



Modelling-based Assessment of Land Subsidence in the Abhar Plain, Iran

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Abstract: In this paper, the subsidence modelling of Abhar plain, Northwest of IRAN, was performed by developing the SUB sub-model in the numerical code structure of the MODFLOW Finite Difference. In order to measure the quantitative model of groundwater flow in unsustainable conditions, 70% of piezometric data during the period (2010-2020) and PEST automatic code were used and 30% of the piezometric data during the period (2014-2017) were used for validation. The data was chosen, as it was complete and unused. An examination of the vertical changes in the structure of the earth's crust showed that during the ten-year period, the aquifer had a subsidence of 34 cm from the base year i.e. 2010. In the study of complementary fuzzy model using gamma overlap between effective layers with the maximum occurrence of correlation of linear regression of subsidence points, it was found that the analysis of land use effect corresponds to the interpretation of subsidence changes of fuzzy model. Based on results, urban usage as 4% of the aquifer surface area accounts for 26% of the subsidence event; as 42% of the aquifer surface area, in addition, agricultural usage and garden lands constitute 56% of the subsidence event; constituting 54% of the saturated aquifer surface area, finally, arid lands only account for 19% of vertical subsidence changes in the aquifer structure. Aimed at preventing the subsidence and its destructive effects, the method overlay weighted of layers created by using gamma operator in fuzzy model for zoning as a new technique in calculating land subsidence rates by land use type, can be used in identifying more susceptible lands of subsidence.

Key words: Groundwater model, Fuzzy Model, land-uses, subsidence.

Land subsidence, characterized by its irreversibility, gradual changes, and prolonged duration, exerts significant impacts on urban construction and economic development (Zamanirad *et al.*, 2020., Figueroa-Miranda *et al.*, 2018; Bagheri-Gavkosh *et al.*, 2021). With the rapid pace of urbanization, over half of the global population now resides in cities. As a result, understanding

and analyzing the causes of land subsidence in urban areas has become increasingly important compared to other regions. Prior research has emphasized the significant impact of excessive groundwater extraction on land subsidence, resulting from the compaction of aquifer materials due to the decline in pore pressure and leading to irreversible loss of aquifer storage capacity (Hasan *et al.*, 2023). However, it is important to recognize that land subsidence can be driven by multiple factors, which can be broadly categorized as natural and human factors. Natural factors include climate conditions, earthquakes, and crustal movements, while human factors encompass activities such as groundwater extraction, mining, underground tunnel construction, and landfill operations (Figueroa-Miranda *et al.*, 2018; Bagheri-Gavkosh *et al.*, 2021). While it is common to conduct singular and qualitative analysis of these driving factors, there is a need for comprehensive and quantitative research to gain a better understanding of their contributions to land subsidence.

Land subsidence is one of the consequences of overuse and mismanagement of water resources, which occurs because of the compression of soil due to the reduction of groundwater levels (Pacheco *et al.*, 2006). The subsidence trough and sinkhole, or sometimes called pothole (Lokhande *et al.* 2014), resulted from deformation and collapse of the cavity roof. Accordingly, this geohazard with a widespread, caused by excessive pumping of groundwater has been widely reported in many areas, such as Mexico City (Calderhead *et al.*, 2011), Shanghai (Hu *et al.*, 2004), Tianjin (Lixin *et al.*, 2011), Su-Xi Chang (Chen *et al.*, 2013), Antelope Valley, California (Galloway and Burbey, 2011), Bangkok (Phien-wej *et al.*, 2006), Rafsanjan (Mousavi *et al.*, 2001), Mashhad (Motagh *et al.*, 2007), Arak (Rajabi and Ghorbani 2016), Tehran (Mahmoudpour *et al.*, 2013; Ranjbar and Ehteshami 2019).

In Iran, land subsidence, as a result of the withdrawal of groundwater, has been reported from many plains, such as Abhar plain in Zanjan Province (Asgari and Ebrahimi 2021) and Mashhad plain in Khorasan Razavi Province (Lashkaripour *et al.*, 2014). In Rafsanjan plain, for every 10 m drawdown in the groundwater table, ground surface settle as 42 cm (Rahnama and Moafi, 2009).

Scientific investigation and various instruments, including mathematical models, are required to overcome the problems of groundwater resources (Gaura *et al.*, 2011; Hu *et al.*, 2010). Mathematical models allow for investigating changes in the current and future situations of groundwater tables by incorporating different influential factors (Yaoutia *et al.*, 2008; Zhang and Hiscock, 2010). Therefore, using mathematical models, the situation of an aquifer can be simulated by collecting information on the inputs and outputs of the groundwater system at a small cost in a short time. Such simulation models can provide the mutual effects of surface water and groundwater in short- and long-term periods.

Al-Sittawy *et al.* (2019) studied subsidence by selecting in Esna County, Egypt as the case study. The case study had suffered from an increased groundwater level since the construction of New Esna Dam in 1995 due to the high-water level of some irrigation channels, such as Ramadi Channel. They aimed to investigate the effects of different operation scenarios on soil subsidence and groundwater to achieve a satisfactory scenario. Rashvand *et al.* (2019) developed the tension-dependent groundwater model of MODFLOW-SD and employed it with the nonlinear subsidence model of NDIS to predict the vertical deformation of basins with highly-compacted depositions. The NDIS package was built based on the Darcy-Grusanovic law and major flux to the subsidence model. The simulation results of the conceptual model demonstrated that the applied tension changed homogeneous layers into heterogeneous layers due to pumping. Ranjbar and Ehteshami (2019) suggested that the excessive extraction of groundwater resources led to land collapse at a large area in recent years. Their objective was to use the capabilities of numerical models and data-based algorithms for the strong and quick prediction of subsidence. they employed a subsidence package in the MODFLOW framework to determine the effects of groundwater fluctuations on subsidence through the Tehran area. The model indicated a high correlation value of 0.965 between the simulated and predicted subsidence values.

There are numerous studies worldwide that have focused on the risk zoning of land subsidence and factors that affect it. Moreover,

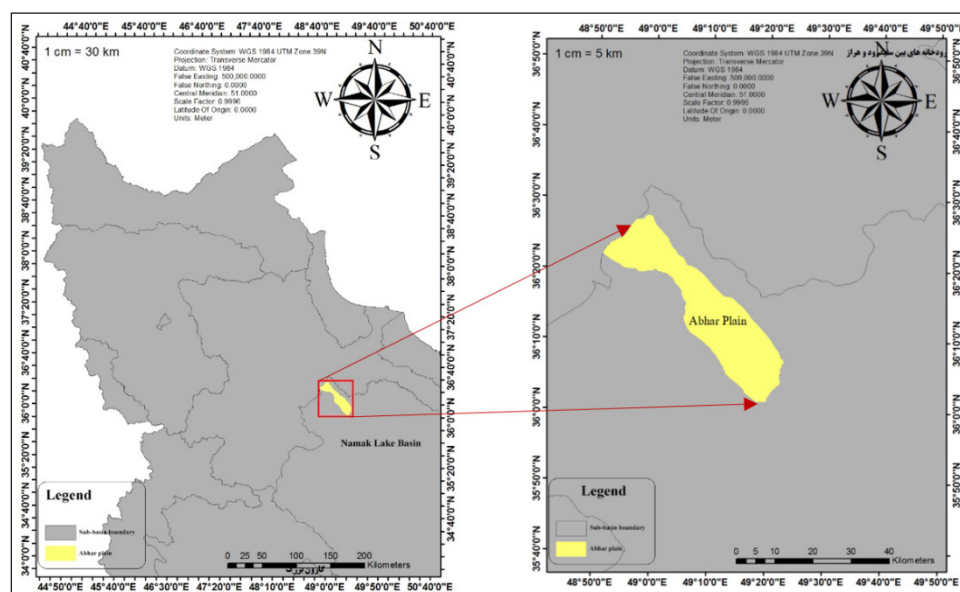


Fig. 1. The geographical location of Abhar Plain.

recent studies have analyzed land subsidence hazards using the results of geological and hydrogeological investigations, as well as probability, statistics, fuzzy algebra (Chanapathi *et al.*, 2019; Choi *et al.*, 2010; Gu and Wang, 2010; Rafie and Namin, 2015; Yu *et al.*, 2018).

The current study developed a conceptual model for the changes in the water table of Abhar Plain with urban, agricultural, and idle land-uses by a completely theoretical method based on the accuracy of previous studies' outputs in the numerical computations of subsidence models. Also, the vertical changes in the ground structure were nonlinearly modeled based on the cellular changes of the finite difference method. To determine the essential factor of the changes, the fuzzy model approach and spatial-statistical analysis were adopted. The largest effect on the appearance of subsidence was studied by the regression relationships of the corresponding points in the spreadsheet setting. This paper is a refined and developed version of Asgari and Ebrahimi (2021).

Materials and Methods

General and geographical location

Abhar Plain is located in the northwest of the Namak Lake Basin, see Fig. 1, below. It occupies an area of 1926.5 km², 1040.92 km² of which is plain, while the remaining area is composed of mountains. The maximum and minimum elevations of Abhar Plain are 2166

and 749 m, respectively. The saturated area of the plain is approximately equal to 657.4 km². The cities of Khorramdareh and Abhar are important settlements in the plain. The Abharrod River flows in the plain along with Saraband, Dardahin, and Aznab Rivers, which join Abharrod River. In general, the flow direction of surface water in the plain is from the northwest to the southeast. Abharrod Range is recognized as the sub-basin of Abharrod Mirage according to the coding instruction. The output surface flows of the case study are carried by the Abharrod River into Ghazvin Range.

The groundwater extraction area of the plain includes 1359 water wells with an annual discharge of 233.36 million m³, 169 fountains with an annual discharge of 4.88 million m³, and 101 aqueducts with an annual discharge of 1.3 million m³.

The mathematical theory of MODFLOW

The simulation of groundwater flow by a mathematical model as a prerequisite of a subsidence analysis is an indirect study method that can solve the existing problems to a great extent at a lower cost than direct or field methods. This study describes the development of a quantitative model and the extraction of results by validation and accuracy examination through an extensive set of raw data for use in MODFLOW.

A system (matrix) of algebraic equations is solved in a computer groundwater model program. Such a matrix is an approximation of the mathematical model developed by the differential equations of groundwater flow (Bear, 1979). The general governing equation of groundwater in free aquifers is shown as:

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) = S_y \frac{\partial h}{\partial t} \quad \dots(1)$$

where h is the groundwater level, S_y is the specific yield, K is the conductivity in the x -, y -, and z -directions of the groundwater table.

Subsidence: Subsidence is modeled as (Young *et al.*, 2009; Cho *et al.*, 2009):

$$v_a = \frac{\sum_{k=1}^n V_k}{\sum_{k=1}^n S_k} = \frac{\sum_{k=1}^n \dot{V}_{ak} S_k}{\sum_{k=1}^n S_k} \quad \dots(2)$$

in which V_a is the annual subsidence of the case study (in mm/year), V_k is the subsidence volume of order k (in mm³), $\dot{V}_{ak}$ is the annual subsidence used in the calculation of each area's volume (in mm/year), S_k is the subsidence area, and n is the number of subsidence regions.

Membership functions: Figure 2 shows the membership function of a fuzzy set. According to Fig. 3, the membership degree $\mu_A(x)$ represents the membership of component x in the fuzzy set A . If the membership degree of a component for a set is 0, the component is completely out of the set. On the other hand, if the membership degree of a component is 1, the component is completely within the set. A membership degree of between (0, 1) represents gradual membership. Also, the member can conceptually fall in another set with a membership degree. For example, assume the quality of a satisfactory trait in a

linguistic variable. Considering the selection of a membership function, such as the Gaussian function, a relatively satisfactory trait can fall in the satisfactory traits set with a small degree of membership, while an unsatisfactory trait appears in the satisfactory traits set with a smaller degree of membership. The membership function of a fuzzy set is an extension of the characteristic function in classical sets. In fuzzy logic, the membership function represents the degree of truth as an extension of assessment. The degree of truth is usually confused with probabilities. However, they are two distinct concepts since the fuzzy truth indicates membership in ambiguously defined sets and not a probability or specific conditions.

In the fuzzy approach, to extract the final decision layer, a geographical information system (GIS) was built by standardizing the input parameters and then using the gamma overlapping operator. Standardization functions include Gaussian, Sigmoid, J-shaped, and linear functions (Le Page *et al.*, 2012).

The gamma operator is the general case of fuzzy multiplying and aggregate operator. It is used when reduction and enhancement effects exist in the entire criteria (Malczewski, 1999).

$$\mu_{\text{combination}} = (\text{FuzzySum})^\gamma \times (\text{FuzzyProduct})^{1-\gamma} \quad \dots(3)$$

which can be considered as equal to

$$\text{Fuzzy Gamma Value} = \text{pow} (1 - ((1 - \text{arg1}) \times (1 - \text{arg2}) \times \dots), \text{Gamma}) \times \text{pow} (\text{arg1} \times \text{arg2} \times \dots, 1 - \text{Gamma}) \quad \dots(4)$$

Considering that parameters involved in the calculation of the final subsidence layer had reduction or enhancement effects on each other and given the descriptions on

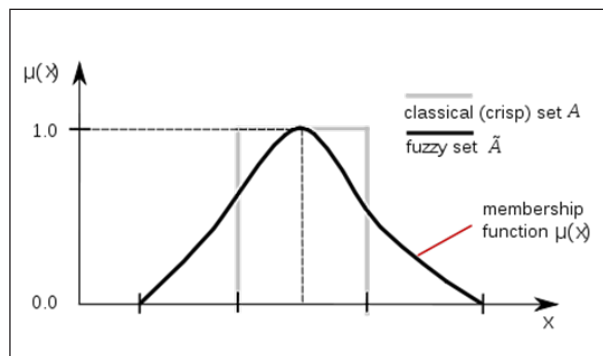


Fig. 2. The membership function of a fuzzy set.

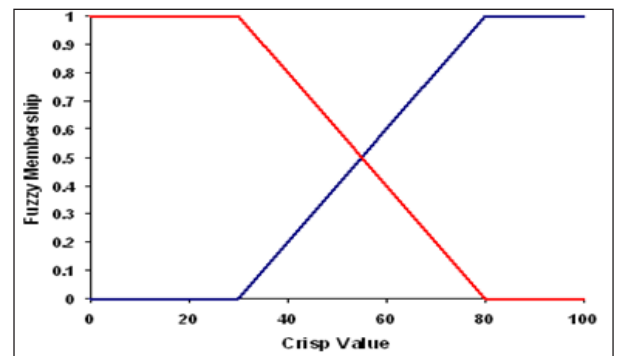


Fig. 3. The concept of a linear transformation with positive and negative slopes in fuzzy membership functions.

the overlapping functions, the current study employed the gamma operator. Once the gamma is 1, the value of the output is equal to that of the aggregate operator. Moreover, once the gamma is 0, the output is equal to that of the multiplying operator. Therefore, a number between 1 and 0 can produce output by combining the two methods.

Results and Discussion

Execution and development of the numerical model

Computation was performed by the MODFLOW-2005 engine in GMS v.10. The study period was selected to be 119 months, which could be made more accurate and rebuilt based on the maximum available data. The computation engine of PCG2 with 100 outer and inner iterations, a critical convergence variation limit of 0.01 m, and a critical convergence error limit of 0.01 m³ per day was selected. 75% of the interval length was used for calibration in non-stable conditions. After seven executions of the calibration model with a certain number of internal iterations, the optimal final number of surface feeding, horizontal hydraulic conductivity and horizontal hydraulic conductivity anisotropy, specific yield in the form of pilot extraction points, and transferability parameters in the boundaries, and the waterway network in the form of the bunches of lines. The layers were also used to develop the fuzzy subsidence model.

In Figures 4 to 9 can be seen the value of each of the above parameters, after the last calibration, to the optimal Possible mode was extracted. The hydraulic conductivity anisotropy parameter had the highest value in the southern regions of the aquifer. While horizontal hydraulic conductivity, in three pilots with south, center and north distributions, respectively, the maximum values after It was calibrated. Finally, the two parameters of surface feeding and special discharge in the middle areas were of higher value. A noteworthy point from the perspective of the maximum distribution of the values of these parameters indicates this, the aquifer in the initial implementation Most cells are considered dry. So the desire to replenish lost water in exchange for a drop taken with these final parameters was to be expected.

Sensitivity analysis

This study employed sensitivity analysis in combination with calibration. The sensitivity analysis results of the parameters affecting the calibration of Abhar Aquifer revealed the large effects of hydraulic conductivity and horizontal hydraulic conductivity anisotropy and a group of waterway network lines. Therefore, the modifications of the boundaries with dynamic hydraulic loads (the conceptual model) in the ranges of highly sensitive parameters satisfactorily minimized the total calibration error in the last stage calibration stage (Fig. 10).

Figures 11 and 12 show the last range of the water level reduction layer of the aquifer in the

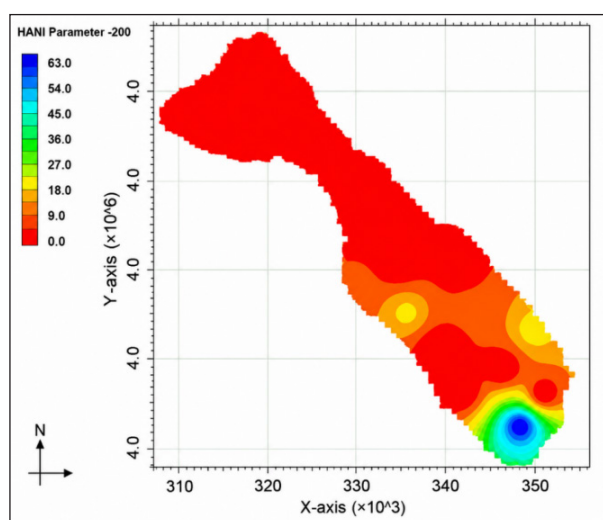


Fig. 4. The continuous distribution of horizontal hydraulic conductivity anisotropy.

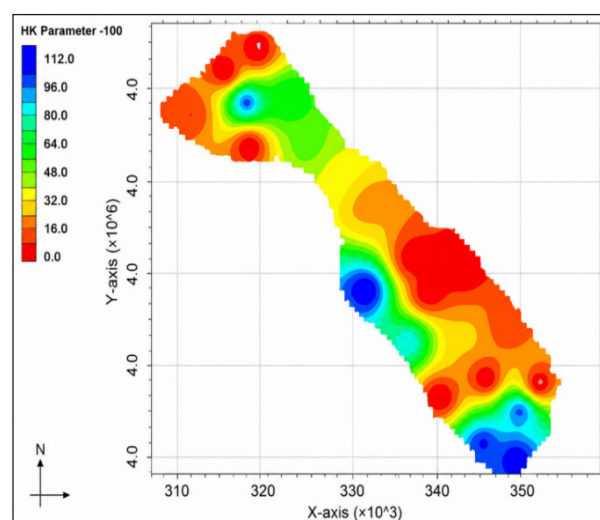


Fig. 5. The interpolation of horizontal hydraulic conductivity.

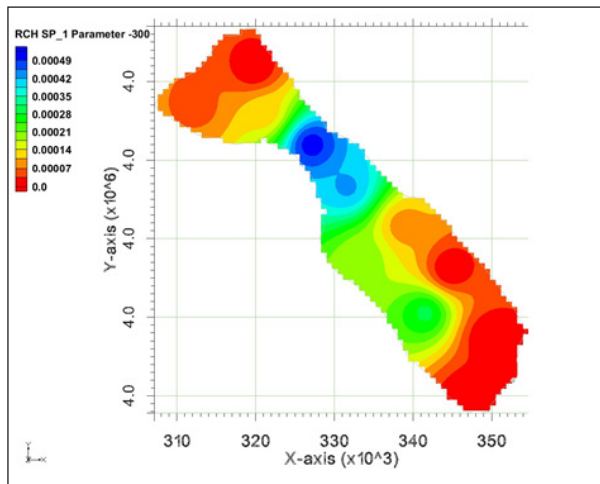


Fig. 6. The ultimate interpolation of surface feeding.

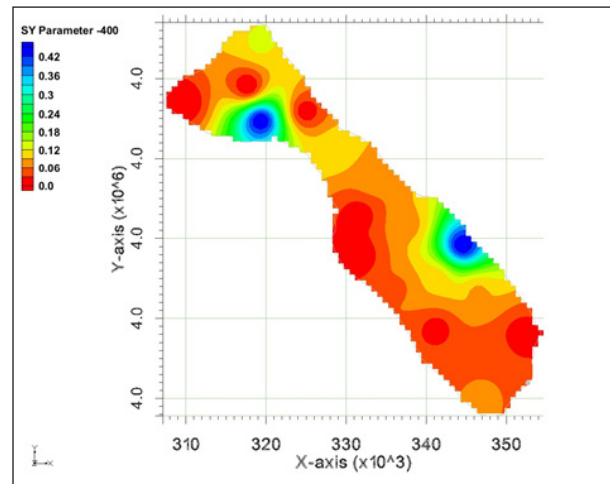


Fig. 7. The ultimate interpolation of specific yield.

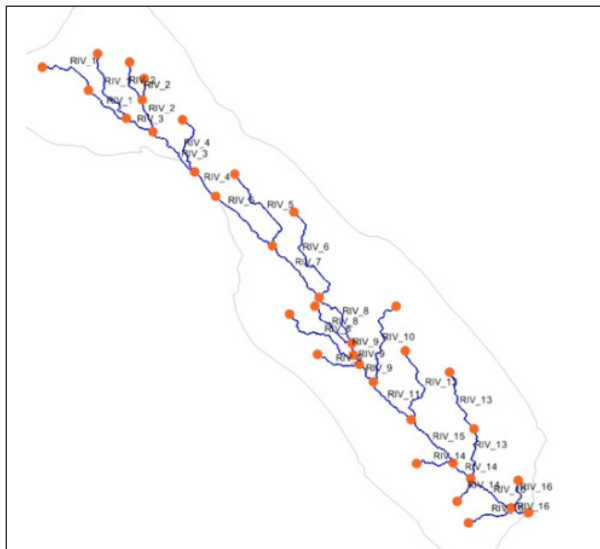


Fig. 8. The ultimate interpolation of the waterway.



Fig. 9. The ultimate interpolation of permeable boundaries.

forms of a raster map and the finite-difference grid with a mean time series, respectively. The essential effect of subsidence arises from the reduced groundwater level. Therefore, the largest vertical structural change is expected to exist in areas with the highest water level reductions.

Figs. 13 and 14 illustrate the raster layer on the finite-difference grid of subsidence in the last range and the times series diagram of the mean subsidence in the aquifer, respectively. The maximum local subsidence was 0.278 m, while the aquifer area covered 657.937 km². The estimated total subsidence volume was 222.030 km³, with an overall subsidence value of 0.337 m. The maximum local subsidence was 0.278 m, while the aquifer area covered 657.937 km². The estimated total subsidence volume

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According to the described fuzzy theory, each of the basic parameters influencing or representing subsidence was transformed into a standard raster map in the range of 0-1 by a linear equation. The fuzzified layers included water level reduction, the difference between the initial and final water levels, horizontal hydraulic conductivity anisotropy, horizontal hydraulic conductivity, saturated aquifer depth, surface feeding, extraction flow rate, and specific yield. Direct fuzzification was applied to all the parameters, except for surface feeding, to which inverse fuzzification was applied. Table 2 shows the zoning errors of the selected layers. The parameters of Table 2 were used

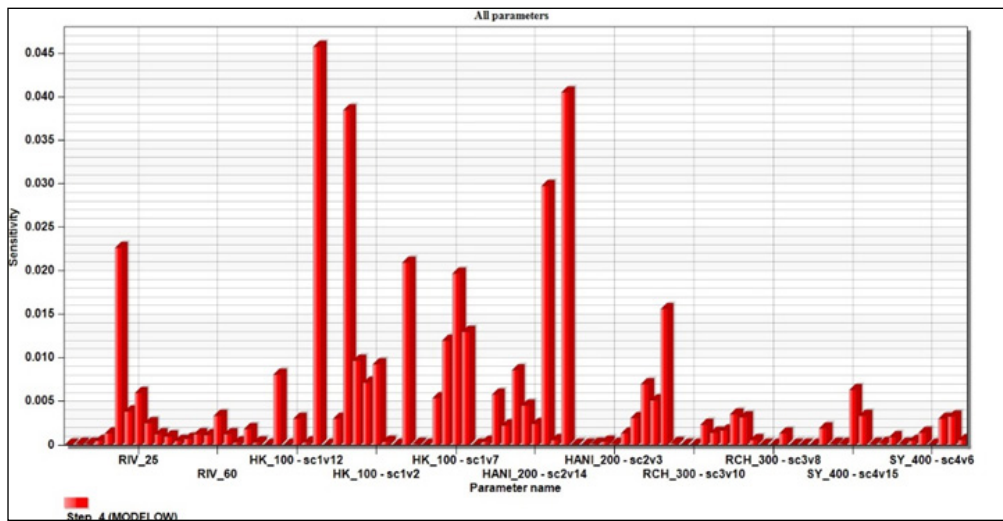


Fig. 10. The sensitivity analysis of the calibration parameters.

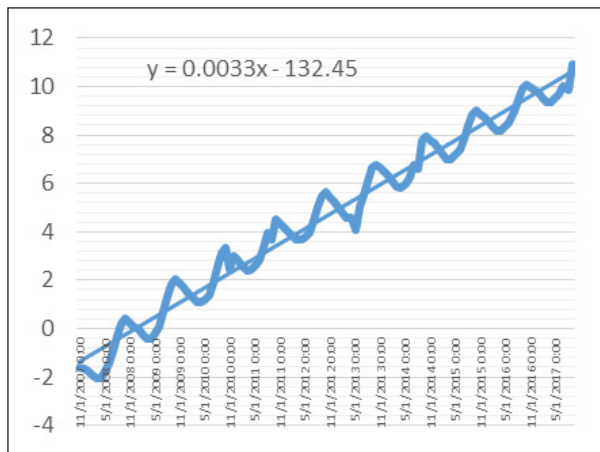


Fig. 11. The water level reduction time series of the aquifer.

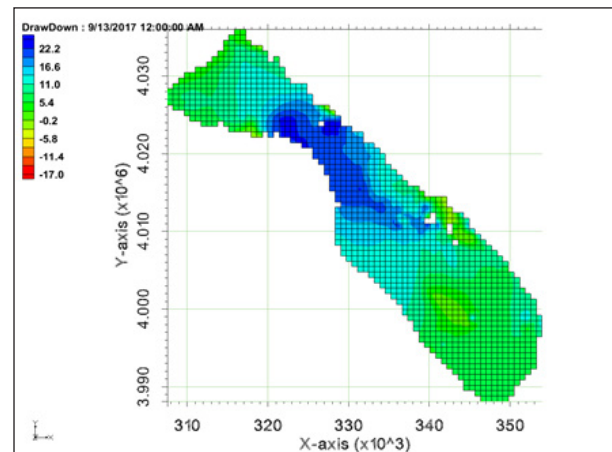


Fig. 12. The raster map of ultimate water level reduction in the aquifer.

to develop the fuzzy model. The coefficients of the aquifer were merely extracted from the last calibration round of the groundwater flow model (Figs. 15 to 22).

For the overlapping of the fuzzified layers in the fuzzy method, the analysis was performed by different methods using the "overlay" command in the GIS, as shown in

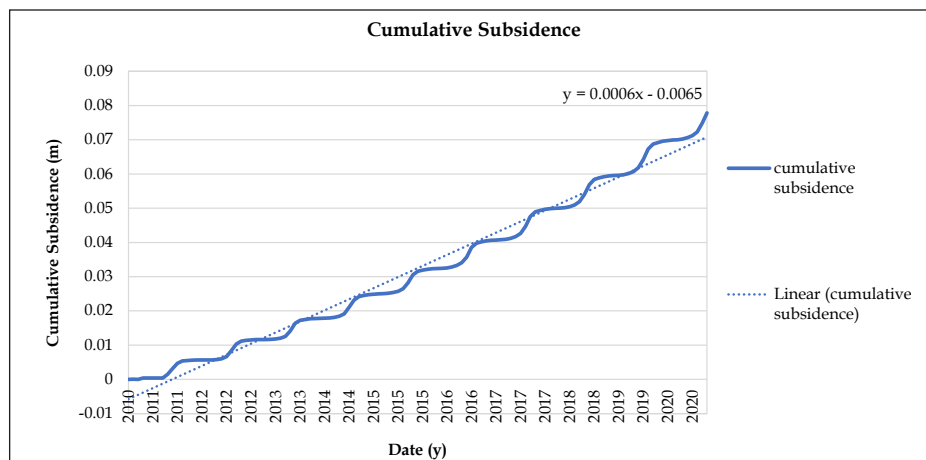


Fig. 13. The subsidence time series of the aquifer

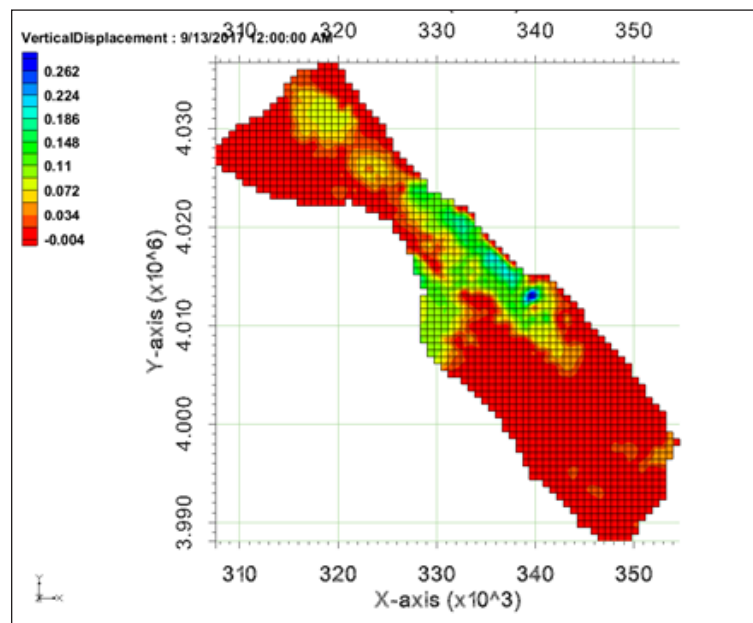


Fig. 14. The raster map of ultimate subsidence in the aquifer.

Table 2. The zoning errors of the selected layers

	Subsidence	initial Water Level	Final Water Level	The difference between Initial and Final Water Levels	Water Level Reduction	Extraction Flow Rate	Aquifer Depth	Hydraulic Conductivity	Anisotropy	Surface Feeding	Specific Yield
Mean	0.077	0.010	0.004	0.092	0.001	-330.662	0.043	1127.103	84.781	0.001	0.006
Root-Mean-Square	0.274	0.961	1.531	1.060	0.981	1926.978	4.062	2067.46	298.34	0.003	0.163
Mean Standardized	-0.217	0.002	0.000	0.016	0.002	-0.779	0.007	0.000	-0.061	-1222.11	-1.354
Root-Mean-Square Standardized	2.386	1.019	0.840	0.985	1.379	3.967	0.898	0.000	0.257	4033.262	5.853
Average Standard Error	0.703	0.882	1.721	2.208	0.693	2322.096	4.789	12049812.74	49682.30	0.004	0.255

the following figures. The output of the gamma method was more considerable than those of the other methods, considering the reduction and enhancement effects of the parameters on each other (Figs. 23 to 28).

Table 3 shows the correlations between the layers affecting the subsidence layer. As can be seen, the maximum correlation of the determination coefficient-based subsidence spotted layer in the fuzzified parameters after creating the regression equation was found with the aquifer depth. The gamma overlapped layer did not lead to increased correlation. The correlation of 30.485% of the depth layer in comparison to the gamma correlation of

17.115% indicates that some layers do not lead to the discovery of a stronger relationship in the development of the overlap model. After the structural depth layer of the saturated aquifer, the specific yield and level difference (which is investigated in the same position as the water level reduction) led to the creation of relative correlations.

In the next step, to investigate the spatial variations of subsidence occurrence, the land-use layer was utilized as the statistical analysis basis of the subsidence raster output. Figures 29 and 30 illustrate initial and class-changed land-uses. The statistical analysis of the subsidence occurrence layer was performed

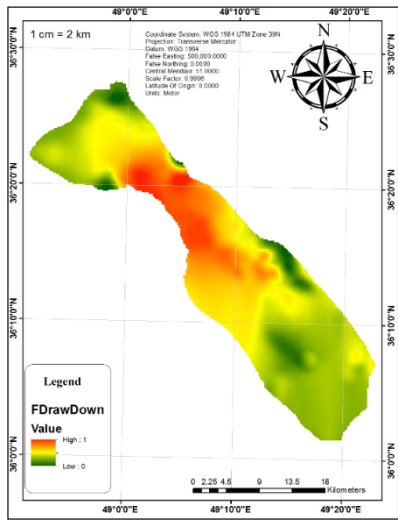


Fig. 15. The water level reduction trend.

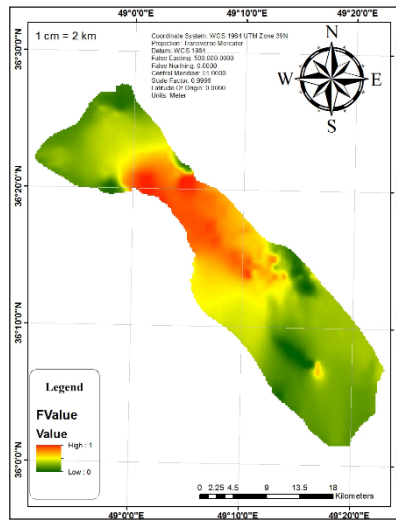


Fig. 16. The trend of the difference between the initial and final water levels.

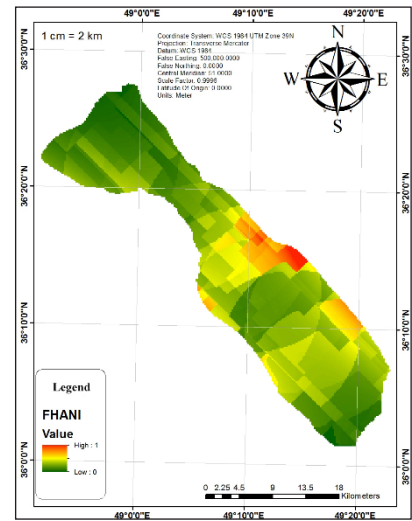


Fig. 17. The anisotropy trend.

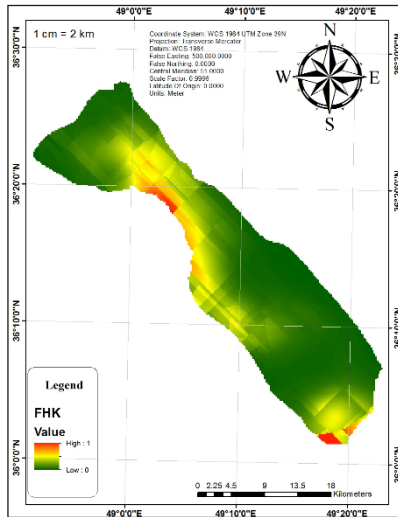


Fig. 18. The hydraulic conductivity trend.

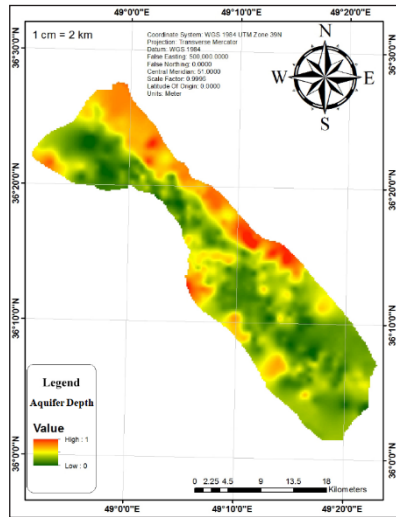


Fig. 19. The aquifer depth trend.

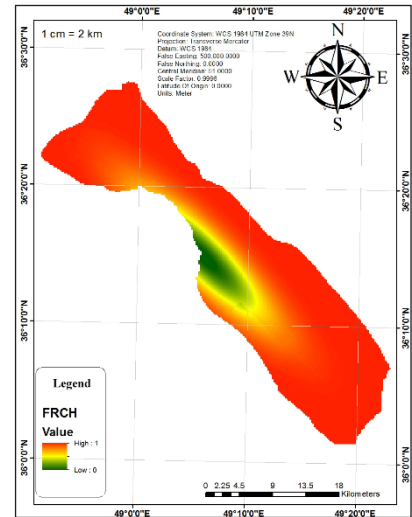


Fig. 20. The surface feeding trend.

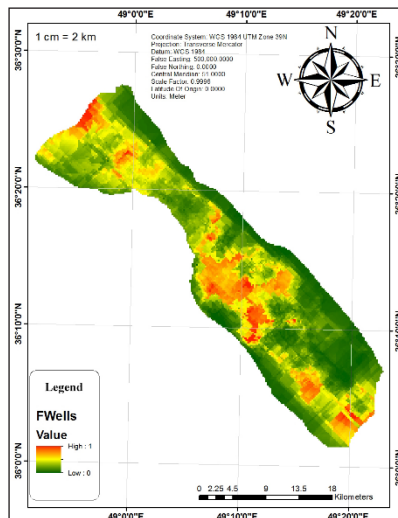


Fig. 21. The extraction flow rate trend.

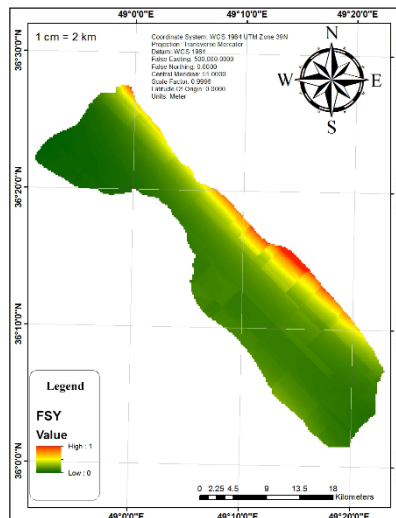


Fig. 22. The specific yield trend.

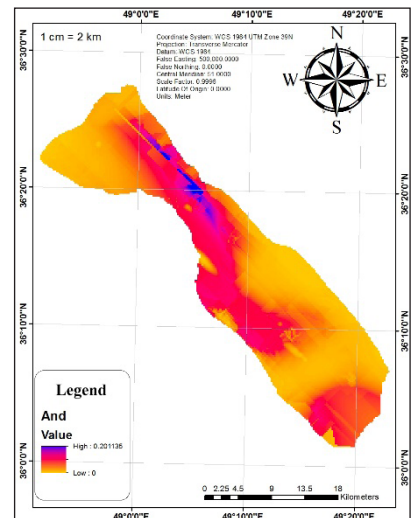


Fig. 23. And overlap.

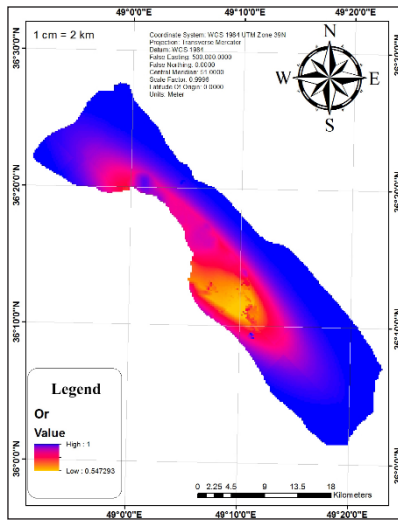


Fig. 24. Or overlap.

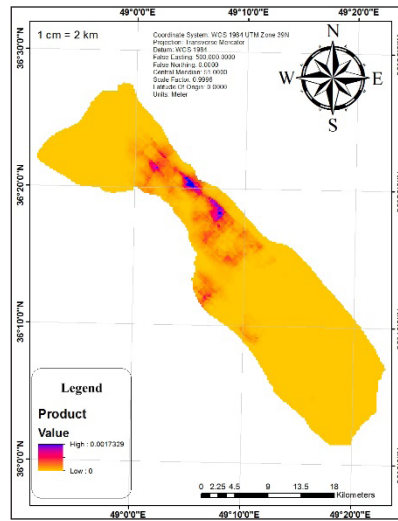


Fig. 25. Product overlap.

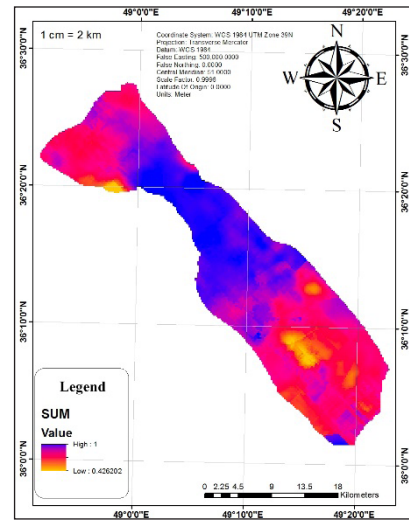


Fig. 26. SUM overlap.

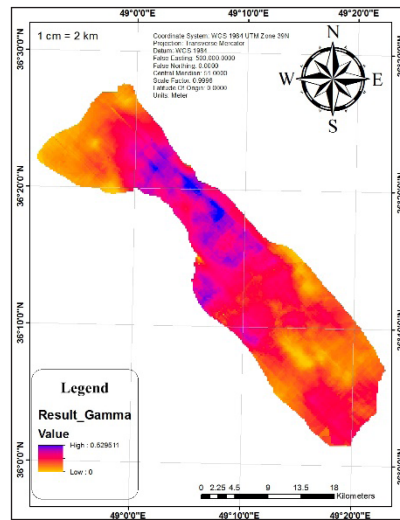


Fig. 27. Gamma overlap.

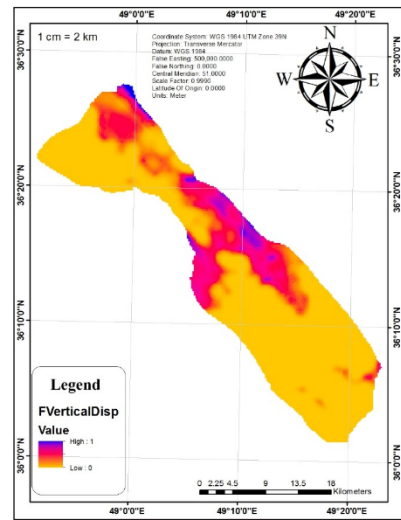


Fig. 28. The fuzzified subsidence layer.

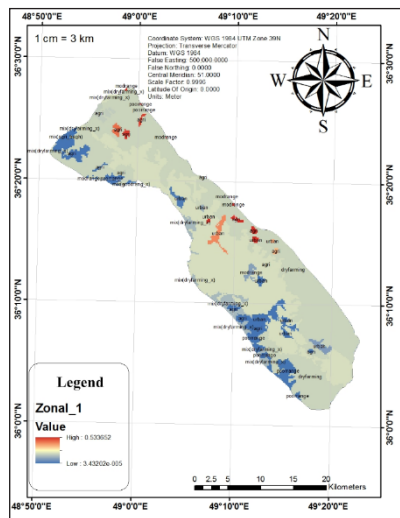


Fig. 29. The statistical analysis based on the geographical distribution of land-uses.

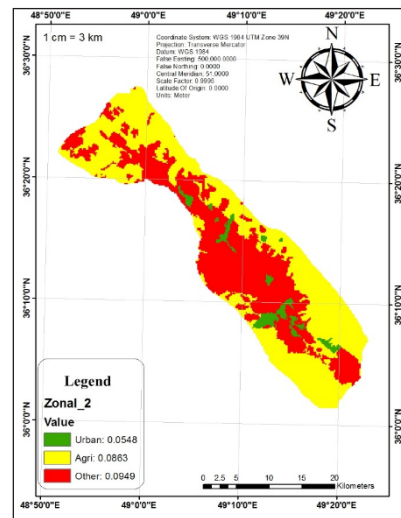


Fig. 30. The statistical analysis based on three land-uses.

Table 3. The correlations of the influential layers with the subsidence layer Convert this information to text

Gamma	Specific yield	Feeding	Anisotropy	Hydraulic conductivity	Extraction flow rate	Water level reduction	Level difference	Final water level	Initial water level	Aquifer depth
30.485%	2.460%	1.765%	17.096%	10.707%	0.022%	0.025%	7.352%	1.553%	17.629%	17.115%

using the statistical analysis command in GIS for two land-use codes and urban, agricultural, and idle land-uses. According to Fig. 29, the highest relative subsidence did not necessarily happen in a specific land-use. The red class was assigned to urban areas in some places and the agricultural class in other cases. According to Fig. 30, the reduction of the statistical indicates that the highest subsidence events occurred for the idle, agricultural, and urban fuzzy layers.

Conclusions

The results of the present study demonstrate that the MODFLOW-based approach can be used to model and assess land subsidence in the Abhar Plain. In developing the groundwater-flow model, 70% of the available piezometric data were used for calibration, while the remaining 30% were used for model validation. The regression analysis between the modelled subsidence layer and the individual hydrogeological parameters showed that aquifer depth had the strongest relationship with subsidence, with a coefficient of determination (R^2) of 30.485%. The other parameters showed considerably weaker relationships.

The fuzzification of the influential parameters and their integration using the fuzzy gamma operator provided a spatial framework for combining the effects of multiple hydrogeological factors. However, the resulting relationship with the modelled subsidence layer was weaker than expected. The final subsidence layer was subsequently transferred to the GIS environment and analysed spatially according to land-use classes.

The results showed that urban areas accounted for 26% of the estimated subsidence while occupying only 4% of the aquifer area. Agricultural areas and gardens, which occupied approximately 42% of the aquifer area, accounted for 56% of the subsidence events. In contrast, idle areas occupied approximately

54% of the aquifer area but accounted for only 19% of the estimated vertical changes.

The relatively high occurrence of subsidence in urban and agricultural areas indicates the importance of groundwater-level decline and human water use in the spatial distribution of subsidence. Considering the alluvial nature of the aquifer, the effects of groundwater-level reduction may become apparent over relatively small spatial distances. Therefore, integrated groundwater management, improved agricultural water-use efficiency, appropriate irrigation and drainage practices, and effective control of groundwater abstraction are important for reducing subsidence risks in the Abhar Plain.

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