Annual	Inner annual	Annual	Inner annual	Annual	Inner annual	Annual	Inner annual
1980s	1.5-5.7	1.4	-0.3-0.08	1.41	-0.22-0.4	0.74	0.04-0.51	1.87
1990s	5.2-7.3	1.35	2.83-6.69	2.33	-0.32-0.43	0.55	-0.67-0.05	0.86
Total	6.5-12.9		2.92-6.73		-0.33-0.59		-0.31-0.23	
Average	9.37	1.37	4.74	1.87	0.22	0.65	-0.002	1.36

Note: "+" means groundwater table decrease, and "-" means groundwater table increase.

In the lower part of alluvial fan, there were not visibly changes of the groundwater table in 1980s with the inner annual fluctuation of 1.41m. However, the groundwater table sharply decreased 2.83-6.69m in 1990s, and the inner annual fluctuation increased to 2.33m averagely. In whole, the groundwater table decreased averagely by 4.74m in recent 20 years (Table2). Under the relative stable-increasing types of long-term groundwater table variation, there were not some visible changes of groundwater table in the fine-grained soil plain and river valley plain with the average groundwater table variation only 0.22m and -0.002m respectively in recent 20 years (Table2). Inner annual groundwater table fluctuation was nearly as same as the upper-middle part of alluvial-diluvial fan in the river valley plain, inversely, the area of fine-grained soil plain have the least inner annual fluctuation of groundwater table.

5. Summary and discussion

In the middle reach of Heihe River, the variations of groundwater table which are influenced by the hydrology of river, irrigation and exploitation present various characteristics in different hydrological regions, as follows:

(1) In various physiognomy units different storage conditions result in remarkable distributions of variations of groundwater. From the top down in the alluvial and diluvial fans, the long-term variations of groundwater are the continuously rapidly decreasing, the

slowly-rapidly decreasing and the stable types, successively. In Linze and Gaotai valley plain in the middle reach, the variation of groundwater is stable-increasing. In the later two decades, in the fine-grained soil plain in the center of basin and its northern and western portions the interannual variations are stable, which reflects that the relationship between recharge and discharge of groundwater in this area presently keeps balance. In most southern basin the groundwater levels decline remarkably after the 1990s, which indicates that the relationship presents a negative balance and it intensifies gradually.

(2) Regional annual variations of groundwater are complicated and have the apparent temporal distributions. In the 1980s, in the simple unconfined aquifer districts of the upper-middle part of the fan, annual variations of groundwater are generally exploitative and hydrological-runoff. After the 1990s, the variations of groundwater are apparent: in the lower part of alluvial and diluvial fan and the fine-grained soil plain they turn to the exploitative and the irrigative, runoff-exploitative types, and in Heihe valley plain in Linze and Gaotai they turn to the irrigative-exploitative types. Only the simple unconfined aquifer districts in the upper-middle part of alluvial and diluvial fan have no change but the range of variations of groundwater levels increases.

(3) The former analysis indicates that in most parts of research regions the annual variations of groundwater turn to the exploitative types or exploitative-factors types, meanwhile, the human exploitative actions become the dominating factors influencing the variations of groundwater and lead to the changes of the inner annual variation types, such as the rapid decrease of groundwater levels in southern basin.

(4) Under the long-term variation of groundwater table, the depth of groundwater table decreased observably by average 4-10m in the upper-middle part and local lower part of alluvial and diluvial fan during recent 20 years. However, there are no visible decreases of groundwater table depth in the fine-grained soil plain and western river valley plain.

Part 3: Evaluation The Impacts of Human Activity on Groundwater System with EIGT Model in Arid Zones of Northwest China

Abstract: Precisely quantitative evaluation of the impacts of human activities on the regional groundwater system has great importance to the rational planning, management and utilization of groundwater resources and to the maintenance of the stability of the ecosystem depended on the dynamical variations of groundwater. Based on the groundwater dynamical data, the evaluation index of groundwater table (EIGT) model, which integrate the evaluating the extraction factor of groundwater dynamic change and the evaluating impacts of human activities on the relationship between river runoff, precipitation and groundwater, is presented in this paper. From the angle of the impacts of extraction factors on groundwater dynamical processes and the interrelation between surface runoff, precipitation and groundwater. The method evaluates the impacts of human activities on groundwater system and their temporal and spatial variation. Taking the Zhangye Basin in the middle reach of the Heihe River in northwest arid area of China as an example, the impacts of human activities on groundwater system in the past 20 years were evaluated. The results showed that since 1995 human activities have produced dramatic impacts on the basin's groundwater system and entirely altered the groundwater dynamics as well as its relation to the surface runoff and atmospheric precipitation in the mid-upper and lower parts of alluvial-diluvial fans, and local zones in the northern part of fine soil plain of the basin, however no evident impacts were imposed on groundwater system in the river valley plain in the western part of the basin. In addition, this paper also presents temporal-spatial variation of the impacts of human activities on groundwater system.

Keywords: Human activity, Groundwater System, Impact Evaluation, Evaluation Model, Heihe River basin

Introduction

Ground water is an important part of the hydrologic cycle and has been a significant source of water to humanity since its beginnings (Alley et al., 1999). The growing demands on freshwater resources create an urgent need to link research with improved water management. Better monitoring, assessment, and forecasting of water resources will help to allocate water more efficiently among competing needs (Naiman, et al., 2001). Recently, the human actives, including water utilization and land use, are becoming a vital aspect which

affects water system (both surface and ground) which in turn has a severe impact on the hydrological regimes and water supply in the world (Belousova, 2003; Alley et al., 1999). Human activities are intricately linked to the evolution and dynamics of groundwater quantity and quality. Given the alarming rate of land-use change globally, it is important to understand the linkages between land-use change and groundwater dynamics, as land use affects the quantity and chemical quality of recharge water (Gehrels, 2001; Querner, 2001). Each ground-water system and development situation is unique and requires an analysis adjusted to the nature of the water issues faced, including the social, economic, and legal constraints that must be taken into account. A key challenge for achieving ground-water sustainability is to frame the hydrologic implications of various groundwater exploitation and groundwater dynamics in such a way that they can be properly evaluated. With time, many issues involving the quantity, quality, and ecological aspects of surface water are interrelated with ground water. Thus, groundwater hydrologists are challenged continually by the need to provide greater refinement to their analyses and to address new problems and issues as they arise (Shah, et al., 2000; Alley et al., 1999).

The characteristics of water resources in arid zones determine that groundwater as a rule is the most important water resources and the best selection of water supply in arid zones. Generally, groundwater resources are the essential element to support the oasis ecosystem in arid zones and to maintain the socioeconomic development in desert regions (Mtembezeka, et al., 1997; Shah, et al., 2000). Globally, groundwater resources play a non-fungible leading role in solving water shortage problem in arid zones. Scientific assessment and effective management are an important guarantee and essential requisite for the better exploitation of groundwater resources in arid zones (Schwartz, et al., 2003; Khazai, 2001). Groundwater dynamic regimes reflect the formation and variation laws of groundwater, and they are mainly controlled by precipitation, surface water and groundwater extraction etc. The output of the response of groundwater system to the external disturbing impacts is an important information source for us to understand the impacts of human activities on the groundwater system (Sato, et al., 2003; Asmuth, et al., 2001). For this reason a dynamical monitoring network of groundwater was gradually established in most of irrigation regions in arid inland basins of China since 1970s (Hydrologic Bureau of WMC, 1995).

The groundwater level directly determines the natural dynamic behaviour of the groundwater system, and is (hence) often the most important information for groundwater

systems management (Ni, et al., 2001). The research of the dynamical changes of groundwater and their affecting factors provides a scientific basis for working out a basin's wateruse planning, agricultural arrangement, irrigation and draining waterlogged areas, control salinization, water resource evaluation and management, and environmental protection (Belousova, 2003; Asmuth, et al., 2001; Xu, 2003). At present, many countries have used the dynamical observation data of groundwater to evaluate the degree of the impact of human extraction activity on groundwater system. In this respect there are two evaluation methods. First, directly using the dynamical variation trend of groundwater to make a qualitative judgment, or making a comparative analysis using the mean water table, maximum water table and minimum water table of a season in a year (Asmuth et al., 2001; Xu, 2003; Khazai, 2001), such method is simple but is not precise and quantitative. Second, mathematical models are used to make quantitative evaluation, such as statistical regression model, response matrix model and groundwater level numerical model etc (Bierkens, et al., 1999; Knotters and Walsum, 1997; Asmuth et al., 2001), this method requires a number of parameters and some hydro-geologic assumption conditions, and hence it is quite complex and inconvenient. Based on the dynamical data of groundwater level, and the interaction of groundwater, surface water and atmospheric precipitation, this paper establishes the EIGT (Evaluation Index of Groundwater Table) model, a corresponding indexes and mathematic model and puts forward a simple integrated evaluation method. This method is used to evaluate the impacts of human activities on the groundwater system in the middle reach of the Heihe River, northwest China, and thereby provides a basis for working out the comprehensive rehabilitation planning of the Heihe River basin.

1. Study region and Methodology

1.1 Study region description and evaluation zoning

The middle reach of the Heihe River—the second largest inland river of China was selected as the study region, which belong to Zhangye Basin in topographic division. It is located in the middle section of the Hexi Corridor, between $97^{\circ}20'\sim 102^{\circ}13'E$ and $37^{\circ}28'\sim 39^{\circ}59'N$, with a land area of 4214 million hm^2 (Fig. 1). The research region has a typical temperate continental climate, mean annual precipitation varies between 60~280 mm, annual evaporation 1000~2000 mm. The mountain-originating river, Heihe River, is the only surface runoff of the Zhangye Basin. Since 1951 no obvious changes in surface runoff and

atmospheric precipitation were observed in the region, or roughly kept stable (Zhang, et al., 2003). The topography in the region dips from southeast to northwest, with a slope of 25-4%. Geomorphologically, the southern part is the piedmont alluvial, alluvial-diluvial Gobi plain and the middle part of the basin is alluvial-diluvial fine soil plain. Owing to the limitation of landform, deposits and tectonic conditions groundwater mainly comes from Quaternary interstitial water. From the southern piedmont to the northern basin centre the aquifer consists of single unconfined aquifer transiting to multilayer confined aquifer, and the groundwater table gradually becomes shallow to reach the spring overflow zone (Gao and Li, 1990; Wang and Cheng, 1999). According to landform, aquifer structure, groundwater storage and groundwater use conditions the study region was divided into four subzones. The extents and location are shown in Figure 1, and the climatic and hydrogeologic conditions, irrigation water sources and observation points of the four subzones are presented in Table 1.

The exploitation of groundwater resources in the Zhangye Basin has a history of nearly 200 years, however, as a whole, its consumption amount was small before 1970s. Since 1980s onwards the region's groundwater was extensively exploited. The temporal variations of groundwater extraction and the spatial distribution of extraction intensity in the Zhangye Basin in the past 20 years are presented in Table 2. During the 10-year period of 1980-1989 the region's mean annual extraction volume of groundwater was 60 million m^3 , starting from 1990s its extraction volume increased rapidly, the extracted volume in 1999 was 2 times the mean volume of the first five years of 1990s and 6 times the mean volume of 1980s. The extraction intensity of groundwater is different from place to place, the mid-upper part of alluvial-diluvial fans in the southern part of the basin has a relatively low extraction intensity, belonging to slight extraction zone, the lower part of the alluvial-diluvial fans have the largest extraction intensity, belonging to intense extraction zone; fine soil plain and river valley plain in the western part of the basin have an extraction intensity ranging from $3.0-25.0 \times 10^4 \text{m}^3/\text{km}^2 \cdot \text{a}$, belonging to moderate extraction zone.

1.2 The quantity evaluation method of EIGT model

In most occasions, human activities, including land use and water resources utilization (both surface water and groundwater), have integrated affections on groundwater system, which impact on the groundwater dynamics and recharge of groundwater system. Based the groundwater dynamic changes and the relationship between groundwater dynamic and recharge factors, normally the river runoff and precipitation, the evaluation index of

groundwater table (EIGT) model, which is an integrated method used to evaluate the degree and characteristics of human activities' affection on groundwater system, is set up by quantifiable index. The method combines two fields of groundwater dynamic evaluation modeling. Firstly, the exploitation index model based on the comparing the annual groundwater dynamic with exploitation season groundwater dynamic is used to evaluate the affection of extraction factor on groundwater system. Secondly, the runoff and rainfall index model is set up to evaluate the affections of human activities on groundwater recharge system. The way in which the each model is carried out is described below.

1.2.1 Exploitation index evaluation modelling

Groundwater dynamical types in arid zones generally included three types (Cheng and Qu, 1992; Gao and Li, 1990) (Fig.2): (1) Runoff hydrological type: dynamical changes of groundwater are closely related to the changes in river runoff and precipitation processes and exhibit an interrelated dynamical processes of river hydrology and precipitation changes; (2) Irrigation type: the dynamical changes of groundwater are controlled by irrigation, groundwater table during irrigation period is in a high water-table interval; (3) Extraction type: the dynamical changes of groundwater are controlled by extraction activity, during extraction period the groundwater system is in a low water-table interval. The main difference in the various groundwater dynamic of runoff type, irrigation type and extraction type is manifested in the water table changes during the irrigation and extraction periods (from June to September) (Fig.2). For runoff hydrological type, the higher groundwater levels appeared between August and November, and it appeared between May and November for irrigation type. If the groundwater table dynamic changed to extraction type under human exploitation, however, the periods between May and September are the low water-table interval. In order to quantitatively evaluate the degrees of the impacts of extraction factors on the groundwater systems in various hydrogeologic units a measuring factor of extraction index, which is based on the relative water table range, is introduced. It is defined as:

$$\delta_t = (\Delta H_{pt} / H_t) \mu \quad (1)$$

Where δ_t is the index of extraction factor of the calculated year (the t year), dimensionless; ΔH_p is the difference between the mean monthly water table elevation from June to September of the calculated year in specified region and the mean water table elevation of current year, $\Delta H_{pt} = H_t - H_p$; H_t is the mean annual water table elevation in specified region or at typical well points. Reference year t may be ages, such as 1980s and 1990s etc. μ is a systematic constant, it is determined by the magnitude of the elevation of groundwater table. In this study region the elevation of groundwater ranges from 1000-2000m, hence

$\mu=1000$.

The evaluation criterion of the intensity of the extraction index is: ① $\delta_t \geq 0.2$, severely affected. The dynamical change of groundwater is controlled by human exploitation, and it was dominated by extraction dynamic type. ② $0.1 \leq \delta_t < 0.2$, moderately affected. Extraction activities have a certain influence on the groundwater dynamics, and groundwater dynamics partly reflect the extraction type. ③ $0.0 \leq \delta_t < 0.1$, slightly affected. Extraction activity has a slight influence on the groundwater dynamical changes, and groundwater dynamics exhibit a weak extraction character. ④ $\delta_t < 0.0$, no effect or no extraction activity. Groundwater dynamics keep original and intact type.

1.2.2 Runoff and precipitation index evaluation modelling

The increased extraction intensity will significantly alter the dynamical type of groundwater and thereby inevitably affect the interrelation between the recharge elements of groundwater, including surface runoff and precipitation. Under the conditions that surface runoff and precipitation keep relatively stable for recent 50 years, the changes in the interrelation between surface water, precipitation and groundwater caused by the variations of groundwater dynamical types are mainly attributed to the impacts of human activities. In order to quantitatively evaluate the degree of the impact of human activities on the relation between surface runoff, precipitation and groundwater, the runoff and precipitation index are introduced and they are expressed as:

$$\gamma_t = \frac{|H_t - f(R_t)|}{H_t} \times \beta, \quad f(R_t) = H(R_t) \pm \varpi, \quad R_t \text{ is relatively stable} \quad (2)$$

$$\rho_t = \frac{|H_t - f(P_t)|}{H_t} \times \alpha, \quad f(P_t) = H(P_t) \pm \sigma, \quad P_t \text{ is relatively stable} \quad (3)$$

Where, γ_t, ρ_t are the runoff index and precipitation index respectively. $H(R_t), H(P_t)$ are the statistical relation functions of surface runoff, precipitation and groundwater established by the data series unaffected by human activities; ϖ, σ are the standard residual variances of statistical function of surface runoff, precipitation and groundwater. β, α are the proportional constants. According to the magnitude of groundwater table H_t may select 10, 100 or 1000. R_t, P_t are the surface runoff and precipitation in the calculated period.

The evaluation criteria of runoff indexes and precipitation indexes are as follows: ① $\gamma_t < 0.1$, there is no significant influence; ② $0.1 \leq \gamma_t \leq 0.5$, there is a slight influence; ③ $0.5 < \gamma_t \leq 1.0$, there is a moderate influence; ④ $1.0 < \gamma_t \leq 2.0$, there is severe influence; ⑤ $\gamma_t \geq 2.0$, there is a very severe influence. The larger the index, the weaker the influences of surface

runoff or precipitation on the groundwater dynamics are.

1.3 Analytical data basis

The evaluation requires the monthly mean values of groundwater dynamical observations, atmospheric precipitation, and surface runoff at representative stations of the region. The data sources used in this study includes: (1) groundwater dynamical observation data: a total of 54 observation wells were arranged in the Zhangye Basin of the Heihe River, 28 of which were started to be observed in 1980, available data include the monthly mean values in 20 years from 1981 to 2000; another 28 wells were started to be observed in the second half of 1983, available data include the monthly mean values in 17 years from 1981 to 2001. (2) Precipitation and surface runoff: the monthly mean precipitation data recorded at Zhangye and Gaotai weather stations in the study region were used, the surface runoff data include the monthly mean discharge values observed at the Yinluoxia Hydrologic Station at the mountain out mouth of the Heihe River and the discharge values observed at the Zhengyixia Hydrologic Station at the downstream outlet of the Basin.

2. Evaluation of extraction impacts on the groundwater dynamical changes

The groundwater dynamical observation wells were unevenly arranged in various evaluation subzones, at least more than 3 wells were selected for the observation. According to equation (1) the indexes of groundwater dynamical extraction indexes at typical well points were calculated and their results are presented in Table 3. Then, according to the above-mentioned evaluation criteria the degrees of the impacts of the extraction factors in different periods in various subzones in the Zhangye Basin were made and their results are presented in Table 3.

Since the 1980s, the index of extraction factors has been larger than 0.2 (Well No. 6 and 8 in table 3) in most of the mid-upper part of alluvial-diluvial fan in the southern part of the basin, this shows that in the past 20 years human exploitation of groundwater has seriously affected the groundwater dynamics in the region. As a result, the groundwater dynamics clearly appear as extraction type (Figure 3a), i.e. it is in a low water-table interval during the extraction period between April and September, and is in high water-table interval during the non-extraction period between November and March.

At the lower part of alluvial-diluvial fan in the center of the basin, human extraction activity did not affect the groundwater dynamics prior to 1990 for the extraction index was

less than 0 in most area of the region, therefore, groundwater dynamics remained its natural types, which were dominated by river hydrologic type and irrigation type (Figure 3b). However, after 1990, especially after 1995, the measuring factors of extraction degree has been exceeding 0.2 in most of the region, suggesting that human exploitation of groundwater has seriously affected and gradually controlled the groundwater dynamics. As a result, the groundwater dynamical type in the region gradually changed into extraction type from original hydrologic runoff type and irrigation type. The transformation of groundwater dynamical types is closely related to the indexes of extraction factors.

In the past 20 years the extraction indexes of groundwater dynamics in most of the fine soil plain in the center of the basin and its northern part were smaller than 0.1, the groundwater dynamics was not significantly affected by human extraction activities and was mainly controlled by the recharge sources of groundwater (well No. 1 in Figure 4a). However, since 1990 the measuring extraction index in the northern part of the fine soil plain dramatically increased, during the 1990-1995 period it experienced a moderate degree of extraction disturbance, and from 1995 onwards the measuring extraction index was generally larger than 0.2, the groundwater dynamics obviously appeared as extraction type controlled by extraction activities (No. 29 curve in Figure 4a). In the past 20 years the extraction index in the river valley plain of Linze and Gaotai, that are a part of the fine soil plain in the northwest of the basin, has always been smaller than 0.1, human extraction activity did not affect the groundwater dynamics in the region (Figure 4b).

The extraction indexes quantitatively reveal the degree of the impacts of human extraction activity on the groundwater dynamics in different regions. As for the Zhangye Basin the extraction index of 0.2 can be viewed as a critical value to judge whether human extraction activity has altered the groundwater dynamic type. Since 1990s the annual dynamical type of groundwater in the lower part of alluvial-diluvial fans and the northern part of fine soil plain has tended to evolve into extraction type, and in local places it has already turned into extraction type since 1995; during the 20-year period since 1980s the annual dynamical type of groundwater in the mid-upper part of alluvial-diluvial fans has turned into extraction dynamical type, which was controlled by extraction activity; however, in the river valley plain in the western part of the basin human extraction activities have not evidently affected the groundwater dynamical changes.

3. Evaluating the impacts of human activities on the relationship between surface

runoff, precipitation and groundwater

3.1 The relationship of $H(R_t)$, $H(P_t)$ and their change

Using the statistic regression method, the statistic relation function between precipitation and groundwater table elevation ($H(P_t)$) and the relation function between river runoff and groundwater table elevation ($H(R_t)$) are established for various subzones and listed in Table 4, Table 5 and Table 6 respectively.

In the lower part of alluvial-diluvial fans the groundwater table depth is relatively shallow, surface water (including river water and irrigation water) and precipitation have significant influences on the groundwater dynamics as compared to the mid-upper part of alluvial-diluvial fans, and there were two groundwater dynamical types, irrigation type and river hydrologic type. As for $H(P_t)$ of these two dynamical types in the region, they are characterized by similar function form and variations. Prior to 1990 the $H(P_t)$ have a weaker quadratic parabolic curve with statistical correlation coefficient was 0.57 or so (Table 4). However, such statistical relationship no longer existed after 1990. During 1980s groundwater dynamical change was closely related to river runoff processes in the river hydrologic type of groundwater dynamic zone, there were positive relationship between runoff and groundwater table elevation, and the $H(R_t)$ have logarithmic curve no matter it is close to or far away from the river channel with the correlation coefficient R 0.78 or so (Table 4). Irrigation type of groundwater dynamic is widely distributed in the old oases at the lower part of alluvial-diluvial fans, since the early 1980s the irrigation type of groundwater dynamical types have been formed due to the effects of irrigation factors, but it has been found that there still existed a certain positive correlation between groundwater table and river runoff; groundwater table exhibited an approximate logarithmic curve change with the river runoff, and the correlation coefficient R was 0.65 or so (Table 4). During 1990s, especially since 1995, the relationship no longer existed both river hydrological type zone and irrigation type zone.

In the fine soil plain in the center of the basin and its northern part the groundwater table depth is less than 10 m, aquifer structure is complex and there is confined water in most of the region. In the 1980s there were three groundwater dynamical types i.e. river hydrologic type, irrigation type and mixed irrigation-runoff type. The river hydrologic dynamical type mainly occurred in the vicinity of the river, there was an relatively positive quadratic

parabolic curve correlation between the precipitation and groundwater table ($R=0.66$) (Table 5), and it was a region that the precipitation had the most significant influence on the groundwater dynamics in Zhangye basin. There was a quite significant correlation between surface runoff and groundwater dynamics in the region, groundwater table exhibited a positive logarithmic curve with the changes in surface runoff ($R=0.89$), it manifested that surface runoff played a control role to the groundwater dynamical changes (Table 5). After the 1990s, the correlation between precipitation and groundwater table no longer existed, and the correlation between surface runoff and groundwater table dramatically changed into a weaker quadratic parabolic curve ($R=0.57$). Irrigation runoff type is a mixed river hydrologic type and irrigation type of groundwater dynamics, it mainly occurs in the eastern and northeastern part of the region. Precipitation has a weak influence on the groundwater dynamics. During 1980s the region's surface runoff had a quite obvious relation to the groundwater dynamics with a positive logarithmic curve ($R=0.8$). After 1990s, the relation between surface runoff and groundwater table became weaker but still maintained a positive logarithmic curve ($R=0.61$) (Table 5).

In the mid-upper part of alluvial-diluvial fans in the southern part of the basin, the groundwater table depth is more than 30m, so that the precipitation has little relation to the groundwater dynamics. Prior to 1990, the region's groundwater dynamics had a better correlation with surface runoff ($R=0.67$) (Table 6), this showed that at that time the groundwater dynamics was significantly affected by the river runoff. However, during the 10-year period after 1990, surface runoff almost showed no relation to groundwater dynamics. The river valley plain, located in the downstream interior basin in the western part of the region, has a groundwater table less than 10m. During the 1980s groundwater table showed a close correlation with surface runoff ($R=0.75$) (Table 6). But such correlation no longer existed in 1990s. Owing to lower precipitation of less than 100 mm, precipitation shows little relation to the groundwater dynamics.

3.2 Evaluation results of runoff index and precipitation index

The runoff indexes and precipitation indexes in different zones and different subzones of groundwater dynamical types were calculated using the statistical regression equation listed in the Table 4-6, equation (2) and (3), and the results are shown in Figure 5.

The runoff indexes in the fine soil plain were small and relatively stable before 1995, but their seasonal amplitudes were large with the difference by 5 times or even 13 times (Fig.

5a). High values generally occurred between May and August, while low values occurred between December and February. During the 1990-1995 period, the runoff indexes in the subzones of river hydrologic type, irrigation type and extraction type were 0.073, 0.119 and 0.069 respectively (Table 7). From 1996 onwards the runoff indexes in the fine soil plain significantly increased, especially in the subzones of the river hydrologic type and irrigation type subzones the extraction runoff indexes increased to 0.152 and 0.176 respectively, or a 2-3 fold increase (Table 7). This showed that after 1995 human extraction activities evidently affected the relation between groundwater and surface runoff in the region. In the subzones of irrigation type and river hydrologic type groundwater and precipitation had a better correlation, of which the precipitation indexes in the river hydrologic type subzone were 0.084 and 0.139 before and after 1995 respectively, further they increased significantly after 1995. In the irrigation type subzone the precipitation indexes changed little before and after 1995, they were 0.108 and 0.101 respectively and were significantly larger than those in the river hydrologic type subzone. As a whole, the extract activities in the fine soil plain only have a slight influence on the relation between surface runoff, precipitation and groundwater table.

Runoff indexes in the lower part of alluvial-diluvial fans in Zhangye Basin were large, with large inter annual range (Fig. 5b). During the 1990-1995 period, the annual mean runoff indexes value in the subzone of river hydrologic type varied between 0.12-0.59, implying a slight degree of influence. The corresponding figure in the subzone of irrigation type ranged from 0.45-1.48, implying a moderate degree of influence (Table 7). After 1996, however, the runoff indexes increased rapidly, in the subzone of river hydrologic type they increased by 0.83-2.3, or averaged 1.63, belonging to severely affected area. The corresponding figures in the subzone of irrigation type were 1.26-4.3, averaged 2.55, belonging to very severely affected area (Table 7).

In the mid-upper part of alluvial- diluvial fans in the basin the runoff indexes and their inter-annual variations were large too (Figure 5c). During the 1990-1995 period, the mean annual runoff indexes varied between 0.24-1.26, belonging to moderately affected area. After 1995 the runoff indexes increased linearly, and reached 0.83-3.7 during the 1996-2000 period, averaged 2.11 (Table 7). This shows that since 1995 the extraction activity has seriously affected the region's relationship between groundwater dynamics and river runoff. Relatively, the extraction runoff indexes in the downstream river valley plain were small and tended to

become stable in the past 20 years, with small inter annual variations (Figure 5c). The runoff indexes during the 1990-2000 period varied between 0.19-0.17 and showed no significant variation before and after the 1995. The mean annual runoff index was 0.181, belonging to slightly affected area (Table 7).

4. Conclusion

(1) Based on the groundwater dynamical observation data, the EIGT model is put to quantitatively evaluate the impacts of human activities on the groundwater system. Integrating the extraction index and runoff and precipitation index, the method could reveal the degree of human activities' impacts on groundwater dynamics and the relationship between river, precipitation and groundwater. Taking account the spatial hydro-geological subzones and the variation of groundwater dynamics, the EIGT model results is a spatial component to time series of affection assessment.

(2) The impact of human activity on the groundwater system in middle reaches of Heihe river basin northwest China, as an example, was evaluated using the EIGT model. The results reveal an evident temporal and spatial differentiation character of the impacts degree of human activities on groundwater system. In the past 20 years the groundwater extraction intensity has being enhanced up since 1995 and specially in the lower parts of alluvial-diluvial fans and the fine soil plain in the middle reach of the Heihe River, and it have seriously affected the groundwater system in the upper to lower parts of alluvial-diluvial fans; the occurrence and development of single extraction dynamical type of the groundwater system as well as the changes in the influences of surface runoff and precipitation on groundwater revealed that a large regional cone of depression has formed in the region; extraction activities also started to significantly affect the groundwater system in local places of the fine soil plain (especially its north part), however no evident variations were observed in the river valley plain in the western part of the basin.

Acknowledgement: This research was funded by the China-Japan Corporation Project "Historical evolution of the adaptability in an oasis region to water resource changes", and the National Natural Science Foundation Project (No. 40171002).

References

Belousova, A.P. (2003) Structure of ecological indicators and indices for sustainable groundwater

- development. IAHS Publ. no. 280, 2003. p. 48–53
- Bierkens, M. F. P., Knotters, M. and F. C. Van Geer. Calibration of transfer function-noise models to sparsely or irregularly observed time series. *Water Resources Research*, 1999, 32: 1741-1750.
- Cheng Longheng, Qu Yaoguang (1992) Water and Land resources and their rational exploitation in Hexi corridor. Science Press, Beijing, pp 36-169 (in Chinese).
- Gao Qiaozhao, Li Fuxing. Rational development and utilization of water resources in the Heihe River Basin. Lanzhou: Gansu Science and Technology Press, 1990.
- Gehrels, J.C. (2001); “Preface” In: Impact of Human activity on groundwater dynamics, Gehrels et al. (eds.) IAHS Publ. No. 269, pp. V-VI.
- Guangheng Ni, Yangwen Jia, Tsuyoshi Kinouchi, Kouei Tojima, Junichi Yoshitani, Tadashi Suetsugi. Field observation and simulation of groundwater level changes due to urbanization in the Yata River basin, Japan. IAHS Publ. no. 269, 2001, pp. 139–145.
- Hydrologic Bureau of Water Resource Ministry of China (WMC). Handbook of Groundwater monitoring. <http://www.mwr.gov.cn/shuiwen>.
- K. Sato and Y. Iwasa. Groundwater hydraulics. Tokyo: Springer-Verlag, 2003, pp204.
- Khazai, E. Urbanization effects on groundwater quantity and quality in the Zahedan aquifer, an arid region in southeast Iran. IAHS Publ. no. 269, 2001, pp. 155–159.
- Knotters, M. and P. E. Van Walsum. Estimating fluctuation quantities from time series of water-table depths using models with stochastic component. *Journal of Hydrology*, 1997, 197: 25-46.
- Mtembezeka, P.; A. J. Andrews; and S. O. Appiah. Groundwater management in drought-prone areas of Africa. *Water Resources Development*, 1997, 13(2): 241-261.
- Querner, E. P. The effects of human interventions on groundwater recharge. IAHS Publ. no. 269, 2001, pp. 59–66.
- Robert B. Jackson, Stephen R. Carpenter, Clifford N. Dahm, Diane M. McKnight, Robert J. Naiman, Sandra L. Postel, and Steven W. Running. Water in a changing world. *Ecological Applications*: 2001, 11(4): 1027–1045.
- Schwartz, W.F and Hubao, Z. Fundamentals of ground water. New York: John Wiley & Sons. 2003, pp583.
- Shah, T.; D. Molden, R. Sakthivadivel, D. Seckler. The global groundwater situation: Overview of opportunities and challenges. Colombo, Sri Lanka: International Water Management Institute (IWMI), 2000, pp23.
- Von Asmuth, J.R. and Mass, K. The method of impulse response moments: a new method integrating groundwater and eco-hydrological modeling. IAHS Publ. No. 269, 2001: 51-58.

- Wang Genxu, Cheng Guodong. Water resources development and its influence on the eco-environment in arid areas of China—The case of the Heihe river basin. *Journal of Arid Environment*, 1999, 43:121-131
- William M. Alley, Thomas E. Reilly and O. Lehn Franke. Sustainability of ground-water resources. U.S. Geological Survey Circular 1186, U.S. Geological Survey, 1999
- Xu Yueqing. Evaluation of groundwater level drawdown driving forces in the Hebei Plain to the south of Beijing and Tianjin. *Progress in Geography*, 2003, 22(5): 490-498.
- ZHANG Jishi, KANG Ersi. Impact of climate change and variability on water resources in Heihe River Basin. *Journal of Geographical Sciences*, 2003, 13(3)

Table 1 Natural conditions, hydrogeologic settings and observation points in the study region

subzone	extent and natural condition	hydrogeologic features and irrigation condition	observation points
Mid-upper part of alluvial-diluvial fans	Located in piedmont alluvial and diluvial gobi plain in the south, 1500-2800m in elevation, annual precipitation 120-300mm.	Single unconfined aquifer, groundwater table depth > 30m; irrigation is dominated by river water, local places are irrigated by river water and well water.	No. 6, 8 and 14
Lower part of the alluvial and diluvial fan	Intersection of alluvial and diluvial Gobi plain with the fine-grained soil plain with elevation between 1400-1800m and the annual precipitation of 100-250mm.	Conversion from single unconfined aquifer to multi layer confined aquifer with the water table depth between 8-30m; irrigated by well water mixed with river water.	No. 3, 4, 5, 11, 13 and 21
Fine-grained soil plain	Located in Zhangye city area of the fine-grained soil plain with elevation between 1300-1600m and precipitation of 100-150mm.	Multi layer confined aquifer with water table depth less than 10m, ground water, spring and river water mixed for irrigation.	No. 1, 2, 18, 15, 25, 28, 29 and 30
River valley plain in the lower part of basin	River valley alluvial plains along the rivers in Linze and Gaotai, northwestern part of the fine soil plain, 1270-1500m in elevation, annual precipitation 60-120mm.	Multi layer confined aquifer with water table depth less than 10m, ground water, spring and river water mixed for irrigation .	No. L11~23, G1~3, G8~16

Table 2 Extracted volume of groundwater and the distribution of extraction intensity in Zhangye Basin

Extracted volume of groundwater ($10^8 \text{ m}^3/\text{a}$)				Distribution of groundwater extraction intensity ($10^4 \text{ m}^3/\text{km}^2 \cdot \text{a}$)			
1980s	1990-1995	1997	1999	Mid-upper alluvial-diluvial fan	Lower alluvial-diluvial fan	Fine soil plain	River valley plain in lower part
0.6	1.951	2.254	3.69	2.9-12.37	13.7-61.2	3.87-15.7	2.73-25.4

Table 3 Measuring factors of groundwater extraction degrees and variations in different hydrogeologic units in the middle reach of the Heihe River

Mid-upper part of alluvial-diluvial fans in the southern part of the basin						Lower part of alluvial-diluvial pans in the center of the basin					
Well No.	1982	1986	1990	1995	2000	Well No.	1982	1986	1990	1995	2000
6	0.46	0.24	0.28	0.11	0.53	11	-0.02	-0.02	0.07	0.09	0.25
8	0.38	0.28		0.27	0.28	21	-0.20	-0.24	-0.14	0.44	0.57
14	0.11	0.06	0.08	0.26	0.23	13	-0.05	-0.11	-0.02	0.28	0.21
Evaluation	Continuously and severely affected areas					Evaluation	Slightly-severely affected areas				
Fine soil plain in the center of basin and its northern part						River valley plain in the western part of the basin					
Well No.	1982	1986	1990	1995	2000	Well No.	1985	1990	1995	2000	
25	-0.27	-0.07	-0.02	0.06	0.02	L12	-0.55	-0.35	-0.22	0.00	
29	-0.13	-0.04	0.12	0.26	0.40	L14	-0.19	-0.11	0.06	0.07	
30	0.15	-0.09	-0.04	0.02	-0.05	G7	-0.26	-0.24	-0.16	-0.17	
1	-0.24	-0.07	-0.11	0.00	-0.15	G 16	-0.17	-0.07	0.03	-0.13	
Evaluation	No influence-slightly affected areas					Evaluation	No influence				

Table 4 $H(R_t), H(P_t)$ and their variations in the lower part of alluvial-diluvial fans in the basin

Sub-zone	$H(P_t)$		$H(R_t)$	
	1980s	1990s	1980s	1990s
Hydrologic runoff type	$y = -0.0002x^2 + 0.03x + 1481.2, R = 0.57$	No significant relation	$y = 0.4707\ln(x) + 1479.7, R = 0.78$	No significant relation
Irrigation type	$y = -0.0003x^2 + 0.0313x + 1478.8, R = 0.57$	No significant relation	$y = 0.3479\ln(x) + 1477.8, R = 0.65$	No significant relation

Table 5 Relations between groundwater dynamics with precipitation and surface runoff in the fine soil plain in the center of the basin and its northern part

Subzone	Relation between atmospheric precipitation and groundwater table		Relation between surface runoff and groundwater table	
	1980s	1990s	1980s	1990s
Hydrologic runoff type	$y = -6E-05x^2 + 0.011x + 1440.3, R = 0.66$	No significant relation	$y = 0.187\ln(x) + 1439.7, R = 0.89$	$y = 4E-06x^2 + 0.001x + 1440.1, R = 0.57$
Irrigation type	$y = -3E-05x^2 + 0.005x + 1433.6, R = 0.56$	No significant relation	$y = 0.0757\ln(x) + 1433.4, R = 0.69$	no significant relation
Irrigation runoff type	$y = -4E-05x^2 + 0.011x + 1463.4, R = 0.41$	No significant relation	$y = 0.317\ln(x) + 1462.3, R = 0.79$	$y = 0.2056\ln(x) + 1462.5, R = 0.61$

Table 6 Interrelations between groundwater dynamics, surface water and precipitation and their variations in the lower part of alluvial-diluvial fans in the basin

subzone	relation between atmospheric precipitation and groundwater table		relation between surface runoff and groundwater table	
	1980s	1990s	1980s	1990s
mid-upper part of alluvial-diluvial fans in the basin	$y = -0.0001x^2 + 0.031x + 1470.6, R = 0.412$	no significant relation	$y = 0.7439\ln(x) + 1468.2, R = 0.67$	no significant relation
river valley plain in the western part of the basin	no significant relation	no significant relation	$y = 0.3849\ln(x) + 1285.3, R = 0.75$	no significant relation

Table 7 Extraction runoff indexes in different subzones of hydrogeologic units and the variations in different periods

	Mid-upper part alluvial-diluvial fans	Lower part of alluvial-diluvia fan		Fine soil plain and its northern part			Downstream river valley plain
		Hydrologic type	Irrigation type	Hydrologic type	Irrigation type	Extraction type	
1990-1995	0.712	0.382	1.06	0.073	0.119	0.069	0.193
1995-2000	2.11	1.633	2.55	0.152	0.112	0.176	0.169
1990s	1.46	0.91	1.85	0.116	0.115	0.127	0.181

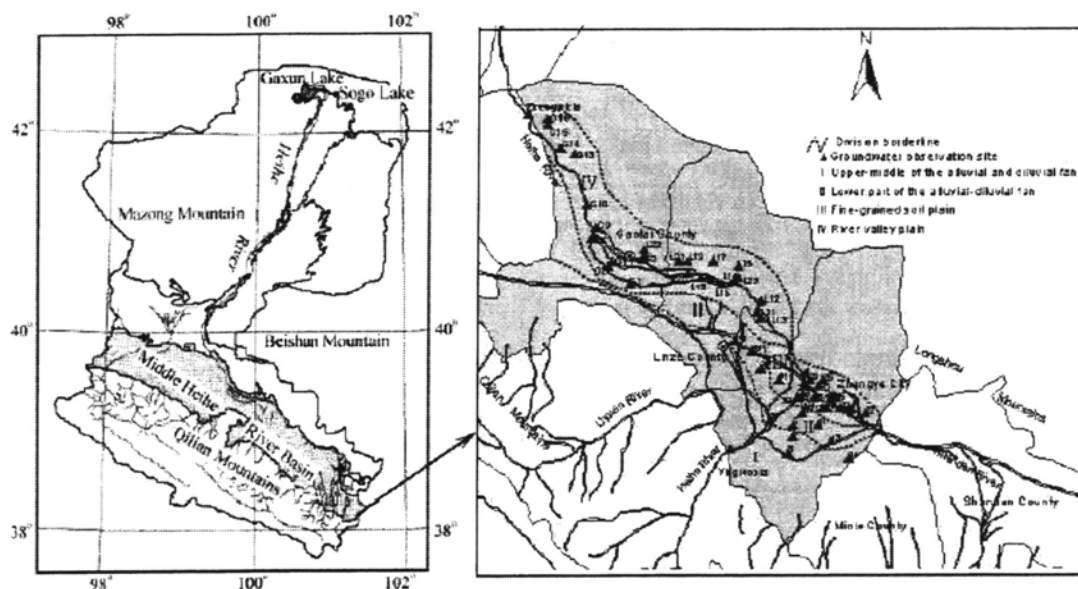


Figure 1 The Diagrammatic map of study area, observation points distribution and sub-zones

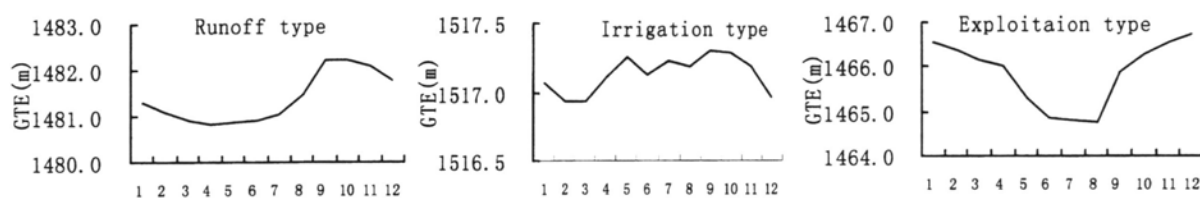


Figure 2 Three main groundwater dynamic types in study area

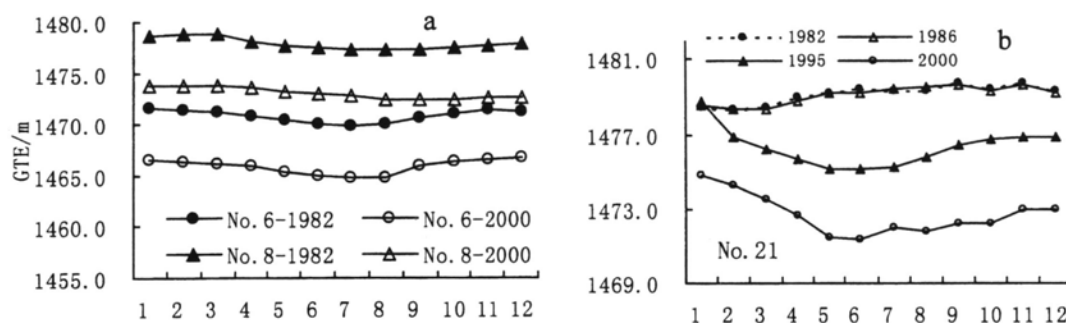


Figure 3 Dynamical changes of groundwater in the mid-upper (a) and lower alluvial-diluvial fans (b) in the basin

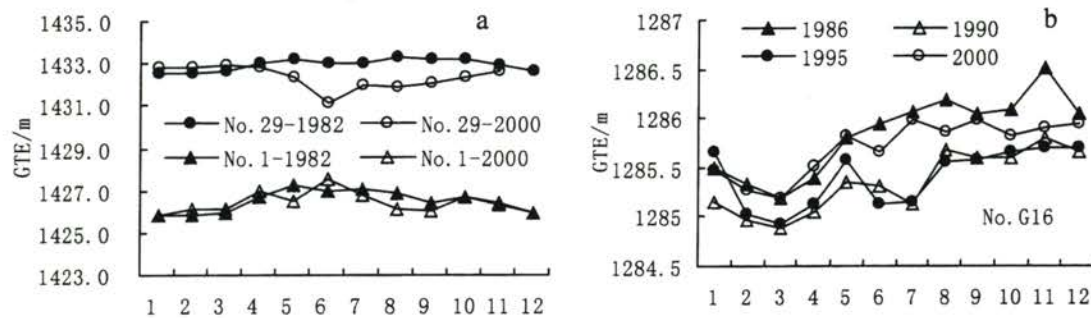


Figure 4 Characteristics of groundwater dynamical changes in the fine soil plain (a) and river valley plain (b)

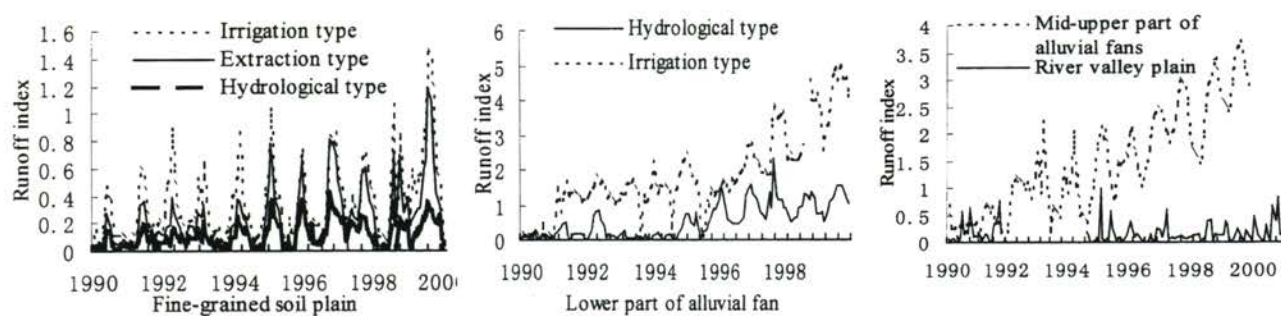


Figure 5 Variation courses of runoff indexes in different evaluation subzones in the Zhangye Basin in the Heihe River basin

Part 4: The groundwater resources change and its cause analysis in the middle of Heihe river basin

Abstract: With three periods of remote sense data since 1960s and the long-term observed data of groundwater since 1980s, the changes of the groundwater resources in the middle reach of Heihe River Basin in recent three decades are analyzed with the aspects of groundwater recharge and discharge system. The results indicate that the groundwater recharge were reduced by $2.168 \times 10^8 \text{ m}^3/\text{a}$ in the former fifteen years (1969-1985) but increased by $0.134 \times 10^8 \text{ m}^3/\text{a}$ in the later fifteen years (1986-2000) due to the different intensity of land-use and land-cover changes. The groundwater discharge decreased of $2.035 \times 10^8 \text{ m}^3/\text{a}$ due to land-use and land-cover changes during 1969-1986, and it increased of $0.678 \times 10^8 \text{ m}^3/\text{a}$ with the both influences of LUCC and groundwater pumping. Resulting from the changes of groundwater recharge and discharge systems, the groundwater storage decreased $0.133 \times 10^8 \text{ m}^3/\text{a}$ during 1969-1986 and $0.545 \times 10^8 \text{ m}^3/\text{a}$ during 1986-2000. As long as under the reasonable range of exploitation (less than $3.0 \times 10^8 \text{ m}^3/\text{a}$), the land-use changes would control the changes of regional groundwater resources. Influenced by the land-use and land-cover changes and the large-scale exploitation in the recent decade, the groundwater resources present apparent regional differences in Zhangye Basin. Realizing the characteristics of spatial-temporal variations of regional groundwater resources may make the programming and management of water and soil resources more scientific and reasonable.

Key words: Groundwater system, Groundwater resources, Change, Cause, Heihe River Basin

Introduction

Nowadays, the research of the influence of land-use and land-cover changes on the regional water balance is most vigorous in the international hydrological fields, and lots of research indicates that large-scale land-use and land-cover changes are the important factors leading to the regional climate and hydrological cycle changes (Hutjes et al., 1998; Zhang et al., 2001). Therefore, the research plan LUCC established by IGBP and IHDP, one key problem was to understand the influence of the regional land-use and land-cover changes on

hydrological process and water resources (Hoff, 2002; Sun et al., 2003; Suzanne, 2001). Lots of research shows that the regional land-use and land-cover changes remarkably affect the regional hydrological cycle process (Deng, et al., 2003; Fu et al., 2001; Zhang et al., 2001), and that the influence of land-use and land-cover changes in the catchment scale on hydrological process, including the groundwater system, are the pop research field and become another important developing field in hydrology.

Groundwater system is the most important portion of whole catchment hydrological process; therefore, every change of hydrological processes must have some impacts on the groundwater system (Schwartz et al., 2003). The characteristics of water resources in arid region determine that groundwater is usually the most important origin and the best water supply choice in such region, at the same time, groundwater is also the primary factor to maintain arid life oasis, especially the social-economic developments in deserts. Worldly, groundwater resources are actually irreplaceable in resolving water scarcity, and scientific evaluation and effective management, which were depended on the recognition to the groundwater changes and its causes, are the important guarantees and necessary preconditions to explore groundwater resources in arid region (Mtembezeka et al., 1997; Alley et al., 1996). In most cases, the land use and land cover changes and human pumping activities are the main factors that lead to the changes of groundwater resources. Thereinto, actual estimation of the influence of human activities on groundwater system is the critical part in establishing reasonable utilization program of regional groundwater resources (Sato, et al., 2003; Asmuth, et al., 2001; Alley et al., 1999). The previous study of the influence of human activities on groundwater system mainly focused on the aspect of the intensity and reasonability of groundwater utilization, but ignored the influence of land-use changes on the groundwater system in the basin. Actually, as the important part of regional hydrological cycle, groundwater system has strong response to land-use and land-cover changes. Selecting Zhangye Basin of Heihe River middle reach in Hexi Corridor as the study area, we analyze the cause of groundwater resource changes, especially the response characteristics of arid groundwater system to land-use changes.

1. Study area and methods.

1.1 Study area

Taking the Zhangye Basin in the middle reach of Heihe River—the second longest inland river in China as the study area, which is located in the middle sect of Hexi Corridor, between $97^{\circ} 20' \sim 102^{\circ} 13' \text{ E}$, $37^{\circ} 28' \sim 39^{\circ} 59' \text{ N}$. The total area is $421.4 \times 10^4 \text{ km}^2$. It is the typical continental temperate climate with scarce precipitation and strong evaporation, the mean annual precipitation is 62-280mm and the mean annual evaporation is 1000-2000mm. Since 1951 no obvious changes in surface runoff and atmospheric precipitation were observed in the region, or roughly kept stable (Zhang, et al., 2003). The topography in the region dips from southeast to northwest, with a slope of 25-4‰. Geomorphologically, the southern part is the piedmont alluvial, alluvial-diluvial Gobi plain and the middle part of the basin is alluvial-diluvial fine soil plain. Owing to the limitation of landform, deposits and tectonic conditions groundwater mainly comes from Quaternary interstitial water. From the southern piedmont to the northern basin centre the aquifer consists of single unconfined aquifer transiting to multilayer confined aquifer, and the groundwater table gradually becomes shallow to reach the spring overflow zone (Gao and Li, 1990; Wang and Cheng, 1999). According to landform, aquifer structure and the topographic units, the study area is divided into four hydrogeologic units from south to north: the upper-middle part of alluvial-diluvial fan in the south, the lower part of alluvial-diluvial fan, the fine-grained soil plain in the basin center, and the river valley plain in the lower reach of the basin (Figure 1).

In the past two decades, land-use and land-cover in Heihe River Basin changed intensively, which was indicated by the shrink of the natural oasis system, namely, the expansion of man-made oasis system and the abandonment of original riverway caused by the increase of irrigated fields (Wang and Cheng, 1999; Wang et al., 2002). All these changes would lead to the thorough spatial-temporal variations of water resources system, especially those of such core factors as recharge, runoff and discharge of groundwater system.

1.2 Method and data

The elementary formula of composing change and management of groundwater resources is as follows (Sato, et al., 2003):

$$Q_R - Q_D = \Delta S$$

(1)

Where: Q_R is the groundwater recharge, such as riverway infiltration, precipitation infiltration, irrigating water infiltration, and groundwater lateral inflow; Q_D is the groundwater discharge, mainly the spring outflow, evapotranspiration of unconfined groundwater, exploitation and groundwater lateral outflow; ΔS is the groundwater change of the entire system. Changes of all these composing factors reflect the response of groundwater system to land-use and land-cover changes.

1.2.1 Method for analyzing the changes of recharging and discharging factors

In recharging factors, the precipitation infiltration is ignored in this study because a little of precipitation in the arid inland plain which had little influence on groundwater resources. The analyzing method of the main factors—riverway and irrigating water infiltration is as follows:

For the recharge of riverway water:
$$\Delta Q_r = \sum_{i=1}^n q_i \Delta L_i \lambda_i$$

(2)

While for the main stream, the riverway is divided into two parts—the part of head-up above the main irrigation cannel diversion mouth and that of head-down from diversion mouth to spring outflow area. The head-up part infiltration is closely related to the stable mountainous out runoff but changed for power generation diversion with a stable volume per every year, so its measurement is calculated as a constant in this study.

For the recharge of the part of head-down:

$$\Delta Q_{rm} = (Q_0 - Q_{RI} - \Delta q_c) \lambda_m \quad (3)$$

In the formula (2) and (3), q_i is the mountainous out runoff of each river; ΔL_i

represents length change of each river; λ_i is infiltration coefficient; Q_0, Q_{RI} represent the mountainous out runoff of main stream and head-up river seepage, respectively; Δq_c is the change of water diversion of head-up river part, which is close to irrigation field; λ_m is the riverway infiltration rate of the part of head-down part to spring outflow section.

Irrigating water recharge is farther divided into canal infiltration and field infiltration, and the analyzing formula is shown as follows:

$$\text{For the recharge of canal:} \quad \Delta Q_c = q_c (1 - \Delta\alpha) \beta \quad (4)$$

$$\text{For the recharge of field:} \quad \Delta Q_i = \sum_{j=1}^m \Delta F_j q_{0j} \eta_j \quad (5)$$

In which: q_c, q_0 represent the water diversion of head-up river and the net irrigation rating, respectively; $\Delta\alpha$ is the change of canal utilizing coefficient along with canal length; β, η_i represent the canal infiltration coefficient and irrigating infiltration coefficient, respectively; ΔF_j is the area change of each irrigating field.

In the groundwater discharging factors, there are mainly the groundwater evapotranspiration, spring outflow and the groundwater pumping. The field with different type of land-use and land-cover has different evapotranspiration of groundwater, and the evapotranspiration magnitude was controlled by groundwater level too. Therefore the groundwater evapotranspiration is the coupling result of groundwater level and land-use changes, shown in the following formula:

$$\Delta Q_E = \sum_{p=1}^K \sum_{v=1}^L F_{p,v} \gamma_{p,v} \quad (6)$$

In which, $F_{p,v}, \gamma_{p,v}$ represent the area of p th divided region according to groundwater level (hm^2), and evapotranspiration intensity in v th sub-area according the land using and land cover type, mm/a .

The increase of the area of well irrigating field leads to the increase of exploitation that is closely related to the land-use changes. Additionally, spring outflow, indirectly affected by the land-use changes, is determined by the change of groundwater level. The two factors of groundwater discharge were determined by the statistical data of the changes of exploitation and spring outflow.

1.2.2 Method for analyzing the groundwater storage changes

Based on the hydrogeologic divisions of the entire region and using the observing data of groundwater table changes, the annual variations of groundwater storage are calculated as following formula, which comes from Darcy Law.

$$\Delta W_{ij} = \mu_i F_i (\overline{H}_{ij} - \overline{H}_{i0}) \quad (7)$$

Where: ΔW_{ij} is the relative groundwater storage change of the j th year in the i th division area compared to the groundwater storage of the year of 1981 (1984) when it start to observe the groundwater table, m^3 ; μ_i is storage coefficient, no dimension; F_i is the area of i th division, hm^2 ; \overline{H}_{ij} , the average observing groundwater level of the j th year in the i th division area, m; and \overline{H}_{i0} is the average observing groundwater level of the year of 1981 in the i th division area, m.

1.2.3 Data sources and parameters

(1) Data of land-use changes: With the regional aerial data of 1969, TM data for regional satellite remote-sense research of 1986 and 2000, we marked the plots of diverse land-use in the topographic map of 1:100000 according to the national standard of the division of land-use (Wang et al., 2002), and picked up the areas of irrigating field, grassland, woodland, desert (naked rock, soil, desert and Gobi, et al), river, and canal system. And then, based on the groundwater table isograms of 1986 and 2000, compared with the land use change data obtained from the satellite remote-sense data, the areas of land use change under the groundwater table less than 1.0m, 1-3.0m, 3-5.0m and 5-10.0m were respectively calculated.

(2) The observing data of groundwater: There are 54 observing points along the Heihe River in Zhangye Basin, in which, the observation of 28 points began in 1980 and the effective data concerning the average annual and mensal observing values of two decades, and the observation of the other 26 points began in late 1983 and the effective data concerning the average annual and mensal observing values of 17 years.

(3) Parameters: In 1986-1989 lots of large-scale investigation of groundwater resources was conducted successively, and through some fields pumping test, fields groundwater dynamic observation, a serial of parameters were established in Zhangye Basin by Gansu Hydrogeological Investigation Team (Gansu Hydrogeological Investigation Team, 1990). The permeability coefficient, hydraulic conductivity, Specific yield, irrigating infiltration coefficient and evapotranspiration intensity used in this paper come from these broadly used testing results (Gansu Hydrogeological Investigation Team, 1990; 1998) .

Table 1 The measurement of parameters used in this study

Groundwater table (m)		<1	1-3	3-5	5-10	Subarea	Upper-middle part of alluvial-diluvial fan	Fine-grained soil plain
Irrigating infiltration coefficient (%)		28.1	34.9	28.4	18.5	Specific yield (m ³ /m)	0.15	0.1
Evapotran- spiration of unconfined groundwater (mm/a)	Irrigating area	327.79	55.3	41.0	12.0	Riverway infiltration rate (%)	0.32-14.7	0.67-1.52
	grassland	191.43	34.69	23.9	7.01	Canal leak recharging rate (%)	0.7-0.8	0.8-0.9

2. The changes of the groundwater recharging system

2.1 The changes of infiltration recharge of riverway and channel

Before 1985, $5.186 \times 10^8 \text{ m}^3/\text{a}$ runoff of the distributaries of Heihe River out of the mountainous in Zhangye Basin was taken into canals and reservoirs, which caused the intensive changes of riverway distribution (Table 2). Based on such information, the riverway infiltration recharge decreased $1.608 \times 10^8 \text{ m}^3/\text{a}$ in 1970-1985 and $0.266 \times 10^8 \text{ m}^3/\text{a}$ in 1986-2000. Moreover, infiltration recharge decreased by $0.529 \times 10^8 \text{ m}^3/\text{a}$ in the head-up part of riverway due to the power generation diversion $7.2 \times 10^8 \text{ m}^3/\text{a}$ from the main river at the mountain out mouth before 1985. After the water diversion to canals, infiltration decreased $1.156 \times 10^8 \text{ m}^3/\text{a}$ in the head-down riverway part between canal diversion mouth and spring outflow zone in 1970-1985 and $0.313 \times 10^8 \text{ m}^3/\text{a}$ in 1986-2000 (Table 2).

Table 2 The changes of infiltration recharge of riverway and channel

Period of time	Changes of river length (km)	Changes of diversion ($10^8\text{m}^3/\text{a}$)	Changes of river infiltration ($10^8\text{m}^3/\text{a}$)	Changes of canal diversion ($10^8\text{m}^3/\text{a}$)	Canal utilizing rate	Changes of canal infiltration	Changes of canal system
1970-1985	-59.07	6.02	- 3.293	2.27	0.5	0.908	- 2.385
1986-2000	-17.63	1.49	-0.579	1.92	0.65	0.537	-0.042

During 1970-1985 the irrigating agriculture developed with a most fast rate in the Zhangye basin, and the length of canal system and its water efficiency increased, respectively, which directly lead to more canal water diversion. Additionally, the average canal efficiency was 0.5 before 1985, but after 1986, especially in 1990s, it increased to 0.65 averagely. Based on such information and the former formula, the changes of canal infiltration recharge are calculated and listed in table 2. In the fifteen years before 1985, with the increase of water diversion the canal recharge to groundwater increased $0.908 \times 10^8 \text{m}^3/\text{a}$ and $0.537 \times 10^8 \text{m}^3/\text{a}$ in 1986-2000. The changes of river infiltration concentrated on the upper-middle part of alluvial-diluvial fan because a large amount of rivers were inducted into canals or reservoirs, while the changes of canal infiltration concentrated on the center of man-made oasis located in the middle-lower part of alluvial-diluvial fan and fine-grained soil plain.

2.2 The changes of infiltration recharge of irrigating field areas

Groundwater recharging changes caused by the changes of irrigating field areas are the one of the most important factors of groundwater recharge system changes. In the arid inland region, the groundwater table of the area where irrigating infiltration could recharge to groundwater is generally lower than 10m. To compare the the groundwater table isograms of 1986 and 2000 with the land-use change plots in 1969-1986 and 1986-2000, the two periods irrigating area changes with different groundwater table were calculated and listed in table 3. Different field has different irrigating quota, for example, the average total irrigating quota in Zhangye is $7872 \sim 14191.5 \text{m}^3/\text{hm}^2$, but it is $10092 \sim 10957.5 \text{m}^3/\text{hm}^2$ in Linzhe and $9618 \sim 17356.5 \text{m}^3/\text{hm}^2$ in Gaotai. The efficiency of irrigation system was selected the average 50% before 1985 and 65% after 1986. Then it is calculated that the increase of recharge owing to the increase of irrigating area is $2169.69 \times 10^4 \text{m}^3/\text{a}$ in 1970-1985, and $1767.09 \times 10^4 \text{m}^3/\text{a}$ in 1986-2000 (Table 3).

Table 3 Influence of the changes of irrigating fields on groundwater recharge

Groundwater table (m)		<1	1-3	3-5	5-10	Total
1970 ~ 1985	Area changes of irrigating fields (km ²)	5.5	41.35	40.67	53.05	140.57
	Average irrigating rate (m ³ /ha)	4950	5400	6150	6150	
	Infiltration (10 ⁴ m ³)	76.5	779.28	710.34	603.57	2169.69
1986 ~ 2000	Area changes of irrigating fields (km ²)	6.5	15.41	30.03	46.34	98.28
	Average irrigating rate (m ³ /ha)	5250	7035	7560	7560	
	Infiltration (10 ⁴ m ³)	95.89	378.34	644.75	648.11	1767.09

3. The changes of the groundwater discharge system

Since evapotranspiration mainly happened in the zone whose groundwater table is less than 10m (Gansu Hydrogeological Investigation Team, 1990), where the most grassland with low cover degree (such as the desert grassland), semi-fixed and fixed dune, and the desert have turned to irrigating fields, the changes of irrigating area from the original grassland according to the groundwater table were used to calculate the influence of land-use changes on evapotranspiration. The groundwater evapotranspiration in the grassland with high cover degree (>70%) in the plain is thought to be equal to that of cropland (Gansu Hydrogeological Investigation Team, 1998). The influence of woodland on groundwater evapotranspiration is intensive. According to some research in this region (Gansu Hydrogeological Investigation Team, 1998), the evapotranspiration of woodland is about 2700m³/ha. All the groundwater evapotranspiration changes were calculate with the former formula and shown in table 4.

Table 4 Evapotranspiration changes in different land-use

Groundwater table (m)		<1	1-3	3-5	5-10	Woodland changes	Total
1970 ~ 1985	Area changes of irrigating fields (km ²)	2.3	31.15	38.54	53.05	88.45	213.49
	Vaporizing intensity (m ³ /ha)	3277.9	553	410	120	2700	
	Evaporation of unconfined groundwater (10 ⁴ m ³)	75.39	172.25	158.02	63.66	2388.15	2857.47
1986 ~ 2000	Area changes of irrigating fields (km ²)	3.5	12.74	30.03	46.34	-33.03	48.58
	Vaporizing intensity (m ³ /ha)	3277.9	553	410	120	2700	
	Evaporation of unconfined groundwater (10 ⁴ m ³)	114.72	70.45	123.12	55.6	-891.81	-527.92

The other groundwater discharging items are spring outflow and human exploitation,

which are calculated directly used the statistical and metrical data according to the investigating results obtained by Gansu Hydrogeological Investigation Team (Gansu Hydrogeological Investigation Team, 1990; 1998). The measurement of the changes of spring outflow and groundwater exploitation is shown in table 5, in which the spring outflow of 2000 is the prognosticated result with some statistic model (Gansu Hydrogeological Investigation Team, 1998).

Table 5 changes of spring outflow and exploitation

Year	1970	1985	1995	2000	1970-1985	1986-2000
Spring outflow ($10^8\text{m}^3/\text{a}$)	10.19	7.23	5.34	5.17	-2.96	-2.06
Exploitation ($10^8\text{m}^3/\text{a}$)	0.186	0.83	1.086	3.62	0.644	2.79

According to the results of table 4 and table 5, the change of groundwater discharging system cause by land-use changes in Zhangye Basin averagely decreased $2.035 \times 10^8\text{m}^3/\text{a}$ in the fifteen years before 1985 mainly because spring outflow decrease sharply, while in the fifteen years after 1986 it increased $0.6785 \times 10^8\text{m}^3/\text{a}$ mainly because outflow tended to decrease more slowly and the exploitation increased intensively.

4. Groundwater storage changes and balance analysis

4.1 Groundwater storage changes

The groundwater storage changes are calculated with the formula (7) and the observing data of groundwater level variations in every hydrogeologic unit, and the results are shown in table 6. The results indicate that the groundwater storage of upper-middle part of alluvial-diluvial fan presents an apparent declining trend, thereinto, the storage declined $6.27 \times 10^6\text{m}^3$ annually in the 1980s, and $15.08 \times 10^6\text{m}^3$ in the 1990s, totally $220.7 \times 10^6\text{m}^3$ in two decades, and averagely $11.0 \times 10^6\text{m}^3$ every year. In the lower part of alluvial-diluvial fan, groundwater storage tended to decline generally, but there's spatial-temporal distribution. In the 1980s storage declined slowly, thereinto, it decreased $11.80 \times 10^6\text{m}^3$ totally in 1980-1989, that was, $1.2 \times 10^6\text{m}^3$ every year. And in 1981-1983 storage did not decline but increase. In the 1990s, however, storage in this area declined rapidly, totally $56.86 \times 10^6\text{m}^3$ in the decade,

and averagely $5.7 \times 10^6 \text{ m}^3$ every year. In the fine-grained soil plain, groundwater variation kept relatively stable, and the change was between $0.02 \times 10^6 \text{ m}^3 \sim 0.33 \times 10^6 \text{ m}^3$. In the river valley plain, the range of storage variations was small, and from the late 1980s and the early 1990s, storage showed an increasing trend.

Table 6 annual changes of regional groundwater level and storage

Year Subarea	1981 (1984)–1985		1986–1990		1991–1995		1996–2000 (2001)	
	Level change (m)	Storage change (10^6 m^3)	Level change (m)	Storage change (10^6 m^3)	Level change (m)	Storage change (10^6 m^3)	Level change (m)	Storage change (10^6 m^3)
Upper-middle part of alluvial-diluvial fan	-0.60	-15.82	-1.11	-29.39	-1.96	-52.04	-2.47	-65.60
Lower part of alluvial-diluvial fan	-0.32	-3.42	-1.06	-11.21	-1.89	-19.97	-2.43	-25.68
Fine-grained soil plain	0.03	0.11	-0.05	-0.17	-0.04	-0.15	-0.18	-0.66
River valley	-0.03	-0.40	-0.22	-2.95	0.49	6.77	0.7	0.93
Zhangye Basin	~	-19.53	~	-43.72	~	-65.39	~	-91.01

4.2 Balance analysis of recharge and discharge of groundwater system

Changes of regional groundwater recharging system: $\Delta Q_R = \Delta Q_r + \Delta Q_{rm} + \Delta Q_c + \Delta Q_i$, based on this formula and the former results, the changes of recharge of diverse time period in Zhangye Basin are analyzed as following:

$$1970-1985: \Delta Q_R = -2.385 + 0.217 = -2.168 (10^8 \text{ m}^3/\text{a});$$

$$1986-2000: \Delta Q_R = -0.042 + 0.176 = 0.134 (10^8 \text{ m}^3/\text{a}).$$

Changes of regional groundwater discharging system: $\Delta Q_D = \Delta Q_E + \Delta Q_M + \Delta Q_S$, where $\Delta Q_M, \Delta Q_S$ represent the changes of groundwater exploitation and those of spring outflow, respectively.

$$1970-1985: \Delta Q_D = -2.035 (10^8 \text{ m}^3/\text{a}); 1986-2000: \Delta Q_D = 0.6785 (10^8 \text{ m}^3/\text{a}).$$

$$\text{The result: } 1970-1985: \Delta Q_R - \Delta Q_D = -0.133 (10^8 \text{ m}^3/\text{a});$$

$$1986-2000: \Delta Q_R - \Delta Q_D = -0.545 (10^8 \text{ m}^3/\text{a}).$$

The result indicates that the changes of groundwater recharging and discharging system made groundwater storage decline $0.133 \times 10^8 \text{ m}^3/\text{a}$ before 1985, and $0.545 \times 10^8 \text{ m}^3/\text{a}$ in 1986-2000. While for groundwater storage change calculated with the change of

groundwater level (shown in table 6), it declined $0.195 \times 10^8 \text{ m}^3/\text{a}$ in 1981-1985 and $0.667 \times 10^8 \text{ m}^3/\text{a}$ in 1986-2000. Comparing the results of two calculating method, we get that the deviation of the results before 1985 is $0.062 \times 10^8 \text{ m}^3/\text{a}$ and $0.126 \times 10^8 \text{ m}^3/\text{a}$ in 1986-2000, and their relative errors are both less than 20%, while it is unable to analyze the errors for the results of 1970-1986 because the storage change calculated with the change of groundwater level was only between 1981-1985. However, the two storage change results before 1985 have a similar trend. Considering that all parameters used in this study are the testing results carried out by Gansu Hydrogeological Investigation Team in 1980s, which unavoidably have some deviation for the hydro-geological condition changes, and the investigating data of spring outflow after 1990 are absent and remedied by using some statistics model, which also lead to the errors, therefore, the analysis results have good veracity under such study precision.

Presuming that the increase of exploitation is taken into rational extent (such as to $2.62 \times 10^8 \text{ m}^3/\text{a}$ in 2000), the balanced relationship between recharge and discharge in 1986-2000 should be: $\Delta Q_R - \Delta Q_D = 0.457 \times 10^8 \text{ m}^3/\text{a}$, followed by a little increase of regional groundwater storage. The results showed that, as long as we keep a reasonable range of exploitation (less than $2.62 \times 10^8 \text{ m}^3/\text{a}$ in the study area), land-use changes would control the changes of groundwater resources. In the recent fifteen years, large amount of exploitation concentrated on the middle-lower part of alluvial-diluvial fan, but the changes of recharging system caused by the land-use changes primarily happened in fine-grained soil plain in the basin center and the river valley plain in west of the basin, so the apparent diversity of regional changes of groundwater resources appeared in the entire region. Groundwater storage in the upper-middle and lower part of alluvial-diluvial fan decreased continuously, but in the fine-grained soil plain and river valley plain it increased apparently, instead (Table 6).

5. Conclusion and discussion

Since the large-scale development in Zhangye Basin of Heihe River Basin from the 1970s, groundwater recharge decreased $2.168 \times 10^8 \text{ m}^3/\text{a}$ due to the land-use changes up to

1985, and discharge decreased $2.035 \times 10^8 \text{ m}^3/\text{a}$. All these changes led to $0.133 \times 10^8 \text{ m}^3/\text{a}$ decrease of groundwater storage. In the later fifteen years (1986-2000), regional land-use had further changes and human pumping expanded too, which led to $0.1342 \times 10^8 \text{ m}^3/\text{a}$ net increase of recharge, and led to $0.6785 \times 10^8 \text{ m}^3/\text{a}$ net increase of discharge. All these changes made groundwater storage decreased $0.545 \times 10^8 \text{ m}^3/\text{a}$. However, under reasonable exploitation, land-use changes would control the changes of regional groundwater resources.

In recent three decades, the former fifteen-year (1970-1985) is a period when regional land-use changed intensively, and the impact on groundwater recharging system occupied 92.27% of that of thirty years. Thereinto, riverway and canal system changes had the biggest impact on the groundwater recharge, which occupied 91.6% of the total change of recharging system. The residual 8.4% came from the changes of irrigating areas. In all the discharging factors, spring outflow changed most, and of evapotranspiration, which was directly related to land-use was 7.33% of the total discharge. In the later fifteen-year period (1986-2000), the range of land-use changes was relatively smaller than former fifteen years, followed by smaller influence on groundwater. In contrast to that in the former fifteen-year period, the impact of change of irrigating area occupied 80.7% of total recharge. From 1986 on, groundwater exploitation increases and apparently affected the groundwater discharging system. Under the combined influence of land-use and exploitation changes of groundwater resources in the basin presented apparent regional diversity in the later fifteen years.

It is well known that influence of land-use and land-cover changes on water resources system is intensive in arid inland river basin, and that the spatial-temporal distribution of surface water system changes continuously with the changes of land-use pattern. This study indicates that land-use and land-cover changes also affect intensively the groundwater system in the basin, and in some extent, the land use change would control the groundwater changes. In Zhangye basin, the land use change and human pumping are the two key factors that control the groundwater resources change. Realizing the impact of land-use changes on groundwater system may make the programming and management of water and soil resources more scientific and reasonable.

Acknowledgement: This research was funded by the China-Japan Corporation Project “Historical evolution of the adaptability in an oasis region to water resource changes”, and the Chinese Natural Science Foundation Project (No. 40171002).

References:

- R. W. A. Hutjes, P. Kabat, S. W. Running, W. J. Shuttleworth, C. Field, B. Bass, et al. Biospheric aspects of the hydrological cycle. *Journal of Hydrology*, 1998, 212-213: 1-21
- L. Zhang, W. R. Dawas, P. H. Reece. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resour. Res.*, 2001, 37(3): 701-708
- Hoff H. The water challenge: Joint Water Project. *Global Change Newsletter*, 2002, No.50, 46-48
- Sun Chengquan, Lin Hai, Qu Jiansheng. *International Core Programs and Integration of Global Change Research*[M]. Beijing: Meteorological Press, 2003.
- Suzanne Serneels. Priority questions for land use/cover change research in the next couple of years. *LUCC Newsletter*, 2001
- Nunes, Auge J I. Land-use and land-cover change implementation strategy. *IHDP Report 10*, 1999
- Xia Jun, Tan Ge. Hydrological science towards global change: progress and challenge[J]. *Resources Science*, 2002, 24(3): 217-224. (In Chinese)
- Deng Huiping, Li Xiubin, Chen Junfeng, et al. Simulation of hydrological response to land cover changes in the Suomo Basin. *Acta Geographica Sinica*, 2003, 58(1): 53-62. (In Chinese)
- Fu Bojie, Qiu Yang, Wang Jun, et al. Effect simulations of land use change on the runoff and erosion for a gully catchment of the Loess Plateau, China[J]. *Acta Geographica Sinica*, 2002, 57(6): 717-722. (In Chinese)
- P. Mtembezeka; A. J. Andrews; and S. O. Appiah. 1997. Groundwater management in drought-prone areas of Africa. *Water Resources Development* 13(2): 241-261.
- Alley, W.M., T. E. Reilly, and O. L. Franke. Sustainability of groundwater resources. *U.S. Geol. Surv. Circular*, 1999, 1186
- Schwartz, W.F and Hubbert, Z. *Fundamentals of ground water*. New York: John Wiley & Sons. 2003, pp583
- K. Sato and Y. Iwasa. *Groundwater hydraulics*. Tokyo: Springer-Verlag, 2003, pp204

- Von Asmuth, J.R. and Mass, K. The method of impulse response moments: a new method integrating groundwater and eco-hydrological modeling. IAHS Publ. No. 269, 2001: 51-58
- Wang Genxu, Cheng Guodong. Water resources development and its influence on the eco-environment in arid areas of China—The case of the Heihe river basin. *Journal of Arid Environment*, 1999, 43:121-131
- ZHANG Jishi, KANG Ersi. Impact of climate change and variability on water resources in Heihe River Basin. *Journal of Geographical Sciences*, 2003, 13(3): 286-293
- Gao Qianzhao, Li Fuxing. Reasonable development and utilization of water resources in Heihe River Basin[M]. Lanzhou: Gansu Science and Technology Press, 1990.
- Wang Genxu, Wang Jian, Wu Yanqing. On the features of eco-environmental changes in heihe river basin over recent 10 years. *Journal of Chinese Geographical Sciences*, 2002, 22 (5) : 527-534
- Gansu Hydrogeological Investigation Team. Groundwater resources and its reasonable exploitation and utilization in the middle reach of Heihe River (not published). 1990,
- Gansu Hydrogeological Investigation Team: Report of regional hydrogeological investigation in Zhangye (not published). 1998