China Geology 3 (2021) 455−462

China Geology

Journal homepage: http://chinageology.cgs.cn
https://www.sciencedirect.com/journal/china-geology

Changes of groundwater flow field of Luanhe River Delta under the human activities and its impact on the ecological environment in the past 30 years

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ARTICLE INFO

Article history:
Received 8 July 2021
Received in revised form 18 August 2021
Accepted 29 August 2021
Available online 17 September 2021

Keywords:
Ecological environment
Human activities
Groundwater flow regime
Groundwater resources
Groundwater depression cone
Land subsidence
Hydrogeology survey engineering
Luanhe River Delta
Hebei Province
North China

ABSTRACT

The Luanhe River Delta is located in the center of the Circum-Bohai Sea Economic Zone. It enjoys rapid economic and social development while suffering relatively water scarcity. The overexploitation of groundwater in the Luanhe River Delta in recent years has caused the continuous drop of groundwater level and serious environmental and geological problems. This study systematically analyzes the evolution characteristics of the population, economy, and groundwater exploitation in the Luanhe River Delta and summarizes the change patterns of the groundwater flow regime in different aquifers in the Luanhe River Delta according to previous water resource assessment data as well as the latest groundwater survey results. Through comparison of major source/sink terms and groundwater resources, the study reveals the impacts of human activities on the groundwater resources and ecological environment in the study area over the past 30 years from 1990 to 2020. The results are as follows. The average annual drop rate of shallow groundwater and the deep groundwater in the centers of depression cones is 0.4 m and 1.64 m, respectively in the Luanhe River Delta in the past 30 years. The depression cones of shallow and deep groundwater in the study area cover an area of 545.32 km² and 548.79 km², respectively, accounting for more than 10% of the total area of the Luanhe River Delta. Overexploitation of groundwater has further aggravated land subsidence. As a result, two large-scale subsidence centers have formed, with a maximum subsidence rate of up to 120 mm/a. The drop of groundwater level has induced some ecological problems in the Luanhe River Delta area, such as the zero flow and water quality deterioration of rivers and continuous shrinkage of natural wetlands and water. Meanwhile, the proportion of natural wetland area to the total wetland area has been decreased from 99% to 8% and the water area from 1776 km² to 263 km². These results will provide data for groundwater overexploitation control, land subsidence prevention, and ecological restoration in plains and provide services for water resources management and national land space planning.

1. Introduction

The Luanhe River Delta lies in the northeastern part of Hebei Province and borders the Bohai Sea in the south and the Yanshan Mountain in the north, China. It connects North China and Northeast China and is located in the heartland of the Circum-Bohai Sea Economic Zone with the most enormous development potential (Chen P et al., 2014; Hao H et al., 2012; Dang XZ et al., 2020). Administratively, it mainly covers the plain area of Tangshan City and some areas in the southern part of Qinhuangdao City, with an area of 9200 km². The Luanhe River Delta is flat in terms of terrain and inclines from north to south, with a ground elevation of 10–50 m and a land slope of about 1.2‰–0.2‰ (Li SX, 1994; Yan J et al., 2015; Wang YX et al., 2016). The major geomorphic units in the study area include the Luanhe-Yanghe alluvial-diluvial plain, the coastal alluvial-marine plain, and the coastal zone (Fig. 1). The rivers in the study area mainly include the Luanhe River and coastal rivers separately flowing into the sea including the Douhe, Huanxiang, Shiliu, Shahe, Yinma, Daihe, Yanghe, and Shihe rivers, all of which originate from the hilly area at the southern foot of the Yanshan Mountain (Bao K et al., 2017; Tian Y et al., 2019; Haihe River Water Conservancy Commission of Ministry of Water Resources, 1993).

The Luanhe River Delta is a part of the northeastern end

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doi:10.31035/cg2021060
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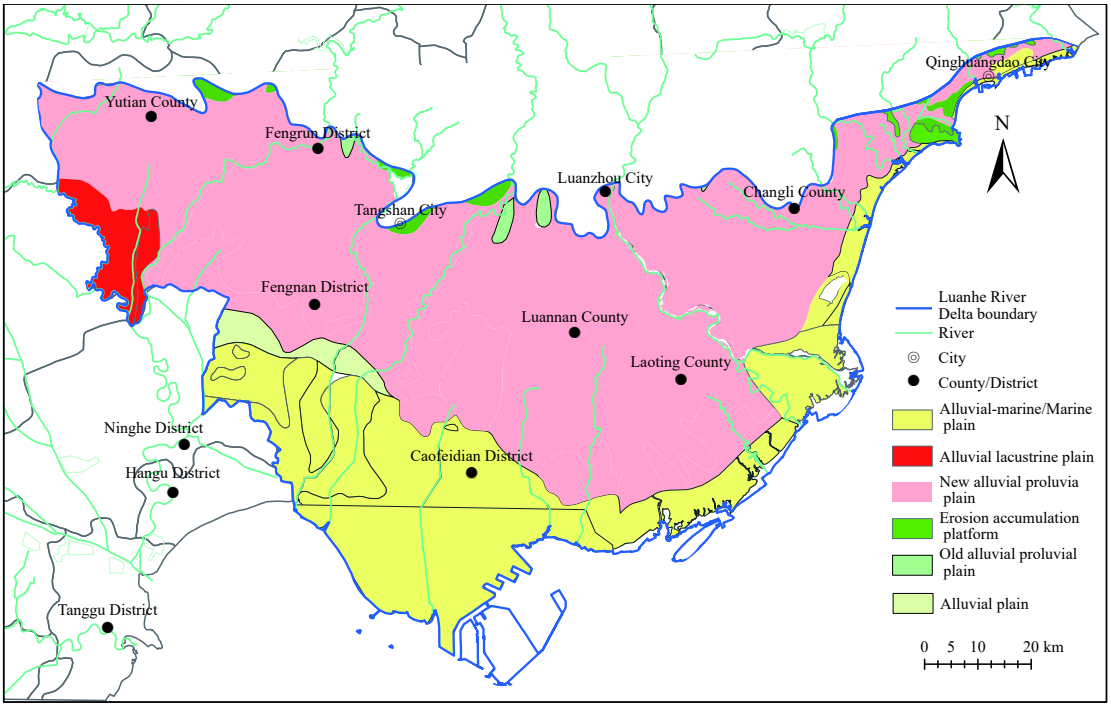

Fig. 1. Landform types of Luanhe River Delta, North China.

of the Huanghua depression (Shi Y et al., 2019; Wang Y et al., 2021). In this area, hugely thick Cenozoic strata have developed, and the Tertiary sediments greatly vary in thickness, lithology, lithofacies, and ore-bearing features and are locally discontinuous. As for the Quaternary sediments in the Luanhe River Delta, their thickness roughly changes with the fluctuation of the basement, they have various genetic types, and the burial depth of their lower boundary is generally 350–500 m (Zhang YF et al., 1983). The Quaternary aquifer system in the study area can be divided into four aquifer groups from top to bottom according to the lithology and hydrogeological characteristics of the Quaternary sediments. As for the first aquifer group, the burial depth of the bottom boundary is 10–20 m. It is dominated by medium-coarse-grained sands in piedmont plains and has good permeability. Meanwhile, it is predominated by silty and fine sands in the coastal plain areas. As for the second aquifer group, the burial depth of the bottom boundary is 120–170 m. It is distributed in the form of fans in piedmont plains and consists of two or three sets of medium-fine-grained sands - medium-coarse-grained sand-gravels and pebbles and has high permeability and high water yield property. The second aquifer group in coastal plain areas is dominated by thin-laminated fine sands and silty sands as well as clays between aquifer groups. It has weak permeability and weak water yield property. The burial depth of the bottom boundary is 250–350 m for the third aquifer group and is 350–550 m for the fourth aquifer group (Zhang ZJ, 2009).

2. Exploitation status of water resources

The Luanhe River Delta is located in Tangshan City except for its eastern part, which lies in Qinhuangdao City (Chen WH et al., 1999). The population and economy in the area have rapidly developed. The Tangshan and Qinhuangdao cities had a population of 6.750×10^6 and 2.571×10^6, respectively in 1995 and 7.965×10^6 and 3.095×10^6, respectively in 2020. Therefore, the population in the two cities increased by 1.739×10^6 in total in the 25 years. The total GDP of the two cities was 52.58×10^9 CNY in 1995 and increased to 889.7×10^9 CNY in 2020, with an increase of nearly 17 times (National Bureau of Statistics of China, 1995). The water consumption per 10000 CNY GDP in Hebei Province was 285 m^3 in 2000 and 51.6 m^3 in 2020 (Department of Water Resources of Hebei Province, 2001–2019). Based on this, the water consumption of the two cities increased from 1.5×10^9 m^3 in 1995 to 4.59×10^9 m^3 in 2020. The sharp increase in the water consumption of the two cities was mainly reflected in the increase in urban domestic and industrial water consumption, while the agricultural water consumption roughly remained stable (Fig. 2).

According to the latest monitoring data, the annual water consumption of Tangshan and Qinhuangdao cities in recent years was 3.36×10^9 m^3/a and 820×10^6 m^3/a, respectively. It included 1.98×10^9 m^3/a and 520×10^6 m^3/a of exploitation volume of groundwater, respectively, which account for 58.9% and 63.2% of total water consumption, respectively (Zhang BC, 2013; Zhao YF, 2019; Du SP, 2020; Lu SB et al., 2020). Therefore, groundwater is the major source of water supply in Tangshan and Qinhuangdao cities and it is mainly used for domestic and agricultural purposes. During the groundwater exploitation and utilization, shallow freshwater was mainly exploited in piedmont plain areas, while deep groundwater was mainly exploited in coastal plain areas.

The ratio of groundwater consumption to total water consumption in the Luanhe River Delta has constantly

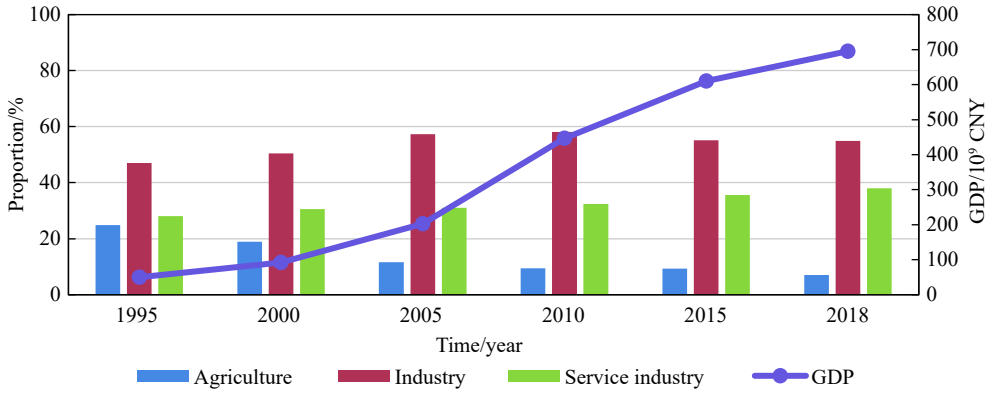

Fig. 2. Agriculture, industry, service industry, and GDP of Tangshan City, Hebei Province from 1995 to 2018.

changed over the years. It was 65.6% in 2000, 64% in 2010, and 58.9% in 2019. Therefore, the proportion of groundwater consumption is decreasing overall. Most especially, with the implementation of the groundwater overexploitation control engineering and the promotion of water conservation technologies in Hebei Province, the water consumption has started to decrease after reaching its peak and the proportion of groundwater supply has also significantly decreased in the study area since 1980.

3. Changes of groundwater flow regime

The groundwater flow regime in the study area in 2005 is as follows (Fig. 3). The elevation of the shallow groundwater level in the study area varied in the range from −10 to 24 m. The flow regime of shallow groundwater was affected by terrain slope overall, featuring a high water level in the piedmont area and a low water level in the coastal area. Accordingly, the groundwater flowed from north to south and from the piedmont area to the coastal area. However, the southern part of the Yutian area was an exception, where a local low water level center was formed due to overexploitation and thus groundwater flowed toward the center from the periphery. The elevation of the deep groundwater level varied in the range of −50–10 m. The flow regime of the deep groundwater was mainly affected by human exploitation. Owing to a high exploitation volume, a low groundwater level center was formed in the Ninghe-Caofeidian area, which served as the major discharge area of deep groundwater.

The groundwater flow regime in the study area in 2020 is as follows (Fig. 4). The elevation of the shallow groundwater level in the study area varied in the range from −15 to 24 m. The shallow groundwater still flowed from the piedmont area to the coastal area and from north to south. However, with the expansion of the overexploitation of shallow groundwater, low groundwater level centers occurred in many places, namely the southern part of Tangshan City, the northwestern part of Caofeidian District, and the southern of Luannan County. The elevation of the deep groundwater level varied in the range of −90–2 m. Water flowed from the peripheries toward the low groundwater level centers in the groundwater flow regime of deep groundwater. As a result, two low groundwater level centers were formed in Heiyanzi and Nanpu towns in the south, with a maximum burial depth of groundwater of up to 90 m.

According to the comparative analysis of the groundwater level 2005 and 2020, the shallow water level in the study area declined as a whole. It decreased by 5–7 m on average, with an average annual decreasing rate of 0.4 m/a. Compared to the shallow groundwater, the flow regime of deep groundwater was more notably affected by human activities and the overall groundwater level declined to a greater extent. Taking deep monitoring well in Nanpu Town, Caofeidian District as an example (Fig. 5), the average annual water level declined from −28 m to −56 m during 2002–2019, with an average annual decreasing rate of 1.64 m.

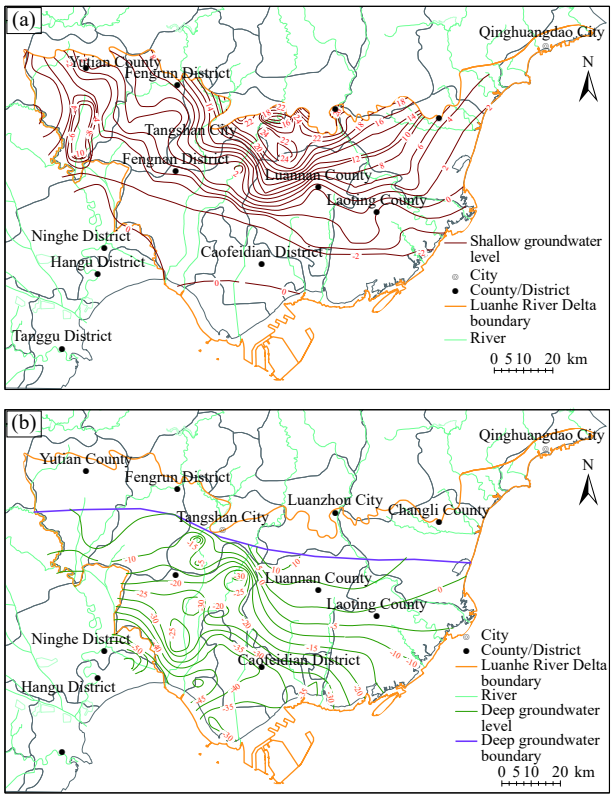

Fig. 3. Groundwater flow regime in Luanhe River Delta in June 2005 (a–shallow groundwater; b–deep groundwater).

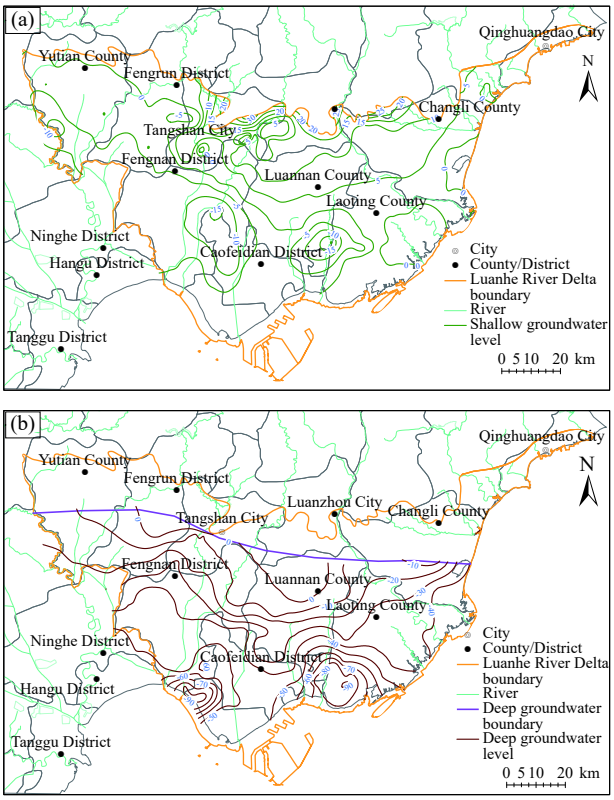

Fig. 4. Groundwater flow regime in Luanhe River Delta in June 2020 (a–shallow groundwater; b–deep groundwater).

4. Major problems of environmental geology

4.1. Development of groundwater depression cones

The scopes of groundwater depression cones were delineated according to the groundwater contours of the Haihe River Basin (Cheng MH et al., 2020; Guo LL et al., 2021). In detail, the depression cones of shallow groundwater in the study area were delineated according to the groundwater contours of −5 m or −10 m, while those of deep groundwater were delineated according to the groundwater contour of −60 m. According to the delineation results, no depression cone was formed in both shallow and deep groundwater in 2005, while two and four depression cones had developed in shallow and deep groundwater, respectively by June 2020 (Fig. 6). The two depression cones of shallow groundwater were the Fengnan-Tanghai cone and Luannan-Laoting cone, with a minimum water level of −15.4 m in the cone centers and a total area of 545 km^2. The four depression cones of deep groundwater included the Tanghai-Laoting cone, Ninghe-Hangu cone, eastern Laoting cone, and Fengnan-Tanghai cone, with a total area of 548.79 km² and a minimum groundwater level of −98.3 m in the cone centers (Table 1).

4.2. Land subsidence

The land subsidence in the Luanhe River Delta has become increasingly serious with continuous overexploitation of groundwater.

According to InSAR monitoring data, land subsidence of varying degrees occurred in the southern part of the study area in 2010, with a maximum subsidence rate of 20–30 mm/a (Fig. 7a) (Zhao Y et al., 2021; Jones J et al., 2021). The land subsidence was connected and several distinct subsidence centers were distributed in Heiyanzi Town and Laowangzhuang Village in the border area of Tanghai County and Fengnan District, the border area of Tanghai and Laoting counties, Liuzan Town, and Guhe Town. The subsidence rate in these areas was greater than 20 mm/a generally and even greater than 30 mm/a locally.

Two distinct land subsidence centers were formed in the study area in 2014, namely the Caozhuangzi-Liuzan cone of depression and the Heiyanzi Town - Laowangzhuang Village - Qiulaopu depression cone (Fig. 7b). Among them, the depression cone to the north of Liuzan Town had a maximum subsidence rate of up to 75–80 mm/a, and its area with a subsidence rate of greater than 50 mm/a in the subsidence center was 61.67 km^2. The Heiyanzi-Laowangzhuang-Qiulaopu depression cone had a maximum subsidence rate of 50–55 mm/a and smaller than that of the Caozhuangzi-Liuzan cone.

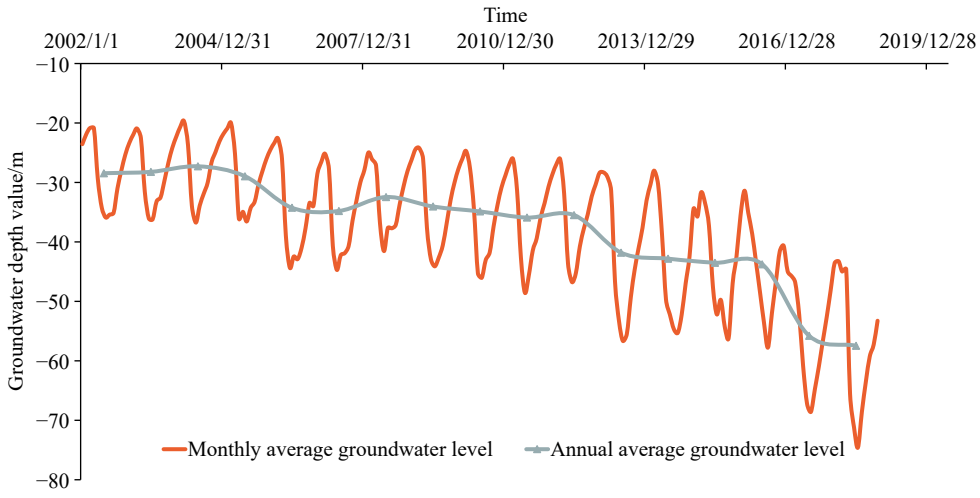

Fig. 5. The variation curve of deep groundwater level in Caofeidian area, Hebei Province.

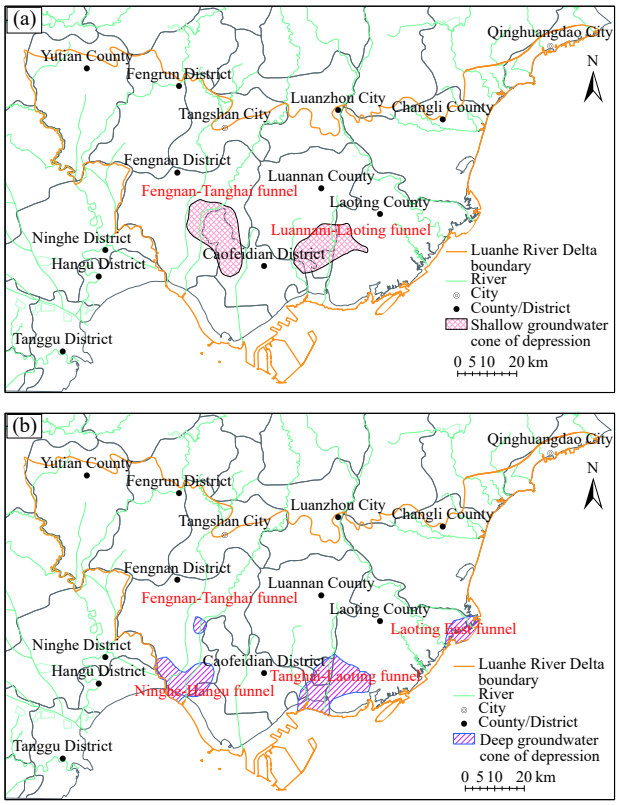

Fig. 6. Distribution position of groundwater funnels in 2020 (a–shallow groundwater; b–deep groundwater).

Table 1. Statistics of funnel area and minimum groundwater level of deep and shallow groundwater in 2020 in plain of Luanhe River watershed.

Type	Funnel name	Groundwater level Elevation of funnel boundary/m	Funnel area and minimum groundwater level in 2020	
			Area/km^2	Center groundwater level/m
Shallow groundwater funnel	Fengnan-Tanghai	−5	240.12	−15.40
	Luannan-Laoting	−10	305.20	−12.45
	Total		545.32	
Deep groundwater funnel	Tanghai-Laoting	−60	276.09	−89.11
	Ninghe-Hangu	−60	181.81	−72.30
	Laoting East	−60	71.97	−98.30
	Fengnan-Tanghai	−60	18.92	−83.31
	Total		548.79	

With the continuous overexploitation of groundwater in the study area, especially the overexploitation in the southern part, land subsidence was further aggravated in 2018 (Fig. 7c). Depression cones were formed in a large scope including the Six Farmland - Liushuquan Town - Heiyanzi Town area, the Ninth Farmland - Guhe Town - Matouying Town area, and Wangzhuang Town, Zhongpu Town. The maximum subsidence rate reached 120 mm/a, which was much higher than that in 2010 and 2014.

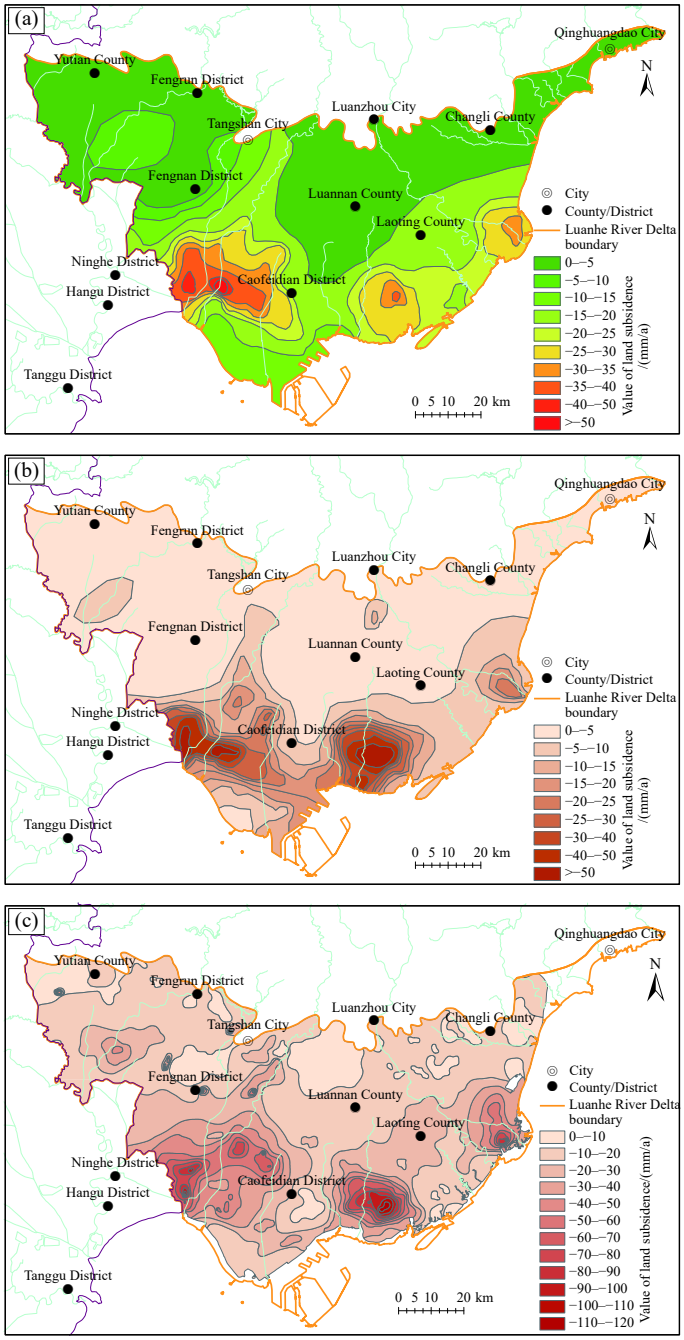

Fig. 7. Contour maps of land subsidence rate in the Luanhe River Delta (a-2010; b-2014; c-2018).

5. Changes of groundwater resources

According to the first and second assessment results of water resources in the study area as well as the latest annual assessment results of groundwater resources, this paper analyzed the changes in the resources and discharge volume of groundwater in the Luanhe River Delta. From the 1960s to the 1980s, the groundwater resources in the study area were mainly composed of recharge of precipitation infiltration and surface infiltration, which jointly accounted for more than 95% of the total groundwater resources. After the 1980s, the groundwater resources were still mainly composed of the recharge of precipitation infiltration and surface infiltration.

However, the total proportion of these two components decreased to about 85.28%, while the proportion of piedmont lateral inflow and the infiltration recharge of surface irrigation water gradually increased. According to the resources assessment results in 2020, this trend has been further enhanced and the proportion of the recharge of precipitation infiltration and the recharge of surface infiltration reduced to 77.14% in 2020 (Table 2).

The changes in the groundwater discharge are as follows. Before the 1980s, the exploitation volume of groundwater was less than the groundwater resources in the study area (accounting for 73.13%), and the groundwater resources were in a positive balance state. From the 1980s to 2020, the exploitation volume sharply intensified and become the major discharge way of groundwater, accounting for 95.96% of the total groundwater resources in the study area. According to the annual assessment results in 2020, this trend was relieved and the ratio of exploitation volume to total resources dropped to 71.9%.

According to assessment results of groundwater resources, the groundwater resources in the Luanhe River Delta remained stable overall during 1956–2020, varying between 840×10^6 m^3 and 890×10^6 m^3. The recharge of precipitation infiltration and surface water infiltration showed a continuous downward trend, while piedmont lateral recharge and the infiltration recharge of surface irrigation water gradually increased over the years. Before the 1980s, the exploitation volume of groundwater was less than the groundwater reserves, and the groundwater resources were in a positive balance state. From the reform and development in 1980 to 2020, the groundwater was overexploited with the rapid increase in the exploitation volume of groundwater. The trend of overexploitation has been relieved to some extent in recent years with the implementation of overexploitation control and water conservation measures.

6. Ecological evolution in the Luanhe River Delta

Given the close coupling between water and the ecological environment, excessive exploitation of groundwater resources induced by human activities will inevitably affect the associated processes of water circulation such as water ecosystems, flow-sediment process, and vegetation distribution while profoundly affecting the groundwater flow regime, water circulation, and hydrological processes, thus endangering the ecological environment closely related to water resources (Lu XP et al., 2014).

For the piedmont zones, the thickness of the unsaturated zone in the piedmont plains has increased from 3–7 m in the 1980s to 10–40 m at present due to the continuous decline of the shallow groundwater level. This has changed the water circulation path of the “water circulation circle” and blocked off the water replenishment of surface soil through the capillarity of groundwater, leading to soil drying and a decrease in the evaporation of phreatic water. As a result, the regional heat island effect has occurred and surface soil has been increasingly dry, resulting in the problems such as soil desertification and water and soil erosion. Land desertification is mainly distributed in five counties and prefectures in the lower reaches of the Luanhe River, namely Qianxi, Luanxian, Luannan, and Laoting counties and Qian’an City. According to previous research data, the area of lands subject to desertification in the five areas is up to 690 km², accounting for 13.2% of the total land area. Furthermore, the land area with potential desertification conditions is 2440 km², accounting for 46.7% of the total land area (Liu K, 2010; Xu J et al., 2021).

Besides, the drop of the groundwater level has caused ecological problems such as zero flow of rivers, riverbed drying, and the shrinkage of lake wetlands. Since there are hydraulic connections between river water and shallow groundwater, the residual small runoff from the upper reaches has mostly recharged groundwater as groundwater level dropped. This has led to a sharp decrease in the amount of water flowing into the sea and the zero flow of lower reaches in dry seasons or even all year round. For instance, the zero flow in the lower reaches of rivers in Luanxian County lasted for about 300 days in 2000 and the whole year in 2001 and 2002 (Li JZ et al., 2007; Kang XN et al., 2016; Yan XL et al.,

Table 2. Statistical table of multi-round water resources evaluation results in plain of Luanhe River watershed (10^6 m^3).

Evaluation time	Evaluation zoning	Groundwater resources	Precipitation infiltration		Surface water infiltration recharge		Precipitation/ mm	Groundwater exploitation	Proportion of exploitation volume/%
			Amount	Percentage /%	Amount	Percentage /%			
First round of water resources evaluation (1956–1979)	North Haihe watershed, Luanhe River, and the eastern coastal area of Hebei Province	32	25.23	78.86	5.45	17.03	564	23.40	73.13
Second round of water resources assessment (1980–2000)	Luanhe River and the eastern coastal area of Hebei Province	8.9	6.10	68.54	1.49	16.74	523	8.54	95.96
Groundwater resources evaluation in 2020	Luanhe River and the eastern coastal area of Hebei Province	8.4	6.17	73.45	0.31	3.69	490	6.04	71.90

2020). Meanwhile, the water in river channels has roughly lost the self-purification function due to slow flow or even zero flow, increasing pollution. According to survey results, the water quality of the Luanhe, Yanghe, and Shihe rivers has gradually degenerated from Class III to Class V and even beyond Class V over the past 30 years (Du D, 2007; Liu Y et al., 2019; Cui XT et al., 2020; Huang W et al., 2021). Moreover, the decrease in river flow has led to the decrease or even death of some aquatic and waterfront biocoenoses. In recent years, with the increase in the water amount from the upper reaches and the water resource protection in lower reaches, the water flowing into the sea has shown an upward trend and the zero flow of river channels have started to gradually reduce.

The natural wetland area and water area in the Luanhe River Delta have gradually decreased under the dual effects of the decrease in the water flowing into the sea and sediments and the intensification of human development and utilization of groundwater. The proportion of the area of natural wetlands to the total wetland area has decreased from 99% to 8%, while the area of constructed wetlands has linearly increased (Tian HL, 2011). Meanwhile, the water area has reduced from 1776 km² to 263 km². In addition, some coastal buffer zones in water basins have been occupied by human activities, causing the serious degradation, instability, and ecological function loss of the ecosystems in the zones. This also led to the gradual disappearance of natural transition zones between water and land and the decrease in the diversity of vegetation species. In addition, the decrease in the water flowing into the sea has caused the shrinkage of the transition sections of estuaries and the sharp reduction in the diversity and quantity of aquatic plants in the estuaries, as well as the ecological problems such as the deterioration of the living environment of aquatic organisms and the outward migration of fishing grounds in the estuaries (Lin TY, 2020).

7. Conclusions

(i) With population growth and rapid economic and social development in the past 30 years, the water consumption in the Luanhe River Delta has increased, and the overexploitation of groundwater resources has been increasingly serious. According to the comparative analysis of the water levels in the Luanhe River Delta in 2005 and 2020, the average annual decline rate of the shallow groundwater level is 0.4 m/a and that of the deep groundwater level in the centers of depression cones is 1.64 m.

(ii) Long-term overexploitation of groundwater in the study area has caused many environmental geological problems, which are mainly characterized by the expansion of groundwater depression cones and the acceleration of land subsidence. The depression cones of shallow and deep groundwater in the study area cover an area of 545.32 km² and 548.79 km², respectively, accounting for more than 10% of the total area of the Luanhe River Delta. The maximum subsidence rate in land subsidence centers was up to 120 mm/a in 2018. The groundwater resources in the Luanhe River Delta remained stable overall during 1956–2020, varying between 840×10^6 m^3 and 890×10^6 m^3. Meanwhile, the recharge of precipitation infiltration and surface water infiltration showed a continuous downward trend.

(iii) Over the past 30 years, the overexploitation of groundwater resources induced by human activities has affected the ecological environment that is closely related to water resources while profoundly affecting the groundwater flow regime, water circulation, and hydrological processes, thus leading to various ecological problems such as soil drying, the zero flow of river channels, the deterioration of water quality, and the shrinkage of lake wetlands. For example, the water quality of the Luanhe, Yanghe, and Shihe rivers has gradually degenerated from Class III to Class V and even beyond Class V. Meanwhile, the proportion of natural wetland area to the total wetland area has been increased from 99% to 8% and the water area from 1776 km² to 263 km².

CRediT authorship contribution statement

She-ming Chen conceived of the presented idea. Fu-tian Liu and Qian Zhang verified the analytical methods. She-ming Chen encouraged Fu-tian Liu, Wei Wang and Zhuo Zhang to investigate groundwater levels and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

Acknowledgment

The authors would like to thank Dr. Zi-Guo Hao for constructive comments on this manuscript. This research is jointly funded by the “Project of Hydrogeological survey of Luanhe River Basin ” of China Geological Survey (No. DD20190338), General Project of National Natural Science Foundation of China (No.41972196), Youth Fund of the National Natural Science Foundation of China (No. 41907149) and China Postdoctoral Foundation (No. 2018M631732). The authors would like to thank the reviewers and editors very much for their constructive comments.

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