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Estimating Land Subsidence Risk Scenarios Using Mathematical Modeling and Field Measurements: Case Study of Qom Aquifer, Iran

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INTRODUCTION

Land subsidence pose severe socioeconomic problems as well as environmental challenges including but not limited to forced migration, damage to building and infrastructures, increase the risks of flood inundation, and inland sea water intrusion, as documented in many places around the world (Burbey, 2008;Carreón-Freyre and Cerca, 2006; Ferronato et al. 2004; Galloway and Hoffmann, 2007; Hu et al. 2009; Hung et al. 2010;Lopez-Quiroz et al. 2009; Munekane et al. 2008;Teatini et al. 2005;Wu et al. 2010).
Among all of the driving forces which lead to land subsidence, excessive groundwater exploitation is utmost importance. Of 544 Iranian's plains which have potential for groundwater exploitation, 291 experience a critical condition due to continues declining groundwater table (Forootan et al. 2014; Joodaki et al. 2014) which consequently have resulted in or not before long would result in significant land subsidence in many plains throughout the country (e.g. see Dehghani et al. 2009, 2013; Motagh et al. 2007; Mousavi et al. 2001).
With the current advances in monitoring technology and software for simulating, decision makers are now enable to use modeling approaches for analyzing and predicting land subsidence. Although data scarcity remains a major limitation of model applications, the field of remote sensing has recently brought useful monitoring techniques such as the application of Synthetic Aperture Radar Interferometry (InSAR) within the field. However, the application of InSAR is also limited when there are temporal changes of cropping pattern although it provides excellent data to calibrate subsidence models even where very little compaction field data is available.
Recently, the application of a coupled model has been frequently used for modeling land compaction based on observation data. It simulates hydraulic heads and deformation in two steps and couples them by relating hydraulic parameter values with hydraulic heads and deformation. For instance, Shi et al. (2012) investigated the relationship between the land subsidence and groundwater level by applying a 3D groundwater model coupled with a 1D deformation model. The model application is analyzed for both periods of before and after implementing a prohibition program to control deep groundwater withdrawal in Suzhou, China. Finally, the model was used as a predictive tool for two scenarios; one for the case of groundwater exploitation in BAU scenario and the other to utilize maximum potential of groundwater resources for emergency situation. In another study, Hung et al. (2012) analyzed stratum compaction in Dacheng, Taiwan using the COMPAC model. Specific hydrogeological parameters of the vertical hydraulic conductivities, elastic skeletal specific storage, and inelastic skeletal specific storage at aquifers were estimated by the genetic

algorithm. Although their study shows sufficient confidence at regional scale, the application of their study was limited in that the applied model was one-dimensional and site specific. A regional three-dimensional groundwater flow model was also developed coupled with a one-dimensional aquifer-system compaction model to simulate the historical land subsidence by Cao et al. (2013). The calibrated model was then applied in order to evaluate and predict future land subsidence in the Hangzhou–Jiaxing–Huzhou (HJH) plain, china considering three management scenarios based on current groundwater pumping practices and various combinations of joint surface and groundwater supply managements. Thanks to several annually ground-based measurements across the study area, in this paper, the groundwater head of aquifer is simulated by mathematic modeling in steady and unsteady condition for seven years. Meanwhile the prediction head is employed to estimate land subsidence.

MATERIAL AND METHODS

Case Study

The model is set up and calibrated for a part of the Saveh plain situated in the Central Iran. The boundary of unconfined aquifer covers an area of approximately 1344 km^2 and is adjacent to the Salt basin. The geographic position of the study area is in the center of the country and proximity to Saveh, Dastjerd and Jafarieh cities (Fig. 1).

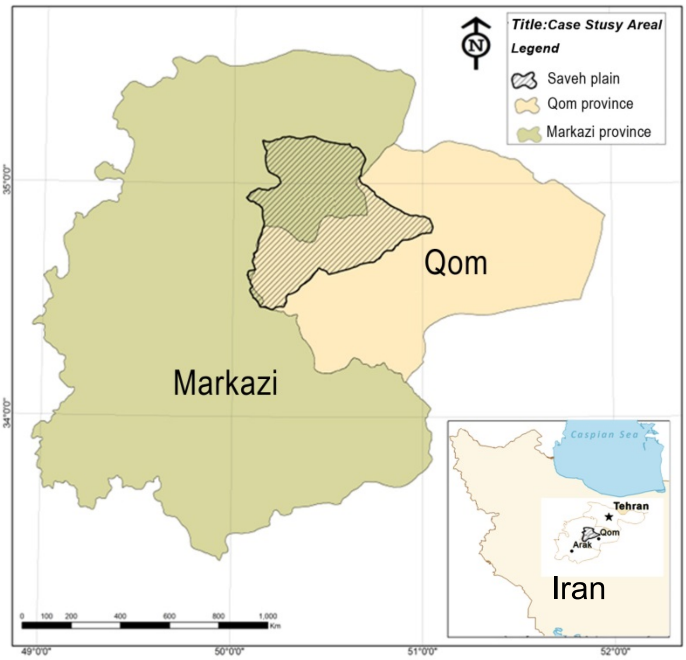

Figure 1. Geographical location of the study area (Saveh plain)

In the western part where rivers flow through the Saveh plain, alluvial deposits have been stored due to the significant river flow as well as reduction in the slope gradient. From the west to the east, alluvial sediment texture turn outs to the fine-grained silt and clay sediments. In years, repetitive fluctuations in the Ghareh Chai river discharge have resulted in a complex hydrogeological system containing silt and clay sediments. As a result, several aquifers have been separated by silt and clay confining layers in the eastern part of the study arae. After the Saveh dam operated in 1994, the only main river situated in the study area has turned out to a seasonal stream drying up most of time. In turn, lacking of sufficient available surface water resources has led to over-pumping of groundwater resources. With regard to the rapid economic development, the groundwater usage has increased gradually especially in order to provide the agriculture sector with their required water allocation.

However, over exploitation of groundwater resources resulted in unit hydrograph of groundwater level decrease in recent years (Fig.2) followed by land subsidence.

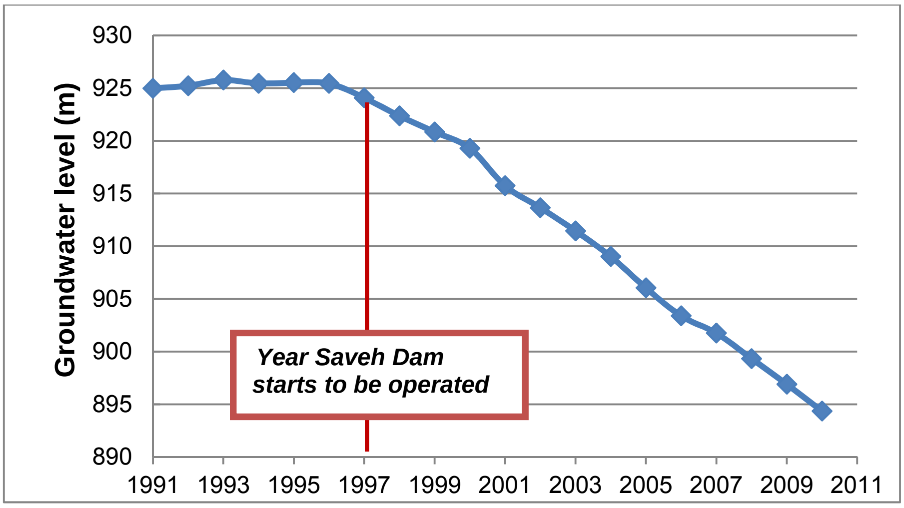

Figure 2. Changes in groundwater level after construction of Saveh Dam (Source: Qom Regional Water Authority, cited in Javadi et al. 2013)

Mathematical Modeling

According to the one dimensional consolidation theory of Terzaghi (1925), changes in the effective stress of soil can result from changes in the total stress or changes in pore pressure. A component of the effective stress tensor (σ'_{ij}) can be expressed as

$$\sigma'_{ij} = \sigma_{ij} - P$$

where σ_{ij} is the total stress,
and P is the fluid or pore water pressure

Based on the given equation, compaction takes place when effective stress increases. To model the land compaction, the methodology used for this study includes integrating a compaction module to the groundwater flow. Figure 3 shows the framework on land subsidence modeling for regional groundwater management. As far as mathematical groundwater modelling is concerned, at the first step, the spatiotemporal characteristic of groundwater level was investigated based on the long-time records of piezometric levels as a part of data collection. The model layer consists of 18 rows and 54 columns with a uniform horizontal spacing of 1000 m. The mathematical model was then calibrated for both of the steady and unsteady conditions. At the first hand, the groundwater model was calibrated under steady state regime for the 2005-2006 water year in which general hydrogeological characteristics including the bedrock as well as the hydraulic conductivity are calibrated. Then, the simulation was carried out under unsteady condition based on groundwater level records. Regarding unavailable seasonal data of groundwater withdrawal, the total simulation period was divided into seven annual stress periods from 2003 to 2009. The Interbed storage package was added to the MODFLOW 3D finite difference code using the PMWIN 5.3 groundwater mathematical model. After successful calibration of the coupled model, a scenario is developed in order to provide useful insights for regional groundwater planning and management.

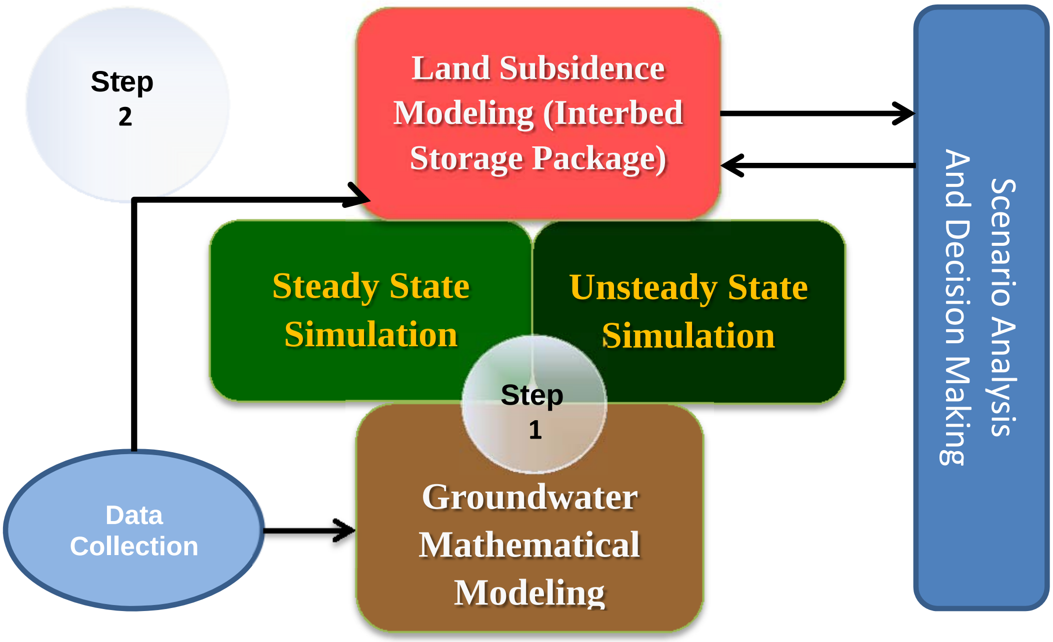

Figure 3. The coupled model for groundwater mathematical modeling and land subsidence

Field Measurements

Many aquifer parameters have to be specified in the model. The package use pre-consolidation head or pre-consolidation stress, elastic as well as inelastic storage factor as input parameters to the model. Data on ground compaction which has been collected based on ground-based compaction observations were used for the model calibration and parameter zonation as shown in Table 1. Figure 4 also show the thiessen polygones for the observed land subsidence.

Table 1. Observed land subsidence in the study area

Name	X (UTM)	Y (UTM)	Land subsidence (cm)
P1	475185	3851959	15
P2	475437	3851780	5
P3	471910	3852237	20
P4	489983	3846486	0
P5	490769	3854391	0
P6	485059	3855776	35
P7	471438	3855555	5
P8	465257	3855605	45
P9	466010	3852602	80
P10	460321	3850047	25
P11	457181	3853197	20
P12	460392	3854958	15
P13	451023	3849882	35
P14	451023	3849880	20
P15	443913	3858010	30

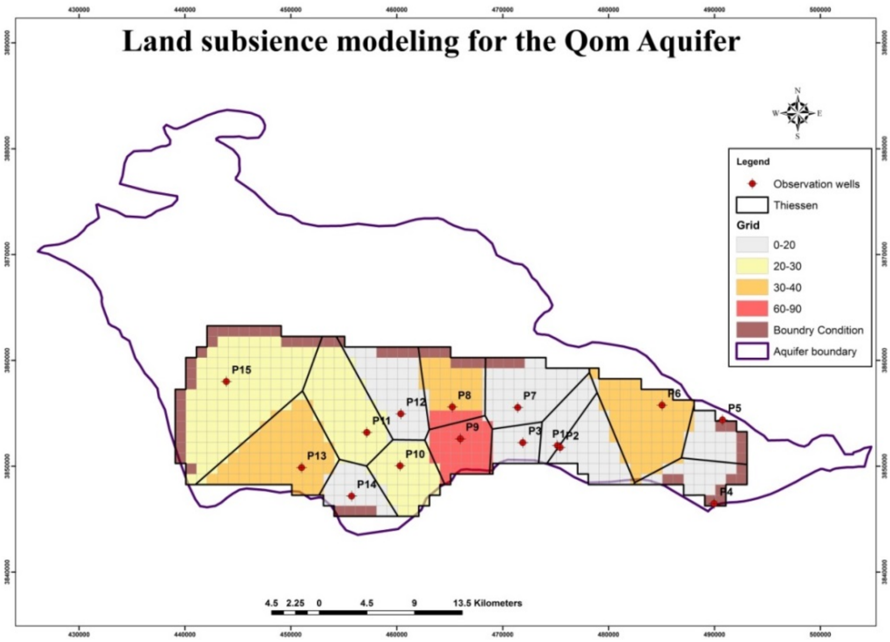

Figure 4. Thiessen polygons of land subsidence based on field measurements

RESULTS

Groundwater Mathematical Modeling

The root mean squared error is obtained 0.53 and 1.29 for the steady and unsteady mathematical modeling, respectively. At the second step, the groundwater model is coupled to the "Interbed storage" package to model the observed land subsidence (Fig.3). Figure 5 shows comparisons between the observed and calculated hydraulic heads for some of observation wells in unsteady condition. Specific storage (S_s) values were also calibrated to fit hydraulic head observations from multi-level piezometers throughout the plain in the unsteady condition. S_s is also a key element for land subsidence modeling. The specific storage ranges from 0.003 to 0.15 in the study area.

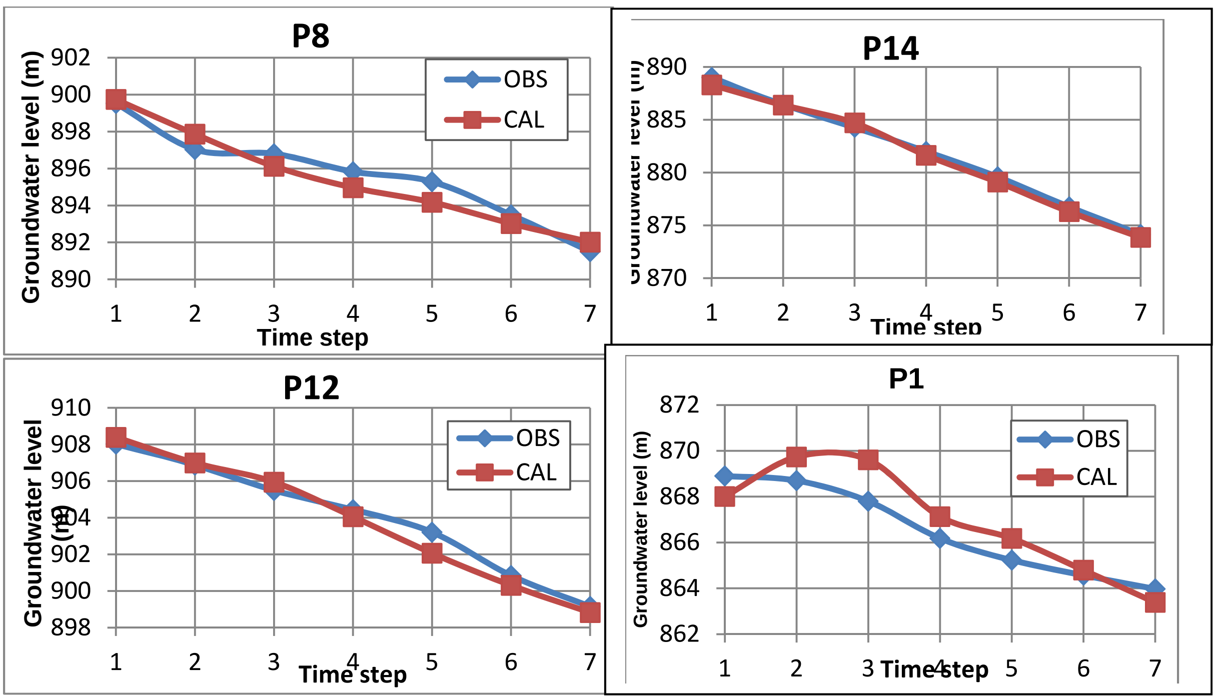

Figure 5. Comparison between observed and simulated groundwater level (in meters) for a number of piezometers (as examples) in n Qom aquifer

Land Subsidence and Scenario Analysis

Using the “Interbed storage”, aquifer parameters preconsolidation head, elastic and inelastic storage factors have been determined for the zone of influence of each observation well. The preconsolidation head has been set as the groundwater level at the start of the simulation. When the effective stress exceeds the preconsolidation stress, the large changes of the skeletal specific storage are determined by the inelastic skeletal specific storage. Sensitivity analysis for modeling land subsidence has also shown that inelastic storage factor is the most sensitive factor in modeling land compaction which is between 0.01 to 0.1 in most part of the aquifer and 0.15 in a small area located in the south central parts. Finally, the calibrated model has been applied for scenario analysis under the Business as Usual (BAU) scenario meaning that the present groundwater exploitation condition is continued for five years. Figure 5 shows the analysis based on the scenario. The result based on this scenario analysis shows that a land subsidence of at least 0.5 meter will most likely occur in the most parts of the aquifer. Given the current trend on groundwater withdrawal, it is likely that more than 1.5 m at maximum will be seen in five years in the central parts requiring immediate prohibition measurements by regional water authorities to prevent later catastrophic impacts and to take risk management into account.

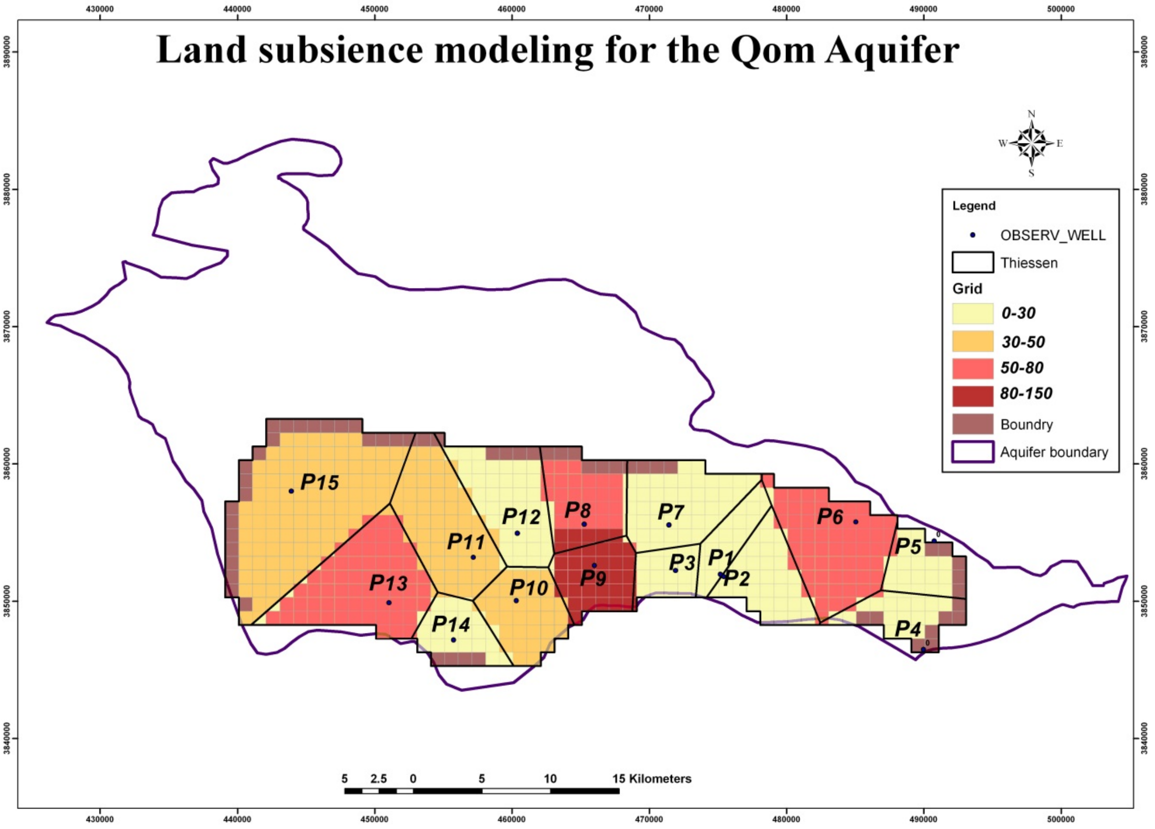

Figure 5. Land subsidence thiessen polygones based on the Busieness As Usual scenario (BAU) in groundwater withdrawal (After five years)

CONCLUSIONS

Limited available surface water in addition to population growth have resulted in unsustainable groundwater exploitations followed by irreversible environmental challenges such as land subsidence. Similar to many other arid or semiarid regions in the world, groundwater overexploitation have caused most aquifers in Iran to face land subsidence. In

this study, a coupled groundwater model which combines a three-dimension groundwater flow with a one-dimension deformation model was used to simulate dynamic evolutions of groundwater level as well as land subsidence for a case study located in the central part of Iran. The model which has been calibrated based on the ground-based measurements was applied as a predictive tool to evaluate the land subsidence in the near future. The results show a sufficient confidence of the developed model as a quantitative hazard forecast approach for regional water resources planning. The analysis based on the Business As Usual (BAU) scenario will most likely result in at least 1 meter of land compaction in the central parts of the aquifer and more than 1.5 m in other parts at maximum requiring immediate prohibition measurements by regional water authorities to prevent later catastrophic impacts and to take risk management into account. Therefore, next studies can address how restrictions imposed by the government on groundwater extractions can change the rate of land subsidence in the short term as well as possible changes in hydrodynamic characteristics of aquifer.
The proposed methodology can be applied for areas where there are no land subsidence monitoring networks (e.g. extensometers and auto-monitor stations) available. Note that current study introduces a framework for modeling land subsidence and the work is a first step for modeling land subsidence changing risks especially for the case of developing countries where monitoring networks have not been well-established. It is suggested that future studies take a quantitative spatial hazard prediction approach by statistical models and expert system methods to quantify physical, socio-economic and, environmental vulnerability indicators for land subsidence risk assessment mapping.

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