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ORIGINAL PAPER

A numerical study on land subsidence due to extensive overexploitation of groundwater in Aliabad plain, Qom-Iran

Ali M. Rajabi[1]

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Abstract

Over the last decade, many areas of Iran have been increased in suffering from land subsidence due to a large exploitation of groundwater, needed to cope with the water scarcity caused by low precipitation. The plateau of Qom, especially the area of Aliabad village (Aliabad plain), has encountered many problems due to subsidence which occurs as cracks in building walls and fractures in wells. In this paper, we are going to evaluate land subsidence in some parts of Qom plateau, in particular Aliabad plain, by a numerical model (PLAXIS® 3D; v1.6) considering aquifer pressure changes, hydrological and geotechnical data. Results of the study reveal that since 2001–2013, the average groundwater level decline was measured 26.35 m and the corresponding subsidence had been 0–76 cm in different areas of the plain. Response of the saturated geologic units toward the changes in ground water level due to groundwater extraction and, in turn, land subsidence depends on the characteristics of geological materials in the units. Moreover, the units containing a combination of grain and fine soil, such as sand and clay which are completely different in the geotechnical parameters, tend to react differently due to all changes in the groundwater level.

Keywords Subsidence · Groundwater · Qom · PLAXIS

1 Introduction

One of the major problems related to excessive exploitation of groundwater tables is water level decline and densification of strata and sediments. It is often observed in semiarid and arid environments and makes the ground subside gradually or suddenly which creates cracks in the ground surface, destroys buildings and pipelines, changes the inclination of streams and roads, gradually sinks rigs and structures, fractures the walls of wells, changes land slope. Subsidence usually does not occur at the same time as the leaving fluid, but it occurs in a longer period of time (Scott 1979). The land subsidence varies from 1 to 50 cm per 10 m drop in the water table, and its range depends on thickness and densification of

✉ Ali M. Rajabi
amrajabi@ut.ac.ir

[1] Engineering Geology Department, School of Geology, College of Science, University of Tehran, Tehran, Iran

strata, loading time and the area's stresses (Lofgren 1969). Globally, the highest risk of subsidence due to water table decline had been since 1950 when urbanization and industrialization grew. The severe outcomes to the environment and economy of the global distribution of land subsidence demonstrate that it requires more and deeper research on an international scale (Hu et al. 2004). Geohazards and destructive effects caused by land subsidence from extensive overexploitation of groundwater have been reported in Houston-Galveston, Texas, USA (Gabrysch 1984), Tianjin, China (Yi et al. 2011), Bangkok, Thailand (Phien-wej et al. 2006), Venice, Italy (Teatini et al. 2012), Quetta Valley, Pakistan (Khan et al. 2013), Mexico City, Mexico (Yan et al. 2012), Jakarta and Samarang, Indonesia (Chaussard et al. 2013). In Iran in recent years, subsidence has been reported in some aquifers like Yazd (Amigh Pay et al. 2010), Rastagh (Zare Mehrjerdi 2011), Salmas (Sedighi et al. 2010), Sirjan (Abbasi Nejad and Shahi Dasht 2013), Mashhad (Motagh et al. 2007), Rafsanjan (Motagh et al. 2017), Tehran (Mahmoudpour et al. 2016) and Arak (Rajabi and Ghorbani 2016) all because of groundwater level decline. One of the other areas subjected to subsidence is Kerman province in which subsidence has been measured 42 cm in Rafsanjan and 27 cm in Sirjan for a 10-m water table depletion (Rahmanian 1986). In Rastagh, south Meybod, a subsidence about 50–120 cm has occurred from 1991 to 2011 (Zare Mehrjerdi 2011). An average 10–15 cm/year of subsidence has also been reported in northwest of Mashhad (Motagh et al. 2007). The destructive effects of this type of subsidence have also been reported in Tehran (Mahmoudpour et al. 2016), Arak (Rajabi and Ghorbani 2016), Mahyar, Nayshabour and Kashmar (Lashkaripour et al. 2010).

Poroelasticity consolidation theory which was formulated by Biot (1941) is used to explain land subsidence phenomenon. Poroelasticity theory is considered as a quite useful method to analyze the interaction between skeletal-matrix deformation and fluid flow (Hsieh 1996). The effective stress, which was firstly introduced by Terzaghi (1925), is applied to elucidate the occurrence of land subsidence depending on the drop in groundwater level (Galloway et al. 1999). Excessive groundwater withdrawal from aquifer systems decreases pore water pressure and increases effective stress. Enhancement of effective stress leads to compaction of hydro-stratigraphic units, including aquitard and aquifer units and consequently land subsidence. According to the Calderhead et al. (2011), aquitard units which consist of clay and silty clay experience higher compressibility and greater compaction than aquifer units consisting of sand. When the stress imposed on the skeleton is smaller than the previous maximum effective stress, aquifer-system deformation will be elastic and recoverable. In conditions that the stress is greater than the pre-consolidation stress, the pore structure of the fine-grained sediments rearranges into a configuration that becomes more stable at higher stress. This may lead to an irreversible reduction in pore volume and in inelastic compaction of the aquifer system (Sneed et al. 2003). Pre-consolidation stress is the maximum effective stress that the soil has ever experienced. This maximum stress separates elastic and reversible deformation from inelastic and partially irreversible deformation (Tomás et al. 2007). According to Calderhead et al. (2011), numerical models are quite effective tools to evaluate the evolution of land subsidence caused by groundwater pumping. They are considered as the most powerful tools to predict and assess future land subsidence (Cao et al. 2013). As an example of numerical simulation applications, PLAXIS (1998) has been used to simulate the effect of the size and number of clay zones on the value and the pattern of distribution of subsidence around the wells (Budihardjo et al. 2014), estimate of consolidation of settlements caused by groundwater drainage (Altinbilek 2006) and estimate of land subsidence and earth fissures due to groundwater pumping (Adiyaman 2012).

The plateau of Qom, in particular Aliabad plain, is one of the most important plains in Iran which is at risk of ground subsidence. This phenomenon has appeared in the form of subsidence and cracks in the walls of buildings and failures in wells (Fig. 1). Providing lots of irrigation and drinking water from the plain on the one hand and low precipitation on the other has been resulted into intensive depletion of the groundwater table. Accordingly, from 1993 to the present, after subsidence occurrence, this plain has been labeled as a

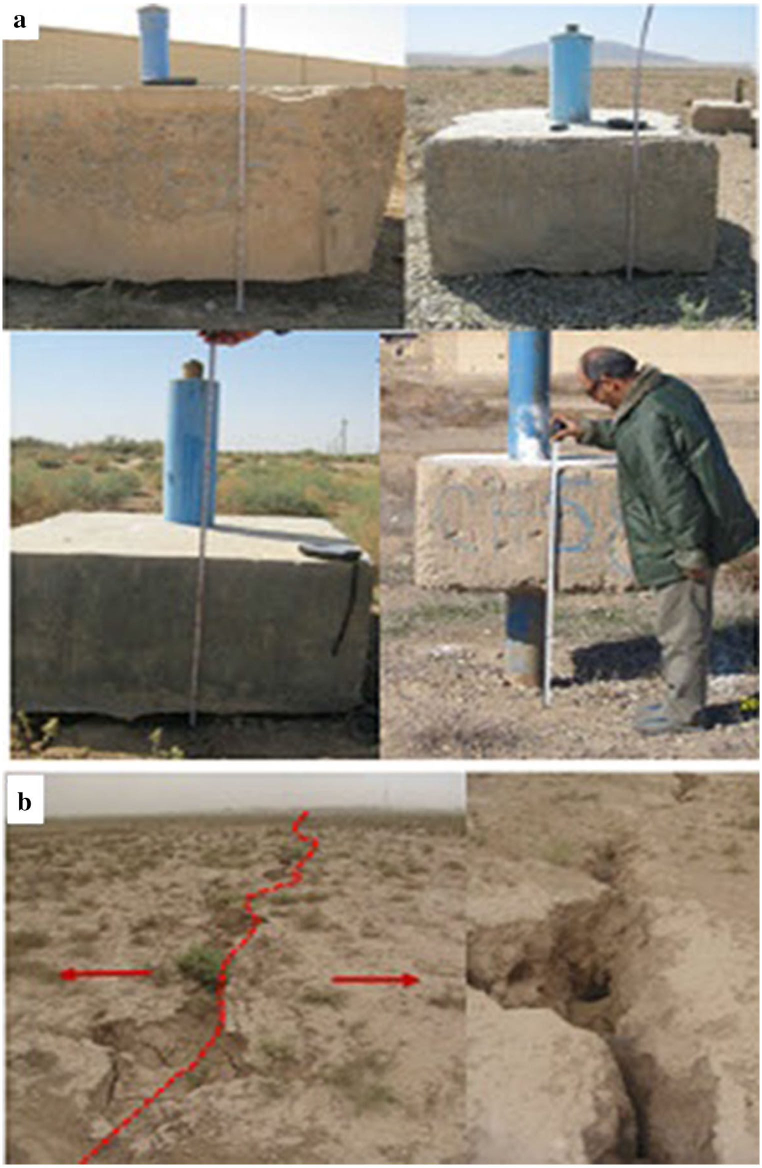

Fig. 1 **a** Subsidence in the vicinity of piezometers, **b** openings caused by subsidence near the Aliabad plain (Reproduced with permission from Qom Regional Water Company 2011a, b)

banned plain. In the present study, we are going to investigate the subsidence in the plain of Aliabad plain and its relationship with water table variations.

2 Previous study

Subsidence has been occurred in many places around the world such as Mexico City, China, Thailand, Japan and the USA (Zhou and Esaki 2003). A number of subsidences ranging from 1.1 to 43.8 mm/year were identified in Ganges–Brahmaputra–Meghna (Brown and Nicholls 2015). Strozzi et al. (2014) also reported significant movements with values ranging from 2 to 12 mm/year above Gotthard Base Tunnel in Switzerland from 2003 to 2010. Bandung basin located in west Java, Indonesia, which is a large intra-montane basin surrounded by volcanic highlands indicated an average subsidence rate of 8 cm/year (Gumilar et al. 2015). Ground failure associated with land subsidence due to groundwater withdrawal is the main geotechnical hazard in the Aguascalientes Valley, in Mexico (Pascheco Martinez et al. 2013).

Sasaoka et al. (2015) described the condition of underground coal mine in Indonesia and then discussed the subsidence behavior due to longwall mining operation based on measured data in Balikpapan coal-breaking formation in Indonesia. Radouane et al. (2015) using a finite element method and applying an elasto-plastic model analyzed the stability of underground mining on the Chaabte El Hamra mine in Algeria. Similar researches also have been conducted by Ammar and Khalid (1997), Abidin et al. (2001), Xu et al. (2007), Abbasi Nejad and Shahi Dasht (2013), Cui et al. (2015), Zhou et al. (2017) and Budihardjo et al. (2014).

In order to assess the subsidence phenomenon qualitatively and quantitatively, several studies have been done in Qom plain. Fereydouni et al. (2006) studied the causes of destruction in some structures of west and southwest of Qom. In this study, it was found that the main cause of subsidence and damage to buildings are finally presence of expandable marls around the foundation. Nazari and Arab Nejad (2006) studied the reasons of subsidence in Qom plain with a quantitative and qualitative assessment and introduced the impact of water extraction on the ground subsidence more than the sediments loading agent. Agha Babaie et al. (2010) studied the land subsidence in the region of Saveh in the Qom basin, using the radiometric techniques. Moghadam Fereydouni et al. (2011) studied the causes of subsidence in the plain of Aliabad Qom. After hydrological and morphological feature assessment, they found that the main cause of subsidence in the area in recent years is the decline in groundwater table. They knew that dam construction on the river Kara-chai, successive droughts and increasing agricultural wells are the main reasons for the change in hydrological regime and ultimately the ground subsidence of the region. Jafari et al. (2013) studied the amount of subsidence due to groundwater exploitation in Qom plain using hybrid modeling and techniques of InSAR. The results showed that the rate of subsidence during the years of 2003–2010 was about 70 cm. However, the subsidence problem in Qom plain is still a challenging issue in the researchers mind. Using numerical modeling, Mahmoudpour et al. (2016) assessed ground subsidence rate in the southwestern plain of Tehran and revealed that assuming a constant rate of pumping in the future, land subsidence will reach 33 cm by 2018. Their study confirmed that land subsidence caused by groundwater pumping is a serious threat to southwest Tehran.

2.1 The study area

The plain of Qom is a vulnerable area due to groundwater exploitations. It is positioned in N/NW of Qom province between the longitude of 49°59′35″ to 51°03′27″E and the latitude of 34°27′23″ to 35°12′16″N. The area of the region is about 4045 km^2, from which 2125 km^2 is under the authority of Qom province water headquarters. The eastern border of plain leads to Sharifabad and Masileh plains. Alborz overthrust is the main structure in the southern border which separates mountains from the plain. The average altitude of the plain from sea level is 958 m, and the common slope is eastward with an average of 34 percent, which increases toward the west. The study area, Aliabad plain, as one of the damaged areas caused by extensive overexploitation of groundwater is commonly located in Qom and Markazi provinces. The most important cities in the area are Qom, Saveh, Dastjerd and Jafariyah. Figure 2 shows the location of the study area.

The study area is located in the northwest tectonical unit of central Iran and is affected by the alpine Zagros orogenic stressing forces from southwest and by Alborz orogenic stressing forces (mainly Pasadenian phase) from north and northwest. Active faults in southwest of the area, such as Hendos, follow Zagros faults trend and lay along the northwest-southeast trend, being the main tectonic phenomenon of the area from south of Gezel Darreh village to the east of Khalajestan sub-catchment. From the north of Gezel Darreh village to the north of Aliabad Shahjerd, a thrust fault has moved Eocene volcanic and sediment strata to the verge of alluvial formation of Hezar Darreh (Fig. 3; Darvish-zadeh 1991).

The plain of Qom mainly consists of clay and clastic formations. From around the village of Saman to the western margin of Louin plain, old alluvial sediment series have been developed. These sediments, mainly consisting of conglomerates, clay matrix and layers of clay, are old fluvial terraces of Mazlaghan River and are not permeable enough for exploitation of the groundwater. Concurrent alluvial includes small and large alluvial

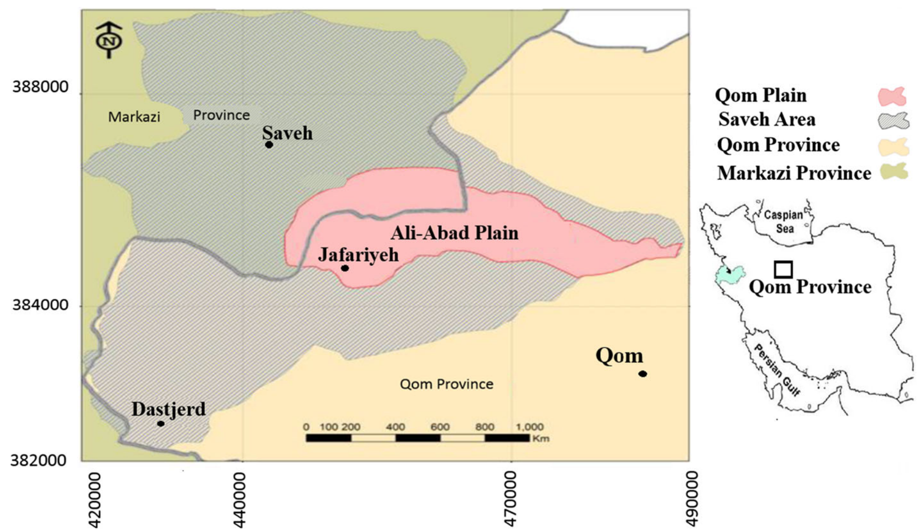

Fig. 2 Location of the study area

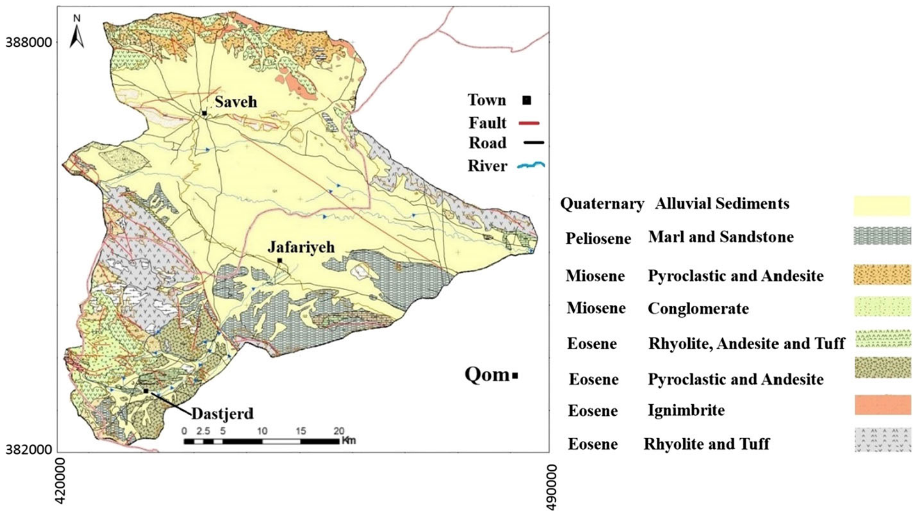

Fig. 3 Geological basic map of the study area (adopted from Qom Regional Water Company 2011a; Geological Survey of Iran 2002)

fans from rivers and streams leading to low plateaus (Qom Regional Water Company 2011a).

In the study area, the average 25-year precipitation has been 218 mm with an average yearly temperature of 16.7 °C. Yearly evaporation rate in Aliabad station has been 238.5 mm. In hydrological terms, the study area is placed on the Basin of Namak Lake. This plain has a major river called Gharreh Chai, which has been drained with the manufacturing of Alghadir Dam in 1993 in the neighborhood of Aliabad village (downstream of the dam). The drinking water in the area has been traditionally provided by the river and Kanat, but today it is supplied by deep and semi-deep wells.

According to hydrograph data of Qom plain, there has been a monotonous trend in groundwater table decline until 2001 (Fig. 4); however, a major decline is seen afterward, such that in 8 years, the whole plain has experienced a 30-m depletion (Qom Regional Water Company 2013).

In Fig. 4, a descending hydrograph shows a critical decline, especially from 2006 to 2013. The balance rate of the groundwater has decreased from 925.81 m in 1994 to 894.64 m in 2013. In other words, during 20 years, the groundwater table depletion has been 31.17 m (an average of 1.56 m/year; Qom Regional Water Company 2013).

2.2 Data and method

This study has been conducted using a numerical simulation of geotechnical software called PLAXIS® 3D (Brinkgreve and Broere 2006). This program is able to calculate consolidation theory based on Biot (1941). This software is used to analyze the deformation and the characteristic of various soils to some extent, similar to their actual behavior (PLAXIS 1998). This program also conducts calculations based on the finite element method used to analyze the deformation and stability of different applications in the geotechnical field.

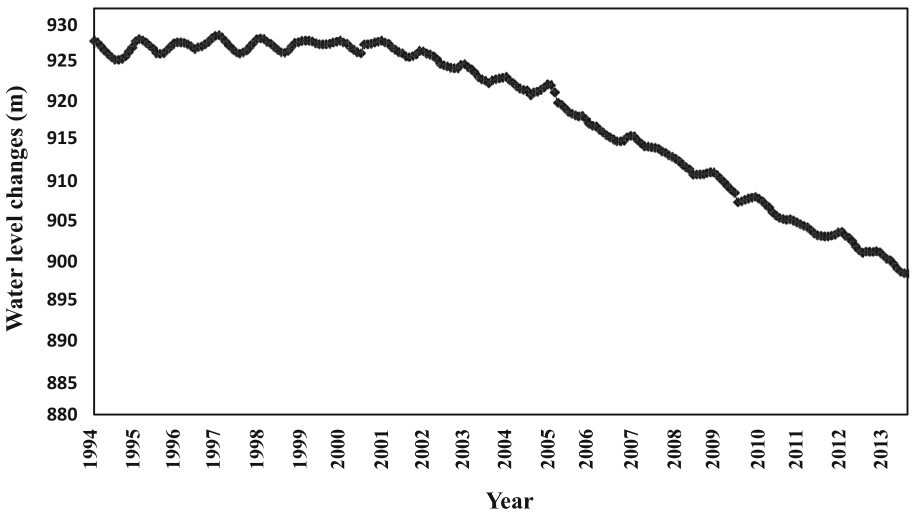

Fig. 4 Changes in groundwater level of Qom plain from 1993 to 2013 (data adopted from Qom Regional Water Company 2013)

The first step of the model configuration is to create realistic and simplified geological profiles of the study area. Other input parameters necessary for the configuration of this model include the geotechnical properties of the various soil layers and the groundwater fluctuations history. By obtaining these data, the constitutive laws reproducing the stress–strain relationship of the materials as well as the loading history of the materials can be appointed, simulating the phenomenon. Considering the depth of the deepest wells exploiting the deep confined aquifers (about 182 m in present study), taking into account the depth of the geologic units (182 m) and the water level variations (between 1.22 through 44.22 in 1993–2013), the thickness of the profiles was selected. In order to configure the excess pore pressure along the boundaries, a close consolidation boundary has been applied at the base and at the sides of the profiles after setting up the simulation profile. In order to identify the soil behavior, in the present study, the Mohr–Coulomb elastic-perfectly plastic model has been taken into account to be the suitable constitutive law for the simulation of the geomaterials. Moreover, using the consolidation theory calculations has been conducted.

In this paper, after field survey, the area of subsidence in Aliabad plain was studied in hydrological and geological point of view. Thereafter, among 26 studied regions/zones, 10 out of all plain areas were selected as representative based on availability of accurate data and geological and geotechnical information. These 10 regions are coincident to wells named Aliabad, Shokuhie, Gazran, Rahahan, Masjed e Abolfazl, Maaref, Ganjineh, Aliabad River, Hajiabad and Einabad. Figure 6 shows the location of each well.

To conduct the required analysis by numerical model using PLAXIS® 3D; v1.6, the required information was collected. This information included hydrological data of the piezometric wells and their water table changes in different years, wells profile information (soil layers at different depths) and parameters needed in the modeling such as coefficient of elasticity, wet and dry density, cohesion, internal friction angle and Poisson's ratio of soil layers in wells. Hydrological data were gathered from Qom Regional Water Authority reports (Qom Regional Water Authority 2013) and geotechnical parameters of different soil layers were selected using literature (American Society for Testing and Materials 1986; Amer and Awad 1974; Hansbo 1960; Tavenas et al. 1983; Mayne and Poulos 1999; Schmertman 1953; Jafari et al. 2013; Nazari and Arab Nejad 2006; Moghadam Fereydouni et al. 2011) and local institutes (such as Qom Regional Water Authority 2013). Furthermore, some supplementary tests were conducted in the study area.

In order to start the process of modeling, the groundwater table changes had been collected in different wells during years of 2001–2013 monthly and annually as mean. According to the mentioned issue, the deepest well and the least deep one in the area were Gazran and Rahahan with the depth of 182 and 66 m, respectively. The highest decline in water table was measured in Aliabad with 44.32 m and the least one in Masjed e Abolfazl with 1.22 m. Groundwater decline in other areas was measured between these two (Table 1). The final values of the mechanical parameters selected for the simulation of the geological formations are presented in Table 2.

According to this table, the profile of wells in the study area is mostly fine-grained with gravel and sand in between. In order to validate the land deformations caused by extra drawdown, the obtained land subsidence results using InSAR (from the ASAR; Envisat satellite) in the studied areas (Qom Regional Water Company 2011b) related to the same years (2001–2013) were also used.

To predict the subsidence of land, after assigning input parameters for each layer in every area and well, soil strata geometry in each area was modeled individually and 2000 meshes were established for each stratum based on the width of the area. In this model, all the analyses were performed in plane strain conditions. Then, based on model, the process of groundwater depletion and subsidence occurrence in each area was studied.

3 Results and discussion

Figure 5 shows the model results around the studied profiles/wells. In Fig. 5, different colors show soil layers in each region and the red arrows in each of the mesh layers represent the amount of displacement which has been taken place in each layer of the soil. The calculated subsidence around the studied profiles/wells by modeling is show in Table 3.

According to the study, the biggest subsidence has been occurred in fine-grained strata of wells and the subsidence in the western parts of the plain was significant. In some areas, the subsidence has been occurred only down to the intermediate strata. Because of coarse granularity of lower strata or lack of groundwater depletion, no significant subsidence has been experienced in the lower/bottom strata (e.g., Lower layers in Aliabad or Aliabad River); however in some regions, subsidence has been occurred till the lowest strata (e.g., Gazran), which is related to the significant decline of groundwater table in whole strata (Fig. 5).

As mentioned before, in this study, the obtained land subsidence results using InSAR (from the ASAR; Envisat satellite) in the study areas related to the same years, i.e., 2001–2013 (Qom Regional Water Company 2011b) were also used to investigate verification of the model results. Accordingly, as can be seen in Fig. 6, the subsidence in the plain of Aliabad was 0–80 since 2001–2013. Comparison of the results obtained by the model with those obtained by InSAR (Qom Regional Water Company 2011b) reveals good correspondence (Fig. 6). Differences between results of the model and InSAR are provided in Fig. 7. According to Fig. 7, large differences in some areas like Aliabad and Einabad are

Table 1 The drop in water level of Qom plain in the study area

Region	Hajjabad	Aliabad River	Ganjine	Maaref	Masjed e Abolfazl	Aliabad	Shokuhie	Gazran	Rahahan	Einabad
Water table decline (m)	3.27	41.69	2.72	11.45	1.22	44.32	32.22	29.1	15.61	33.84

Table 2 The specifications of soil layers in the study area

Region	Layer	Soil type	Depth (m)	Parameters					
				E	γ_{sat}	γ_{dry}	ϕ	c	ϑ
Hajiabad	1	S, C	0–9	38	17.3	14.3	26	23	0.3
	2	S	9–17	32	18	17	32	32	0.3
	3	G	17–30	48	21	19	30	0.2	0.3
	4	C	30–39	8	17	14	26	88	0.2
	5	CS	39–45	45	18	16	22	76	0.3
	6	CS	45–48	68	18	16	26	90	0.2
	7	PC	48–55	120	18.95	16	22	120	0.25
	8	S, C	55–64	67	17.3	14	25	7	0.3
	9	S	64–87	65	19	18	32	22	0.3
	10	C	87–100	25	17	14	20	120	0.2
Aliabad river	1	C, S	0–12	26	20.3	17.5	30	60	0.25
	2	C, S	12–21	20	20.7	14	20	120	0.35
	3	CS	21–30	32	18.8	16.07	30	70	0.27
	4	CS	30–38	48	17.7	14.5	30	25	0.2
	5	CG	38–56	45	22.5	17.4	36	5	0.3
	6	CG	56–75	56	23.2	19.5	25	70	0.2
	7	C	75–80	8	23.66	18.1	27	0.2	0.22
	8	C, S	80–91	25	20.7	15.8	29	10	0.3
	9	CG	91–130	48	20.8	14.7	20	0.2	0.3
Ganjine	1	CS	0–12	40	17.3	14.2	25	7	0.3
	2	G, S, C	12–24	48	18.96	17	35	6	0.15
	3	PC	24–45	25	18.02	15.7	30	125	0.25
	4	PG	45–60	96	21.8	19.2	36	0.2	0.2
	5	CS	60–63	26	19.9	17.7	34	75	0.3
	6	G, S, C	63–69	48	20.02	18.5	22	0.2	0.2
	7	G	69–75	90	21.54	19	30	0.2	0.15
	8	G, S	75–81	40	20.4	18.3	21	1	0.2
	9	GC	81–89	50	23.27	19.5	22	0.5	0.2
Maaref	1	G, S, C	0–24	42	22.68	19	30	0.2	0.3
	2	GC	24–30	45	23.64	19	35	2	0.3
	3	G, S, C	30–34	25	20.67	17	20	30	0.35
	4	CS	34–45	27	22.4	18	25	100	0.35
	5	G, S, C	45–51	120	23.54	19.5	25	0.2	0.27
	6	SC	51–58	23	19.8	17	22	40	0.35
	7	G, S, C	58–69	48	22	20	25	0.2	0.25
	8	G, S, C	69–73	37	22.2	18.5	27	0.2	0.2
	9	C, S	73–84	50	22.7	18.5	23	2	0.25
Masjed e Aolfazl	1	G, S, C	0–12	48	19	18	35	0.2	0.3
	2	CS	12–15	70	17	14	25	7	0.3
	3	G	15–27	120	20.6	18.7	20	1	0.2
	4	C, G	27–30	150	21.05	19	35	0.2	0.35
	5	G, S, C	30–46	148	19.8	18	32	0.2	0.3

Table 2 continued

Region	Layer	Soil type	Depth (m)	Parameters					
				E	γ_{sat}	γ_{dry}	ϕ	c	ϑ
	6	C, G	46–50	78	22	19	35	5	0.3
	7	G, S	50–53	120	19.8	17.7	35	0.2	0.35
	8	G, S, C	53–71	117	21.1	18.3	32	0.2	0.35
Aliabad	1	PC	0–17	2	17.3	14.7	20	30	0.15
	2	C, S	17–24	25	21.2	17.5	22	10	0.2
	3	C	24–30	2	17.3	14.5	22	40	0.2
	4	C, S	30–78	30	21	16–18	20	15	0.2
	5	C, S	78–120	20	20.3	16–18	23	50	0.35
	6	S, C	120–138	50	20.9	17.3	24	30	0.3
	7	C, S	138–166	25	21	16.9	24	33	0.3
	8	G, S, C	166–182	48	21.7	17.5	30	30	0.35
Shokuhie	1	C, S	0–12	27	17.02	15.5	30	50	0.3
	2	PC	12–21	2	16.8	14	20	25	0.43
	3	C, S	21–24	26	19.9	17.5	30	50	0.3
	4	S, C	24–35	27	20.68	17–18	27	15	0.35
	5	G, S, C	35–39	48	21	19	30	15	0.2
	6	G, S, C	39–51	48	19.8	18	30	25	0.25
	7	PG	51–60	65	21.3	19	30	0.2	0.25
	8	S	60–72	60	20.3	17	35	10	0.3
	9	G, S, C	72–74	120	21	18.5	30	1	0.3
	10	G, C	74–102	40	20.2	17.9	32	0.2	0.32
Gazran	1	G, S, C	0–39	120	21	19.3	25	0.2	0.2
	2	S, C	39–49	32	19.7	16	23	76	0.3
	3	S, C	49–54	48	20.3	18.7	32	0.2	0.35
	4	G, SC	54–69	48	19.9	17	35	0.2	0.15
	5	C, S	69–84	25	18.3	16–17	23	7	0.3
	6	C, S	84–93	26	17	16	25	32	0.2
	7	G, S, C	93–114	28	21	19	30	0.2	0.3
	8	C, S	114–126	26	19.8	17	27	75	0.3
	9	S, C	126–143	45	19	17	30	35	0.3
Rahahan	1	C, M	0–11	20	21.6	19	30	100	0.25
	2	C, M	11–14	8	19.8	17	27	10	0.3
	3	G, M, C	14–25	40	20.7	18.5	32	0.2	0.15
	4	G, M	25–30	43	21.3	18–19	38	0.22	1
	5	G	30–33	50	21.8	18–20	32	0.2	1
	6	G	33–36	96	22.3	18–20	35	0.2	0.2
	7	G	36–63	47	22	19.2	30	0.2	0.2
	8	PC	63–66	2	20.5	17	20	107	0.35
Einabad	1	C, S	0–6	28	20.2	17	28	75	0.2
	2	M, S	6–27	24	19.6	17	27	100	0.3
	3	G, S, C	27–45	27	22.3	18	32	0.2	0.3
	4	MC	45–51	8	18.3	16.5	23	75	0.2

Table 2 continued

Region	Layer	Soil type	Depth (m)	Parameters					
				E	γ_{sat}	γ_{dry}	ϕ	c	ϑ
	5	S, C	51–57	25	19.8	16–18	24	100	0.32
	6	C, S	57–63	26	18.9	16.2	24	80	0.2
	7	S, C	63–72	26	19.2	16.6	25	84	0.2
	8	S	72–77	81	20.3	18	32	32	0.3

S sand, *C* clay, *G* gravel, *CS* clayey sand, *PC* pure clay, *CG* clayey gravel, *PG* pure gravel, *GC* gravelly clay, *SC* sandy clay, *M* mud, *E* elasticity modulus; N/mm^2, γ_{sat} saturation unit weight; kN/m^3, γ_{dry} dry unit weight; kN/m^3, ϕ internal friction angle; °, c soil cohesion; kN/m^2, ϑ Poisson coefficient

attributed to modeling hypotheses and lack of accuracy in evaluation of soil parameters has been applied to the model.

It is obvious that the groundwater level decline has caused a reduction in pore pressure in the aquifer system, which is the reason of the great land subsidence. The obtained results by the modeling in the study area show that the observed deformations are related to the overexploitation of the confined aquifer, contributed to the identification of the main triggering factor of subsidence. The results show that excessive pumping of the wells due to the water table drawdown is the main reason of land subsidence. The secondary reason of the occurrence of this phenomenon is attributed to drainage and depletion of aquifer, especially in the agricultural lands of Aliabad plain. Other effective factors on the amount and rate of land subsidence are fine-grain material composition of aquifers and groundwater level location, rate of groundwater extraction, wells location and the dimensions of the fine layer. The soil layers comprising the aquifer system play a major role in the amount of compaction. The geological investigations in the study area show that fine sand, clay layers and sandy silty clay at different depths of aquifer may displace with groundwater flow. Therefore, the geotechnical properties of the geological formations are the main factors of land subsidence phenomenon.

In this area, the most important factor which controls the timing of land subsidence is presence of the thick fine-grained layers in many wells and profiles. Furthermore, thick aquitards which separate the shallow unconfined and the deep confined aquifer systems in most places can also generate a residual compaction which in its own turn leads to a delayed subsidence in this area.

Using the elastic-perfectly plastic model based on the Mohr–Coulomb failure criterion to evaluate the available geotechnical data can be considered appropriate for the direct simulation of the land subsidence. Due to the lack of accurate records of historical displacement, most of the land subsidences cannot be back calculated, and as a result, the implementation of a verified simulation procedure cannot be established. In such cases, the Mohr–Coulomb soil model (a simple model with low requirements on mechanical parameters) in the numerical platform, e.g., PLAXIS, provides appropriate and valuable results. This validated numerical modeling and simulation procedure provide quite useful tool for scientific communities, decision makers and local administrator. The results obtained from this study show that the vertical displacements increase in accordance with the ground water level drop. Based on the results, overexploitation of ground water in Aliabad plane decreases groundwater levels, and consequently, land subsidence creates a great concern which needs careful investigation.

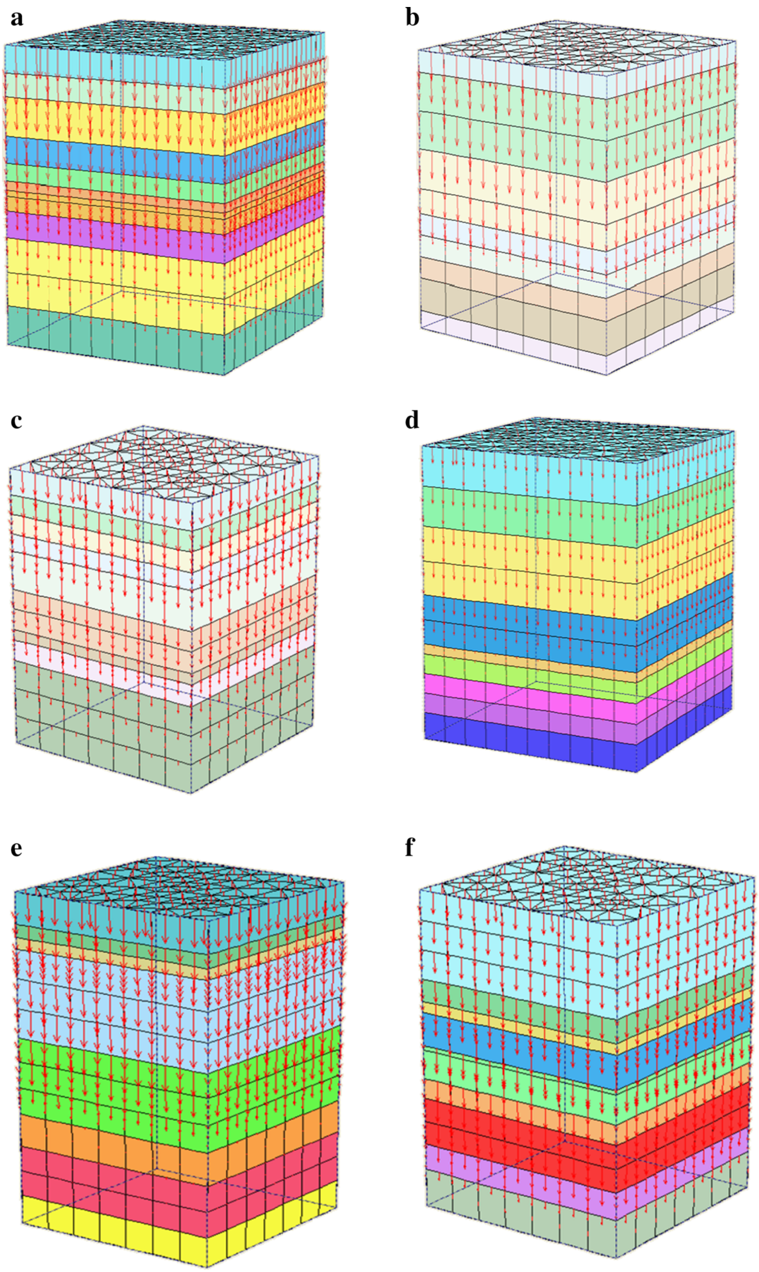

Fig. 5 Subsidence of soil layers around the studied wells according to numerical modeling; **a** Hajiabad, **b** Einabad, **c** Aliabad River, **d** Ganjine, **e** Aliabad, **f** Gazran, **g** Maaref, **h** Rahahan, **i** Masjed e Abolfazl, **j** Shokuhie. Figures and arrows in any profile are non-scale. Each color in each profile represents a layer. The depth, soil type, thickness and geotechnical parameters of each profile are shown in Table 2

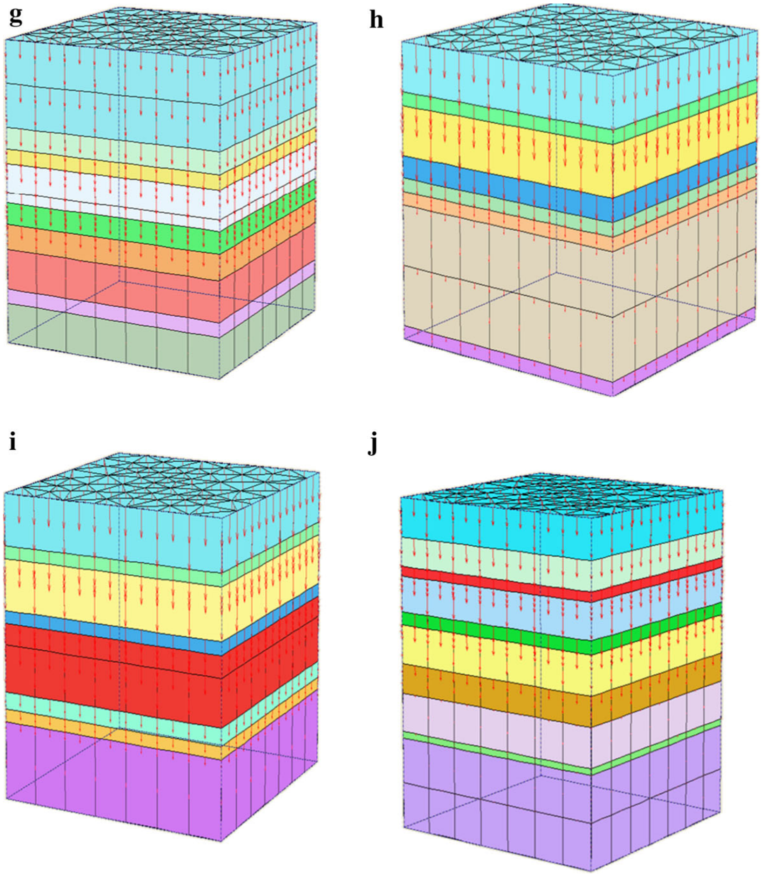

Fig. 5 continued

4 Conclusions

In this paper, by modeling in PLAXIS® 3D; v1.6, the amount of subsidence was studied in the plain of Qom. Ten areas were selected to investigate the subsidence since 2001–2013. A subsidence about 0–76 cm in different areas was obtained by studying the water table changes and using the soil geotechnical parameters in the model. Modeling results are in good agreement with the results obtained from InSAR by other researchers, both showing an approximately equal subsidence in a period of 12 years. The main reason of subsidence is groundwater table and hydraulic pressure decline due to excessive exploitation. The soil layers comprising the aquifer system and the geology and geotechnical properties of the geologic units also play a major role in the occurrence of land subsidence phenomenon. Since overexploitation of groundwater resources may have harmful effects including socioeconomic consequences, careful supervision for the proper use of these resources is required. In order to penetrate into the relation between surface displacement and the lowering of the ground water level, hydrological data including well locations, exploitation rates and litho-stratigraphic maps of subsurface sequence should be invoked. Acquiring such information and continued supervision using InSAR will clarify

Table 3 The subsidence changes in soil layers in the study area (obtained from numerical model)

Region	Hajiabad	Aliabad River	Ganjine	Maaref	Masjed e Abolfazl	Aliabad	Shokuhie	Gazran	Rahahan	Einabad
Ground subsidence (cm)	0.73	24.29	4.45	1.23	0.09	76	10.04	9.34	9.5	20.29

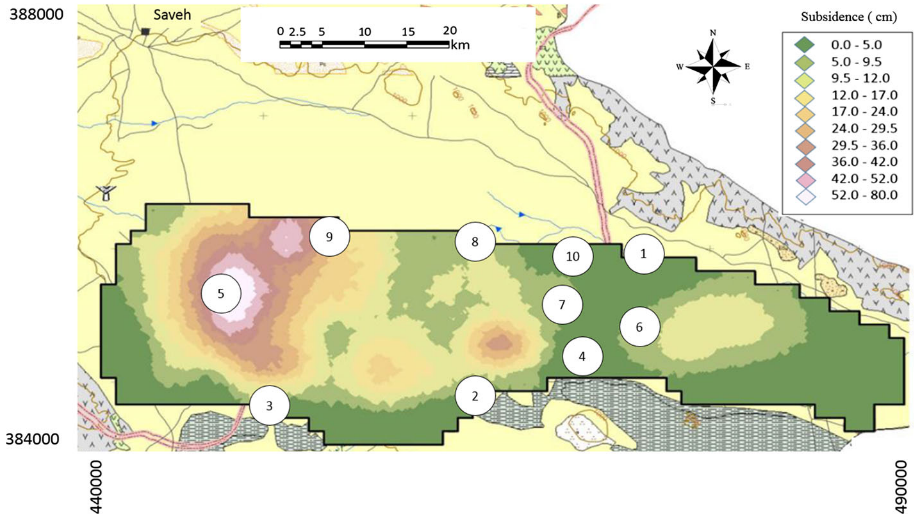

Fig. 6 Comparison of obtained results of the modeling and InSAR time series (Qom Regional Water Company 2011b) in the study area

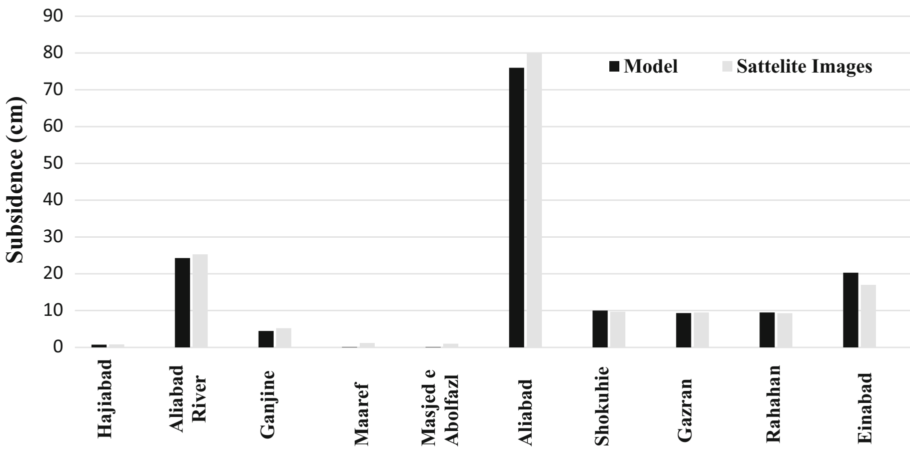

Fig. 7 The difference between the results of the model and satellite images

more details of the hydrology of the areas of subsidence and the geomechanical parameters of the underlying aquifer structure.

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