Title

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Journal

Acta Geotechnica, 16(4)

ISSN

1861-1125

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Publication Date

2021-04-01

DOI

10.1007/s11440-020-01097-2

Peer reviewed

Acta Geotechnica (2021) 16:1303–1314
https://doi.org/10.1007/s11440-020-01097-2

SHORT COMMUNICATION

Long-term groundwater level changes and land subsidence in Tianjin, China

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Received: 19 August 2019 / Accepted: 15 October 2020 / Published online: 29 October 2020

Abstract

A large volume of groundwater is withdrawn annually in Tianjin Municipality, China, to meet agricultural, industrial, and municipal water uses. Groundwater overdraft in the urban districts and the Binhai New District in Tianjin Municipality has caused land subsidence. A series of field observation wells were installed to monitor the long-term groundwater level (GWL). The hydrostratigraphy of the aquifer system underlying Tianjin consists of four aquifer layers. The middle two aquifer layers are the main layers for groundwater withdrawal. The GWL of the top two aquifer layers responded rapidly to recharge from precipitation and seawater intrusion. The GWLs of the bottom two aquifer layers have been dropping steadily over the past 50 years. The aquifer sediments underlying Tianjin Municipality consist mainly of fine sand, silt, and clayey soil. The decline of the GWL has induced substantial land subsidence and led to overconsolidated compressible sediments.

Keywords Groundwater level · Land subsidence · Overdraft · Tianjin

1 Introduction

Groundwater has been increasingly relied upon in recent decades to meet the requirements of people’s livelihoods and socioeconomic development [22]. Three regions in the world, such as the North China Plain (NCP), Northern India, and the midwestern USA, are facing severe groundwater over-abstraction [4, 14]. The NCP, consisting of the Beijing and Tianjin municipalities and Hebei and Shanxi provinces, is one of the most densely populated areas and the largest wheat and maize producing area in China [4–10]. The water for agricultural irrigation in the NCP is highly dependent on groundwater. Over 60% and 80% of the total water supplies for the Beijing municipality and Hebei Province depend on groundwater, respectively [4].

Tianjin has a long history of groundwater withdrawal with the first pumping well installed in 1907 [28]. Many water wells were drilled in the urban and suburban areas of Tianjin during the long-term drought of 1965 through 1972 (i.e., in the Dongli, Xiqing, Jinnan, and Beichen districts). By 1971 there were 534 water wells drilled in the urban districts [23]. By 1981, there were 849 wells in the same area. The annual groundwater withdrawal rate in the entire

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region reached 1.038 × 10^9 m^3. The Chinese government has controlled groundwater withdrawal since the 1980s in an effort to reduce land subsidence. Two hydraulic engineering projects named the Luan River-Tianjin Water Diversion (LRTWD) project and the South-North Water Diversion (SNWD) project were constructed post-1980 that had positive effects on reducing groundwater withdrawal. A large flow of freshwater is transferred annually from the Yangtze and the Luan rivers to Tianjin by the SNWD and the LRTWD, respectively. The groundwater level (GWL) variations of the four aquifer groups (labelled as AqG-I, AqG-II, AqG-III, and AqG-IV) in the past 50 years are presented and discussed in the following sections.

The effective stress of compressible soils increases and land subsidence occurs when groundwater is withdrawn [2, 11]. Severe land subsidence in the Tianjin Municipality was first reported in the 1920s. The land subsidence accelerated since the 1960s [28]. The direct economic loss from land subsidence in Tianjin was approximately 17 billion dollars, and the indirect loss was 11 times that amount [6]. Furthermore, groundwater overdraft in Tianjin caused seawater intrusion from the Bohai Gulf, which reduced agricultural production and adversely impacted environmental health [21]. Other adverse effects of groundwater overdraft may be found, for example, in Loáiciga [12].

Many studies have provided estimates of groundwater loss and land subsidence using Gravity Recovery and Climate Experiment (GRACE) data and field-based monitoring data [4, 16]. Due to the coarse spatial resolution of GRACE data (∼ 200,000 km^2), such studies focused on large-scale surveys encompassing areas several times larger than the NCP's land subsiding region [3]. Few studies have focused on a joint assessment of land subsidence and GWL changes caused by groundwater withdrawal from aquifer 250 m below the ground surface [28, 6]. In addition, the GWL data in each aquifer layer, which may cause overconsolidation in the soil deposits, are rarely reported.

This study reports GWL measurements alongside with land subsidence histories in the study area. A brief description of the geological and hydrogeological characteristics of Tianjin is first presented. The relations between land subsidence and the GWLs of each aquifer layer are subsequently analyzed based on the monitored data of the spatial distributions of GWLs and land subsidence.

2 Geological and hydrogeological conditions

Tianjin Municipality within the NCP is located along the west coast of the Bohai Gulf, bordered by Beijing 120 km to the northwest, and except for the eastern perimeter, is surrounded on all sides by Hebei province as shown in Fig. 1. The total land area of Tianjin Municipality is 11,917 km^2. It lies at the northern end of the Grand Canal of China, which connects the Yellow River and Yangtze River. The Tianjin Municipality is made up of 11 districts within Ji County and the Baodi District located in its northern region, and the Binhai New District located in its southern region.

The main hydrogeologic setting of the Tianjin Quaternary deposits along the cross-section I–I' in Fig. 1 is shown in Fig. 2. Generally, the sediments up to a depth of 1100 m in Tianjin Municipality consist of Quaternary strata and Tertiary strata. Except for the hilly area in Ji County, the elevation of the cross-section I–I' slightly rises from north to south, varying from 2.5 to 20 m. The soils of the Quaternary strata consist of lacustrine, fluvial, and marine deposits. The average thickness of the Quaternary deposit in most of the area is approximately 500 m, mainly consisting of sandy and clay soil layers. The stratigraphic sequence of the Quaternary deposit forms five strata, namely the Holocene series Q_4, the Upper Pleistocene series Q_3, the Middle Pleistocene series Q_2, Lower Pleistocene series Q_1, and the Pliocene Series N_2.

The aquifer system in the Quaternary deposit is divided into four aquifer groups named the AqG-I, AqG-II, AqG-III, and AqG-IV, based on their lithological and hydrogeological conditions [24]. The aquifer layer AqG-I belongs to the Upper Pleistocene series Q_3 and Holocene series Q_4, (see Fig. 3), which is defined as shallow groundwater. The aquifer layers AqG-II and AqG-III belong to the Middle Pleistocene series Q_2 and Lower Pleistocene series Q_1, respectively. The aquifer layer AqG-IV is part of the Lower Pleistocene series Q_1 and Pliocene Series N_2. The water in the aquifer groups AqG-II, AqG-III, and AqG-IV is defined as deep groundwater. The soil profile and their basic engineering properties at location C6 in Fig. 1 are shown in Fig. 3. The total number of observation wells in Tianjin, China are hard to estimate because these wells are governed by different departments. In this paper, 95, 138, 71, and 71 data points for AqG-I, AqG-II, AqG-III, and AqG-IV, respectively, are used to plot the GWL contours.

3 GWL variation in the study area

3.1 GWL in the AqG-I layer

Figure 4a–c presents the spatially averaged GWL zones in the AqG-I layer in 1997, 2005, and 2015, respectively. The GWL in the southern portion of the plain remained relatively stable and ranging between − 2 and − 6 m because of the deep infiltration (recharge) of precipitation and seawater intrusion from the Bohai Gulf [27], which

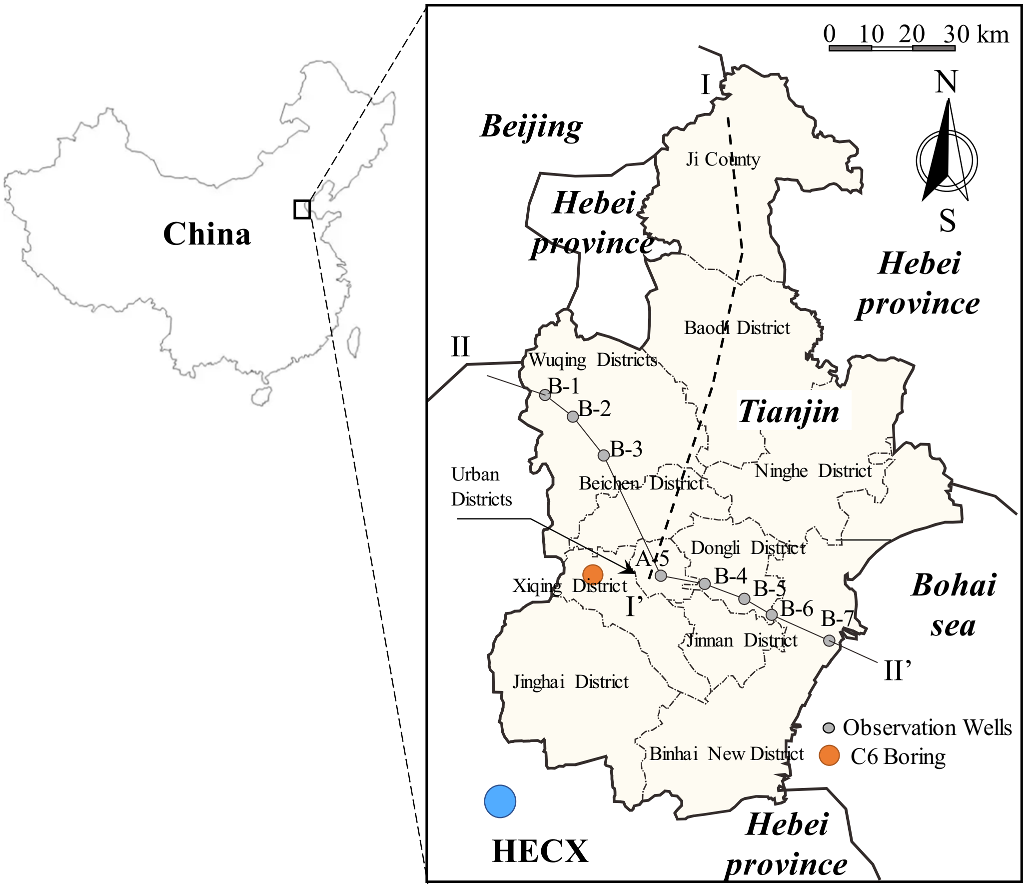


Fig. 1 Location of the study region in China

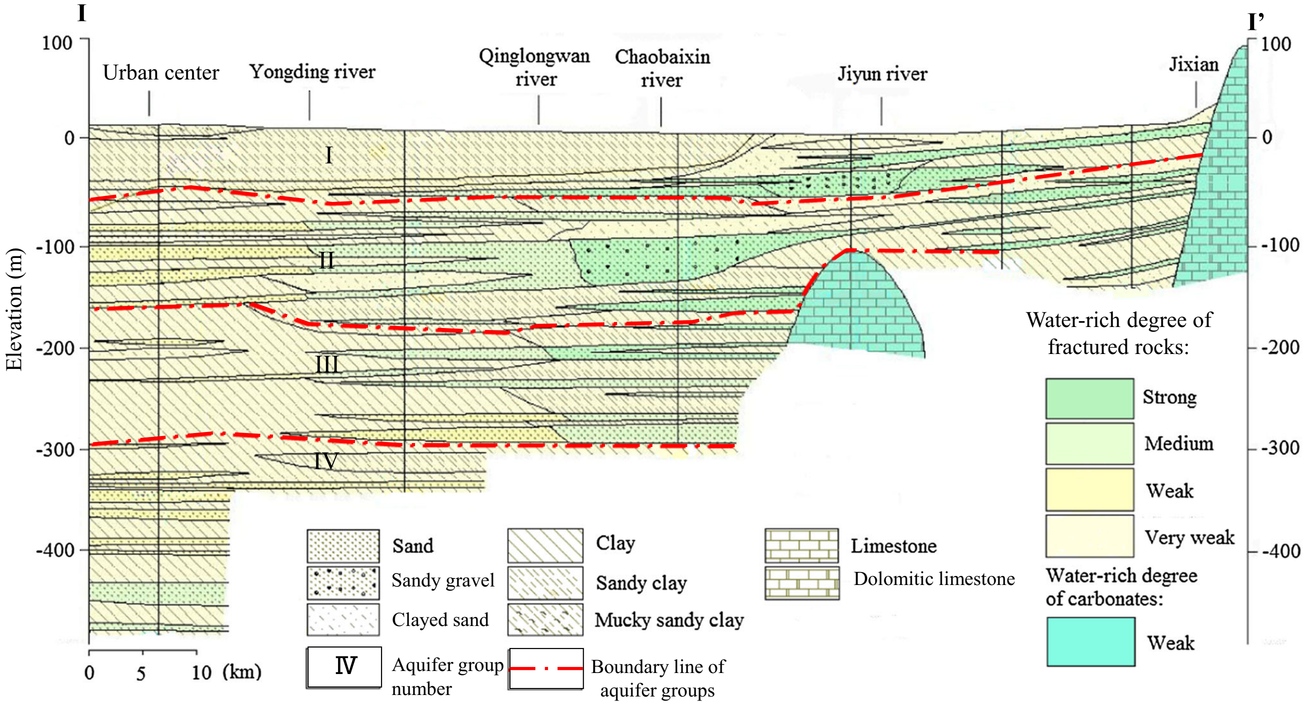
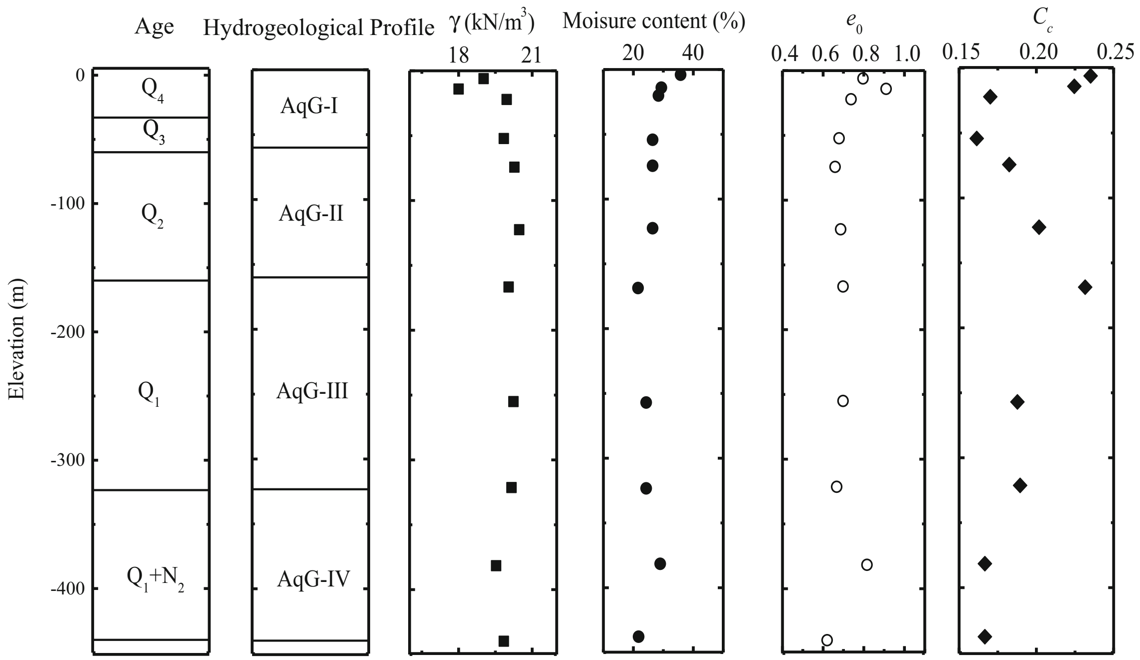


Fig. 2 Geological strata of Tianjin (cross-section I–I'). *Note*: γ = unit weight; e_0 = initial void ratio; Cc = compression index



Note: γ = unit weight; e_0 = initial void ratio; Cc = compression index.

Fig. 3 Illustration of soil profile properties at boring C6 in Tianjin (data from Wang [24])

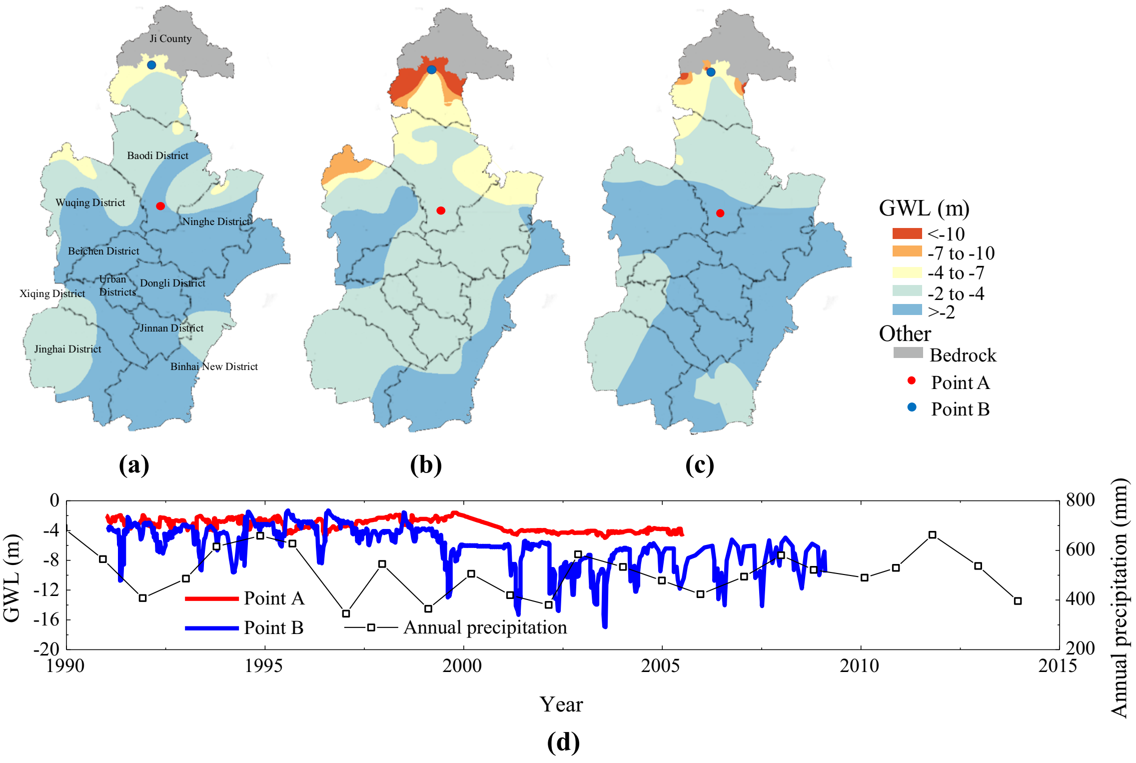


Fig. 4 Spatially averaged GWL zones in the AqG-I layer in **a** 1997, **b** 2005, **c** 2015, and **d** GWL overtime at the monitoring points A and B

salinized groundwater in the AqG-I layer of the southern portion of the plain. The GWL in the northern Baodi District and Ji County were deeper than those in the southern plain, ranging from -4 to -18 m. Groundwater in the latter areas is mostly freshwater.

The GWL in the AqG-I layer at the monitoring points A and B (see Fig. 4a) from 1990 to 2015 is shown in Fig. 4d. The average GWLs at points A and B showed downward trends from 1996 to 2002 because the annual precipitation fell to a relatively low level of approximately 450 mm/year. After this period, the annual precipitation slowly recovered which made the GWL in 2015 (Fig. 4c) return to that of 1997 (Fig. 4a). The GWL of the AqG-I layer became stable with small fluctuations due to the effects of recharge by precipitation and controls imposed on groundwater withdrawal. The monitoring of precipitation and the GWLs in the AqG-I layer established that approximately 70% of the shallow groundwater was recharged by precipitation in Tianjin, which is in agreement with the Tianjin Institute of Geological Survey (TIGS) [23].

3.2 GWL in the AqG-II layer

The spatially averaged GWL zones in the AqG-II layer over the past 50 years are displayed in Fig. 5a–e. Before 1982, a large volume of groundwater in AqG-II layer was withdrawn annually in the urban districts and the Binhai New District along with an insufficient natural recharge, which led to an uneven distribution of the GWL in the AqG-II layer. As seen in Fig. 5a, a cone of depression was formed in the middle part of Tianjin and extended along the cross-section I’–II’ (see Fig. 1). From 1973 to 1983, there was intense groundwater withdrawal from the AqG-II layer in the urban districts, the Jinghai district, and the Binhai New District, which induced three cones of depression as shown in Fig. 5b. A decreasing trend of GWL has occurred in the Binhai New District since the mid-1980s. The GWL in the AqG-II layer recovered due to groundwater withdrawal control. Subsequently, groundwater withdrawal shifted from the urban districts to the suburban area (e.g., Beichen and Xiqing districts), as shown in Fig. 5c. Mounding of groundwater was formed in the urban districts given that the upper aquifer group (AqG-I layer) is the main recharge resource for AqG-II layer. Since 2003 the GWL declining trend has slowed down in most areas of Tianjin, except in the southwestern area due to the LRTWD and SNWD projects. The worsening declining trend in the southwestern area has been caused by groundwater overdraft in Cang County, Hebei Province (HECX) located in the southwestern part of the Jinghai District (see Fig. 1) [6].

The GWL in the AqG-II layer at the monitoring points C and D (see Fig. 5a) from 1973 to 2015 is depicted in Fig. 5f. The GWL of AqG-II layer at point C in the urban districts reached its minimum value of − 50 m in 1983. Since then, the GWL gradually recovered to the range from − 10 to − 20 m and remained stable after 1990. The GWL at point D in the suburban area only partially recovered and remained at a level approximately equal to − 30 m. The GWL changes in the AqG-II layer may overconsolidate the soil deposits in the urban districts. This stress history has to be considered in underground engineering design (e.g., excavation and tunnel engineering [19–30]) through geotechnical surveys.

3.3 GWL in the AqG-III layer

The AqG-III layer is the main source of groundwater for the urban districts and the Binhai New District. By 1973, two cones of depression were formed as shown in Fig. 6a, whose spatial distribution is similar to that of the AqG-II layer shown in Fig. 5a. Since the 1980s, groundwater withdrawal in the AqG-III layer of the urban districts reduced the GWL to approximately − 40 m, as shown in Fig. 6b. The center of the cone of depression shifted from the urban districts to the suburban areas. The GWL in the urban districts continuously decreased to approximately − 100 m due to sustained groundwater withdrawal in the urban districts. From 2005 to 2015, the GWL in the AqG-III layer was relatively low in most areas of Tianjin, as shown in Fig. 6c, d. Because of the LRTWD and SNWD projects, the rate of groundwater pumping decreased and the GWL of the AqG-III layer remained relatively stable in this period.

The variation of the GWL in the AqG-III layer at points E and F located in the Baodi and Jinghai districts is shown in Fig. 6e. The GWL of the Baodi district (see point E) was significantly higher than that of the Jinghai district (see point F) because groundwater was mainly withdrawn from the AqG-III layer in the southern plain. Points E and F do not represent main pumping locations; yet, the GWLs in both areas showed similar declining trend caused by pumping area.

3.4 GWL in the AqG-IV layer

The spatially averaged GWL zones in the AqG-IV layer in 1997, 2005, and 2015 are shown in Fig. 7a–c, respectively. The GWL slowly decreased from 1997 to 2015 and reached its lowest value in 2015. The cone of depression of the GWL was enlarged from the urban districts to the entire region. The groundwater from AqG-IV layer was mainly withdrawn from the southern plain. The GWL from 1991 to 2015 in the AqG-IV layer at point G located in the Jinghai district is shown in Fig. 7d. The GWL in this layer has been dropping steadily over the entire observational period. The downward trend was not significant at point H in the Binhai New District.

Figure 8 presents the GWLs distribution in the AqG-II, AqG-III, and AqG-IV layers along the cross-section II–II’

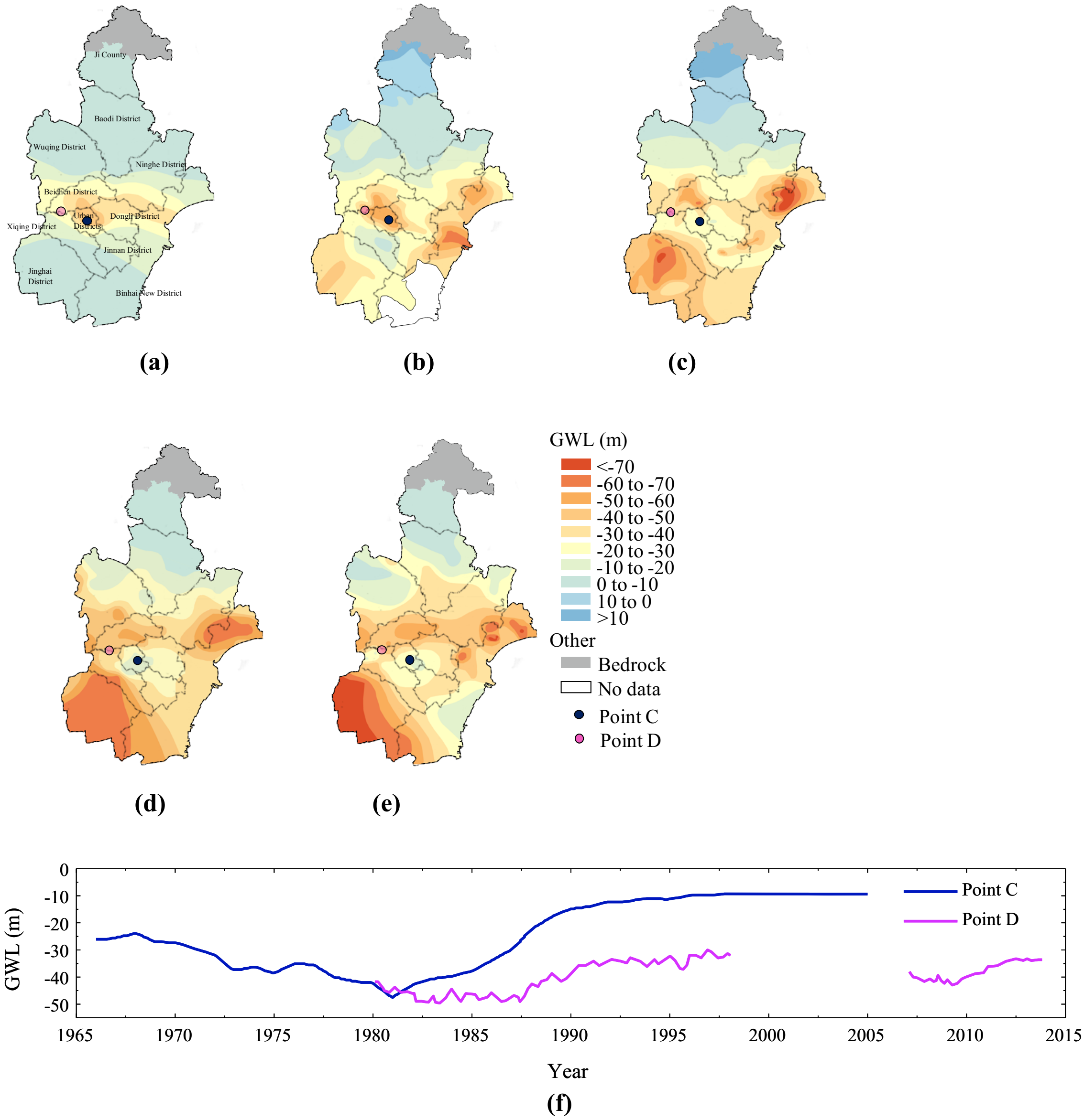


Fig. 5 Spatially averaged GWL zones in the AqG-II layer in **a** 1973, **b** 1983, **c** 1997, **d** 2005, **e** 2015, and **f** GWL change at the monitoring points C and D

(see Fig. 1) in 2005. The GWLs in the three aquifer layers were higher in the western and eastern regions of the Tianjin Municipality, and lower in the suburban areas (i.e., B-3 and B-4). The GWLs in the AqG-II and AqG-III layers of the urban districts were relatively higher than those in the suburban area except for a regional depression cone formed in the AqG-IV layer. It is seen in Fig. 8 that the GWLs in the aquifer layers decrease with depth. The GWL of AqG-III layer was between those of the AqG-II and AqG- IV layers, indicating the groundwater from AqG-III layer recharged the AqG-IV layer and was recharged by groundwater from the AqG-II layer.

4 Land subsidence variations

The soil strata in Tianjin Municipality consists mainly of fine sand, silt, and clayey soil which have very low permeability and high compressibility [11]. Groundwater overdraft increases the effective stress in soils, and land subsidence occurs [11, 23–15]. The land subsidence was mainly measured using general level surveys. For now, the leveling survey monitoring system includes 2300 benchmarks, 2 bedrock marks, and 14 continuous GPS stations. Land subsidence has been occurring over the past 40 years, as plotted in Fig. 9a–c. During 1975 through 1985, land subsidence was centered in the urban districts and the Binhai New District, as shown in Fig. 9a. The subsidence

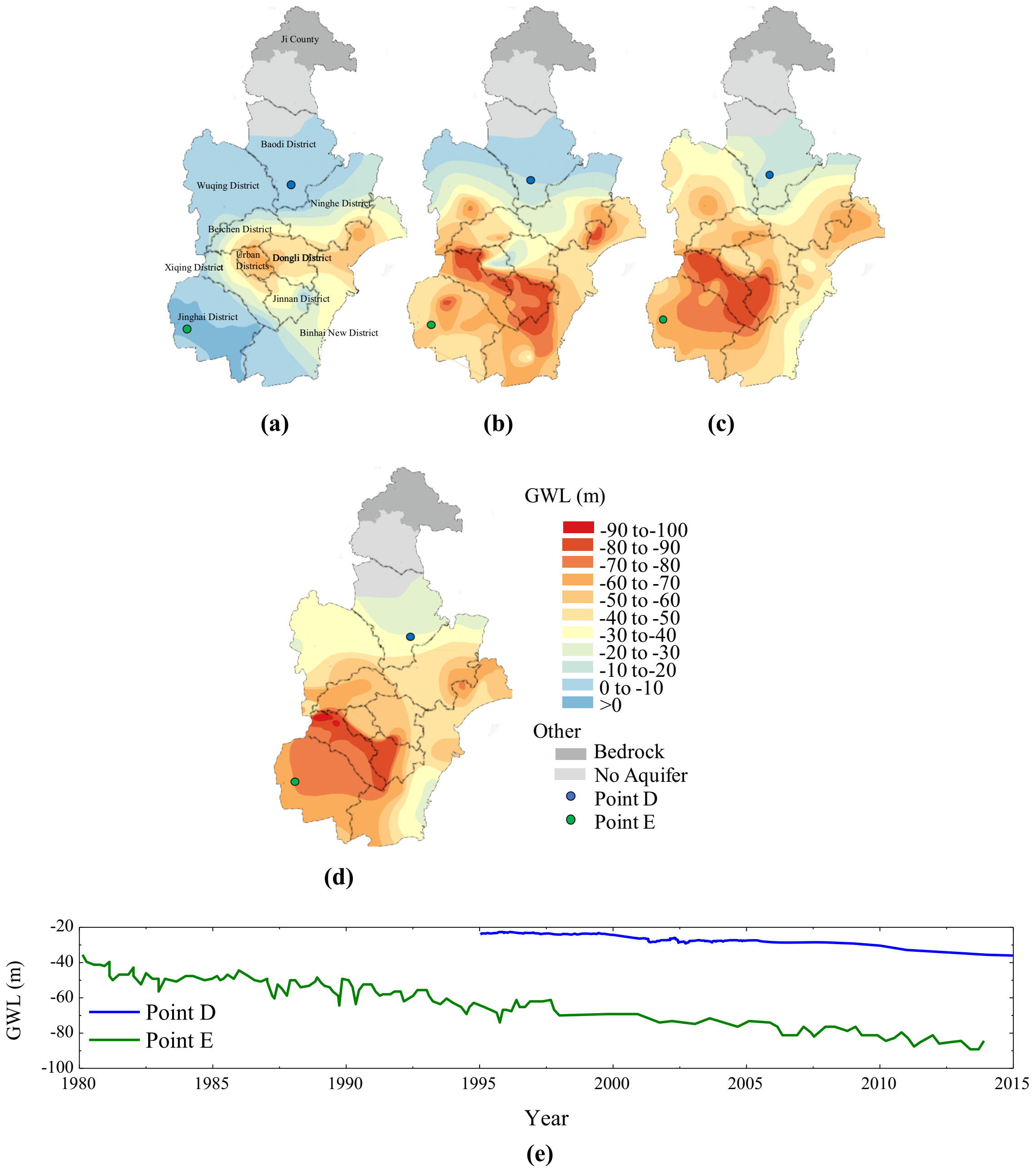


Fig. 6 Spatially averaged GWL zones in the AqG-III layer in **a** 1973, **b** 1997, **c** 2005, **d** 2015 and **e** GWL variations overtime at the monitoring points D and E

was consistent with the variation of the GWL in the AqG-II and AqG-III layers, shown in Figs. 5a and 6a, respectively. The subsidence in other areas was less than 400 mm during this period. During 1986 through 2005, the subsidence trend in the urban districts became gentler, as shown in Fig. 9b due to controls on groundwater withdrawal. The spatial distribution of the land subsidence in 1986–2005 differs from that observed in 1975–1985. The southwestern region exhibited the largest subsidence reaching a maximum approximately equal to 1300 mm. This was due to overdraft in the HECX area, which is consistent with the lowering of the GWL in the AqG-II layer shown in Fig. 5d. The land subsidence in the Binhai New District was also large due to overdraft. The pattern of subsidence shown in Fig. 9b is consistent with the variation of the GWL in the AqG-II and AqG-III layers depicted in Figs. 5a and 6a, respectively. During 2006 through 2015, an obvious land subsidence still experienced in the suburban areas. The pattern of land subsidence is displayed in Fig. 9c, which is

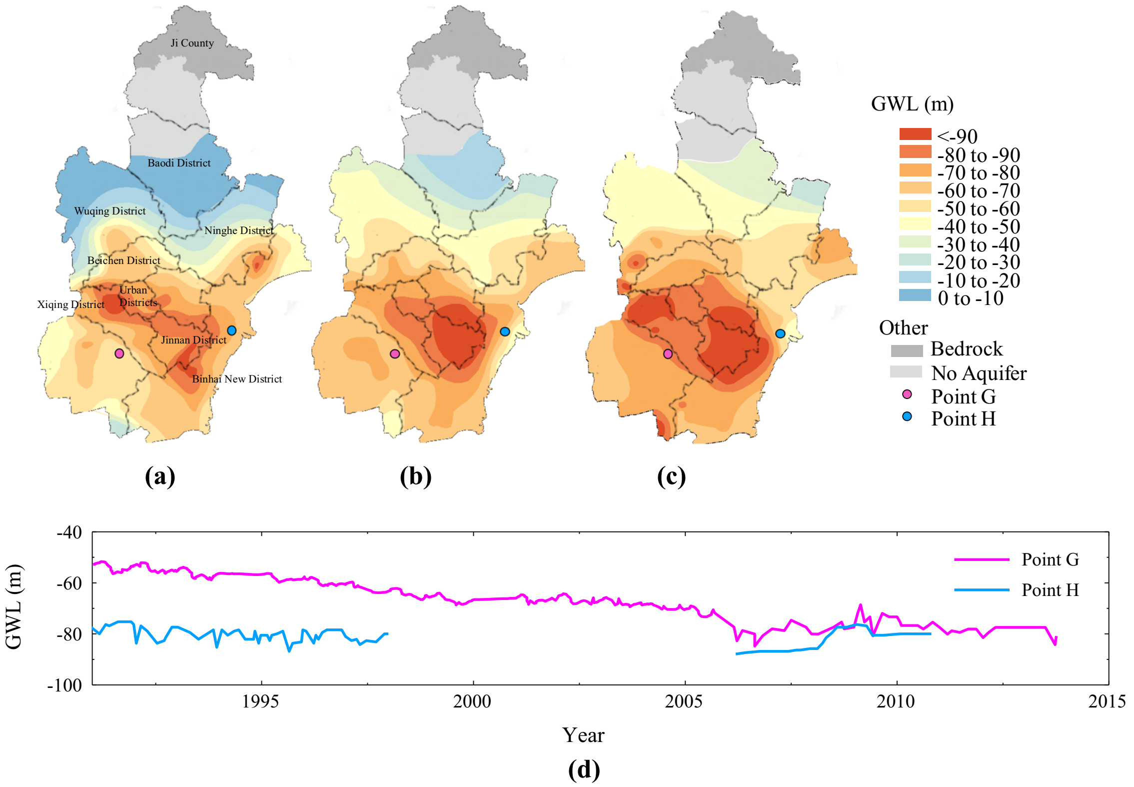


Fig. 7 Spatially averaged GWL zones in the AqG-IV layer in **a** 1997, **b** 2005, **c** 2015 and **d** GWL overtime at the monitoring points G and H

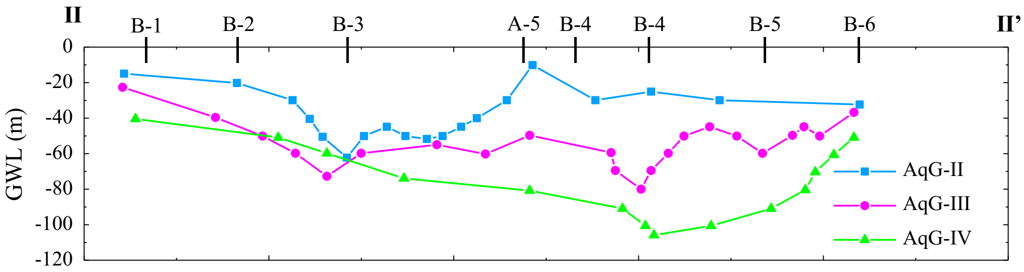


Fig. 8 GWL of the aquifer layers along the cross-section II–II’

consistent with the variation of the GWL in the AqG-III and AqG-IV layers.

5 Land subsidence in the urban districts

The urban districts and Binhai New District experienced the largest subsidence caused by groundwater overdraft. The pumping rate, GWLs in the AqG-I through AqG-IV layers and the average annual subsidence variations at point C (see Fig. 5) in the urban districts are shown in Fig. 10. As shown in Fig. 10b, the downward GWL trend in the AqG-II through AqG-IV layers slowed from 1965 to 1985. This GWL pattern is consistent with the land subsidence and the pumping rate presented at point C, as shown in Fig. 10c. The trends of the land subsidence during the 1985–2005 are also consistent with the GWL patterns observed in that period. The land subsidence history at point C in the urban districts can be roughly divided into three periods, namely, the Rapid development period (1965–1985), Controlled period (1986–1990), and Slow development period (1991–2005). During the Rapid development period, the GWLs of deep aquifer layers exhibited declining trends, and the subsidence rate was relatively high with an average rate of approximately 65 mm/year. In the controlled period, the GWLs in the AqG-II and AqG-III layers gradually recovered except for the GWL in the AqG-IV layer. The land subsidence rate was 70 mm/year in 1985 and 10 mm/year in 1990, as shown in Fig. 10c. This is due to the effects of the SNWD

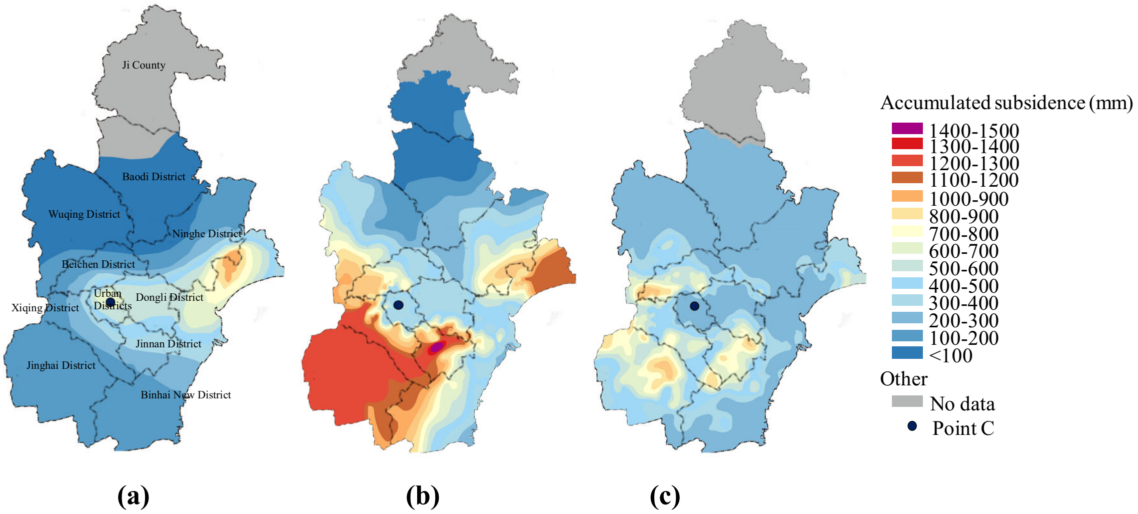


Fig. 9 Variation of land subsidence in Tianjin **a** from 1975 to 1985, **b** from 1986 to 2005, and **c** from 2006 to 2015

project that reduced the groundwater withdrawal. The subsidence rate followed a similar trend and fluctuated from 10 to 30 mm/year.

6 Land subsidence in the Binhai New District

The subsidence was more severe in Binhai New District than in the urban districts [8]. The variations of the pumping rate, GWLs in the AqG-II and AqG-III layers, and the annual average subsidence at point H in the Binhai New District are plotted in Fig. 11a–c, respectively. Appreciable land subsidence mainly formed from 1965 to 1987, reaching a maximum equal to 3180 mm during this period [23]. The maximum subsidence occurred in 1982 with magnitude of approximately 235 mm. The subsidence affected approximately an area of 30 km^2 whose elevation was equal to or lower than mean sea level until 2002 [8]. The subsidence history in Binhai New District varied through a slow period (1959–1977), an accelerating period (1978–1982), and an attenuating period (1982–2005).

Controls imposed on groundwater withdrawal in the deep aquifer layer are essential for preventing land subsidence. Figures 10 and 11 indicate the patterns of GWL variation are consistent with the land subsidence variations, indicating the GWLs changes are the main reason for land subsidence. Artificial recharge (AR) has been implemented to mitigate subsidence [28–26]. In Tianjin, approximately 69% of the groundwater recharge was from precipitation, and approximately 5% was from AR [24]. Groundwater withdrawal in the AqG-II and AqG-IV layers accounted for more than 70% of the total amount groundwater abstraction. Therefore, the vertical recharge from the top two aquifer layers (AqG-I and AqG-II) was not sufficient to increase the GWLs in the two bottom aquifer layers (AqG-III and AqG-IV). AR has, therefore, being effective for recharging the AqG-III and AqG-IV layers.

7 Conclusions

This paper has presented data and data analysis concerning land subsidence and GWLs in Tianjin, China. The detailed information of GWL data in each aquifer layer is reported. A large amount of groundwater has been withdrawn annually in Tianjin Municipality to meet increasing water requirements for agriculture, industry, and the local population. A series of field observation wells were installed to monitor the long-term GWL changes. The deposit of Tianjin was divided into four aquifer layers, so-called AqG-I, AqG-II, AqG-III, and AqG-IV layers, based on their geological and hydrogeological conditions. The GWL of the AqG-I remained relatively stable because of vertical recharge from precipitation. The AqG-II, AqG-III, and AqG-IV layers were the principal layers used for groundwater supply. Due to the effects of the LRTWD and SNWD projects the GWL in the AqG-II layer has recovered slowly since 1990, whereas that of the AqG-III and AqG-IV layers have been declining steadily over the past 50 years. For urban districts, the GWL changes in AqG-II may lead to the overconsolidation in the corresponding soil deposits, and the stress history is suggested to be analyzed for important underground construction.

Land subsidence in Tianjin has been monitored over the past 40 years. The patterns of land subsidence are

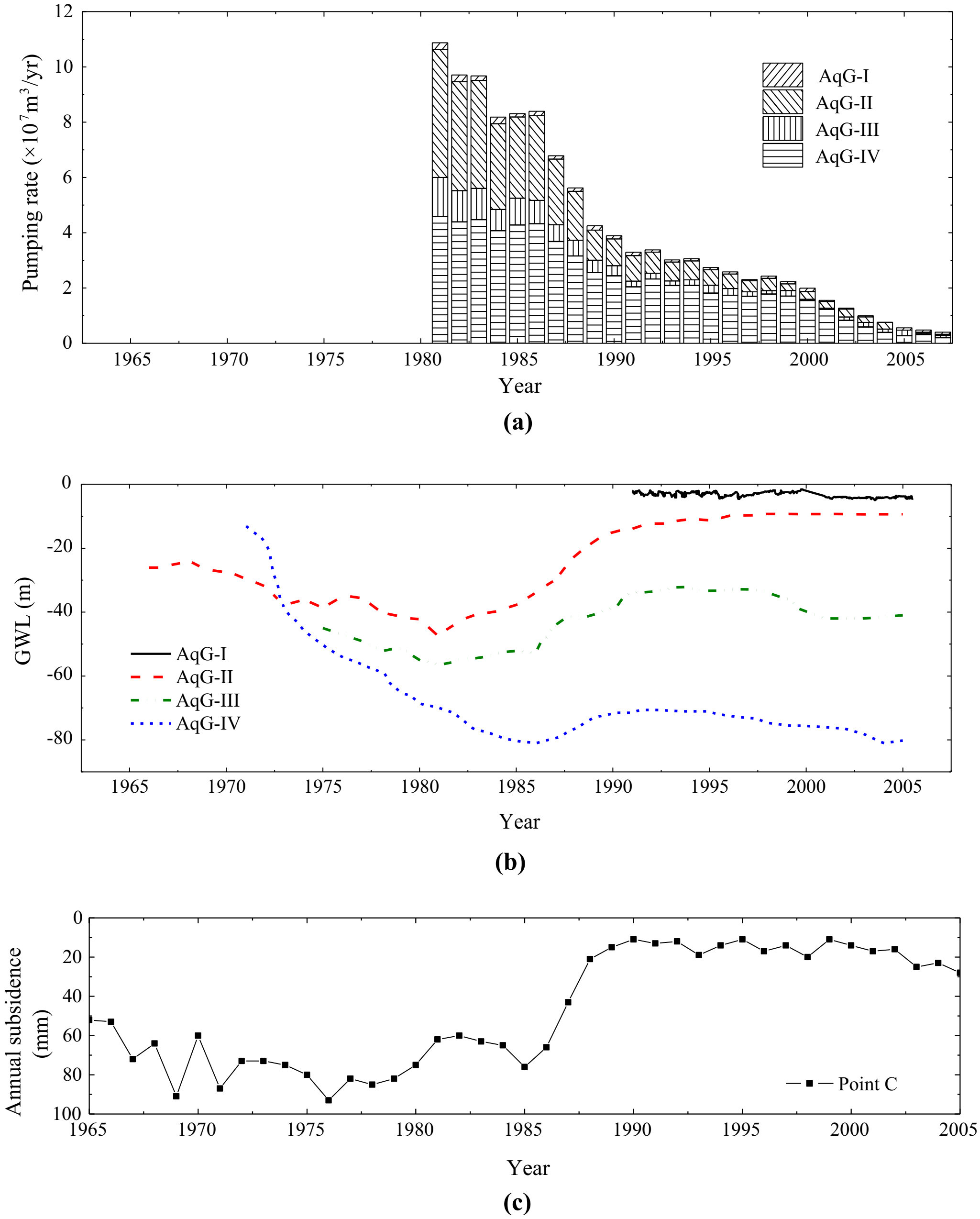


Fig. 10 Variations of the **a** pumping rate (10^7 m^3/year), **b** GWLs in the AqG-I through AqG-IV layers, and **c** annual subsidence at point C in the urban districts

consistent with the patterns of GWL in the aquifer layers indicating the GWLs changes are the cause of land subsidence in the study area. The uneven areal distribution of land subsidence is closely related to that of the cones of depression. The urban districts and Binhai New District were the two regions most heavily impacted by land subsidence. The SNWD project reduced groundwater abstraction in Tianjin, and this has partly alleviated land subsidence in the impacted areas. AR and other method can be potentially implemented in the aquifer layer to mitigate land subsidence.

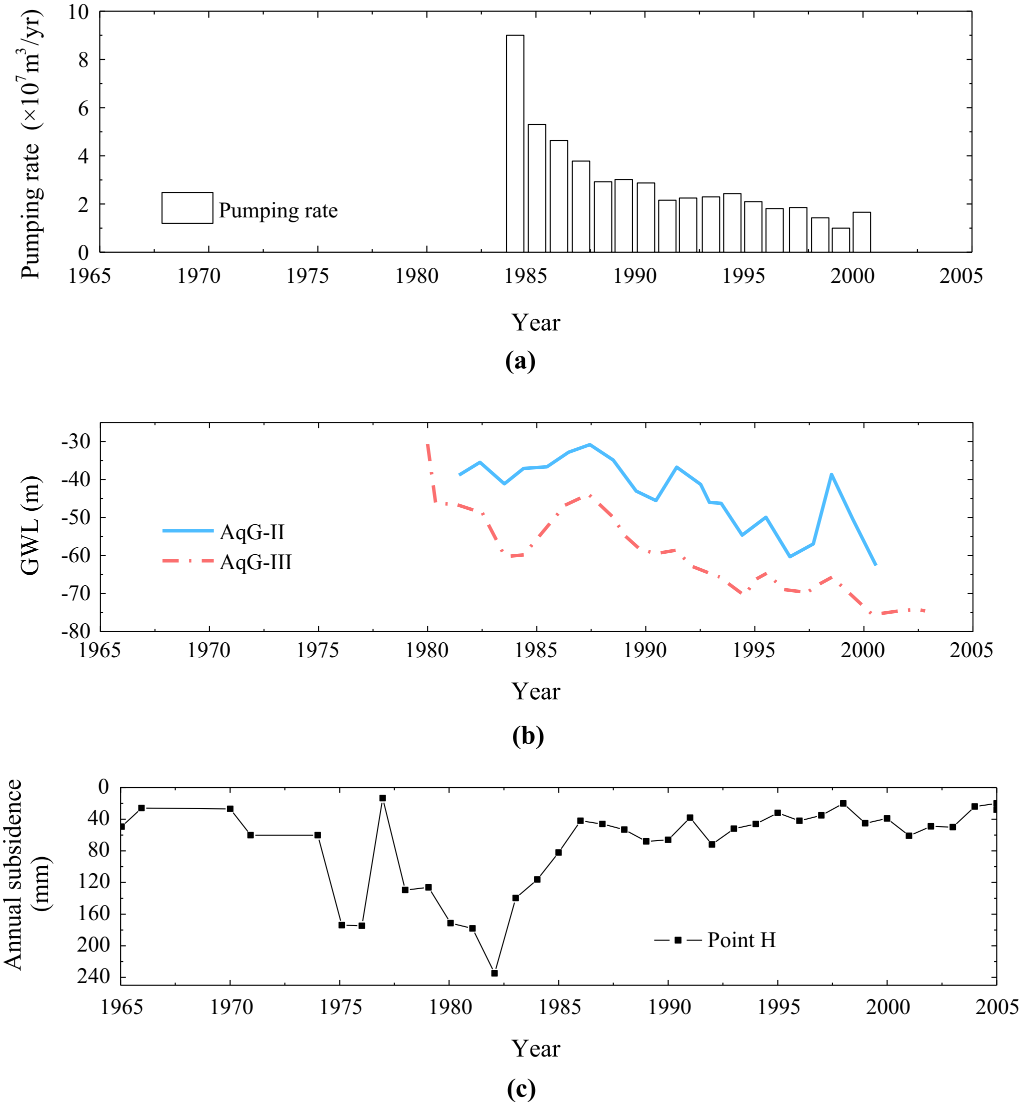


Fig. 11 Variations of the **a** pumping rate (10^7 m^3/year), **b** GWLs in the AqG-II and AqG-III layers, and **c** average annual subsidence at point H in the Binhai New District

This study represents a first step toward the development of a numerical model of the subsidence occurrence to be used for planning remediation strategies in this area.

Acknowledgments Support for this work was received from the National Natural Science Foundation of China (Nos. 52078337, 51708405, 41630641).

Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

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