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Determining safe yield and mapping water level zoning in groundwater resources of the Neishabour Plain

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Abstract: Groundwater is a crucial sources of water supply, especially in arid and semi-arid areas around the world. With uncontrolled withdrawals and limited availability of these resources, it is essential to determine the safe yield of these valuable resources. The Hill method approach was used in this study to determine the safe yield the Neishabour aquifer in Khorasan Razvi province in Iran. The results showed that the safe yield in the Neishabour aquifer is 60% lower than the current pumping amounts during the study period, indicating that further overdrafts could result in the destruction of this aquifer. This highlights the importance of using the Hill method to estimate the permitted exploitation from other aquifers, thus preventing problems caused by over-extraction and maintaining stability of global groundwater levels.

Keywords: Hill method; Water level zoning maps; Groundwater pumping; Safe yield; Groundwater crisis

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Introduction

Groundwater is a vital source of water in countries, particularly in arid and semi-arid regions such as Iran, India, and China, etc (Panahi et al. 2021).

The excessive abstraction of groundwater is a critical issue that requires the development of long-term and comprehensive plans to prevent it. The increasing abstraction of groundwater has led to many important aquifers being exploited, with pumping rates exceeding the capacity of the aquifer system.

In many countries around the world, groundwater abstraction exceeds its annual recharge rate. Water resource managers aim to address this imbalance by reducing the pumping volume to achieve stability (Kalf and Woolley, 2005). A lack of proper understanding and over-use of groundwater resources can result in significant, irreversible harm, including groundwater deline, reduced well discharge and aqueduct discharge, and altered groundwater flow patterns (e.g. saltwater intrusion and mixing of salt and fresh waters (Kamran et al. 2018). The examination of various scenarios in this article aims to determine the appropriate pumping rate, which will be discussed in further detail in this article.

1 Study area

The Neishabour basin is situated in the Khorasan Razavi province, covering an area of 9 157 km^2, with a plain area of 2 360 km^2. Its geographical coordinates are 13° 58′ to 59° 30′ E and 35° 40′ to 36° 39′ N. Its boundaries are defined by the ridge of Binalood heights to the north, Leilajugh and Yal Palang heights to the east, Neyzehband hills, Siah Kooh, and Namak Mountain to the south, and the Sabzevar plain basin to the west (Alizadeh et al. 2013).

The climate of the region is charicterised by dry, semi-arid, and arid conditions. The average monthly temperatures are 13℃ and 13.8℃ in Bar (representing mountainous areas) and Mohammadabad-Fadisheh (representing plain areas) stations, respectively. The average precipitation and evaporation levels are respectively 234 mm and about

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2 235 mm/a (Izadi, 2013). Fig. 1 shows the location of the Neishabour plain basin in Khorasan Razavi province.

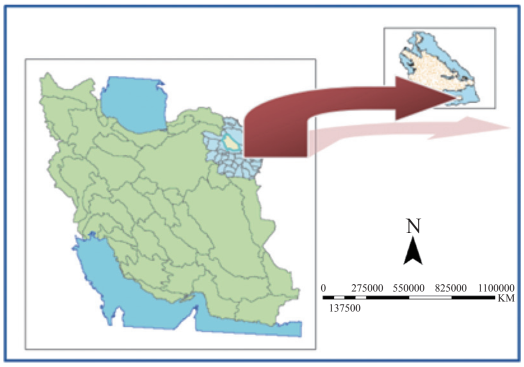

Fig. 1 Location of the study area in Khorasan Razavi province, Iran

According to studies conducted by Izadi (2013), the Neishabour plain aquifer has experienced a severe crisis as a result of excessive and unprincipled groundwater extraction in recent years.

Studies indicated that excessive and unsustainable groundwater extractions have caused a crisis in the Neishabour plain aquifer. The average aquifer recharge was about 390 million m^3 in 12 wet years (2000–2001 to 2011–2012), while the average discharge rate was about 617 million m^3 in 12 years, resulting in an annual excessive extraction of 201 million m^3, causing a negative aquifer balance (Izadi, 2013).

A significant portion of water obtained from wells and springs is utilized for irrigation, 63% of water from wells, over 9% from qanats, 1% from canals, and a total of over 64% from these groundwater sources used for agricultural irrigation. The water is mainly consumed in the agriculture of the region, where wells play a crucial role in supplying water needed for farming (Yazdani and Mansoorian, 2014).

2 Materials and methods

2.1 Data collection

The main data used in this study was pumping data (m^3/d) for 2 488 pumping wells and recharge values (m/d) for 12 wet years (2000–2001 to 2011–2012) in the Neishabour plain study area, obtained through the Modflow model developed by Nazarieh (2017). The pumping data was adjusted in different scenarios and incorporated into the model to calculate the water budget after running the model.

2.2 Determination of safe yield using the Hill method

The Hill method was used to calculate safe yield by plotting the annual pumping rate against the average annual changes in the piezometric surface. Safe yield is defined as the pumping rate at which the average annual water level changes are equal to zero (Sharp, 2016).

The aquifer initial pumping rates (m^3/d) were assumed to be constant throughout the modeling period (water years 2001–2001 to 2011–2012) and introduced to the Modflow model as 2 488 pumping wells in the aquifer over 143 stress periods. Fig. 2 shows the location of the pumping wells in the study area and around the aquifer. After running the model, modelled monthly water levels are extracted from all 20 240 cells.

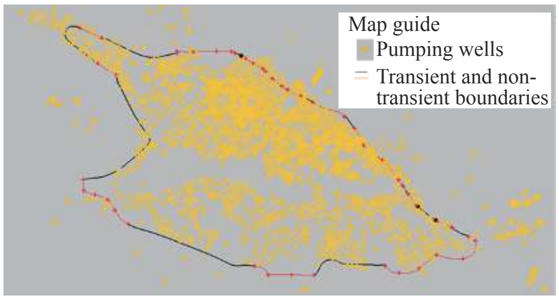

Fig. 2 Location of existing pumping wells in the aquifer and the modeling range

To determine safe yield annually using the Hill method, it is essential to calculate the annual changes in the water level. At the end of this stage, the annual pumping values and the corresponding annual water level drop are plotted against each other for 12 years of study period and are presented in Table 1.

Table 1 Sum of pumping values and water level drop in the water years of the period

Water year	Annual pumping (million m^3)	Annual water level change (m)
2000–2001	680.42	−0.90
2001–2002	671.82	−1.10
2002–2003	662.63	−0.93
2003–2004	655.39	−0.84
2005–2004	644.76	−0.72
2005–2006	635.54	−0.78
2006–2007	626.10	−0.66
2007–2008	616.36	−0.68
2008–2009	609.83	−0.62
2009–2010	611.46	−0.65
2010–2011	611.52	−0.64
2011–2012	547.29	−0.45

According to the Hill method, a pumping rate that results in zero change in water level is considered a safe yield. However, the current pumping rates in the Neishabour aquifer lead to a significantly average annual drop in water level. As a result, the pumping rate that would make the slope of the water level horizontal is not within the range indicated by the data.

2.3 Implementation of the Hill method on modified pumping

This scenario involves reducing the amount of abstractions from the aquifer by different percentages. The goal is to find the pumping level at which the average slope of the water level in the aquifer reaches zero, which would be considered a safe yield according to the Hill method. To determine this, the first step involves reducing pumping by 10% for each of the 2 488 pumping wells in the model in 143 stress periods. After the model is run with the new pumping values, modelled monthly water levels from 20 240 cells are extractedand plotted against time to track the trend of changes in water level slope. If the initial slope is still very negative, pumping rates should be reduced again by a higher percentage and the process is repeated until zero (horizontal) or positive slope is reached.

To implement the Hill method, the average annual pumping rate and average water level changes need to be calculated for each reduced pumping period (10%, 20%, 30%, etc pumping reduction). These values are plotted against each other, and pumping rate is considered safe yield when it results in an average zero water level drop. Table 2 outlines the steps and calculations involved in this part of the study.

Table 2 Average annual pumping values of the period after reducing the pumping percentage compared to initial pumping values

Average annual pumping values of the period (million m^3)	The percentage of pumping reduction compared to existing (initial) values (%)
557.99	−10
495.83	−20
433.99	−30
371.99	−40
315.45	−50
245.84	−60

2.4 Mapping of water level zones in the plain

At this stage of the work, water level zoning is mapped over the course of the study period to demonstrate the range of water level changes under various scenarios. To create the map, the Modflow model was run for the target scenario, and water level contours were generated for the last time step of the study period (the ninth month of 2012). These contours were then added to the contour layer and as a shape file, which was transferred to ArcGIS software to map the zoning of that scenario. The results of this mapping are presented in the subsequent section.

3 Results

3.1 Determining safe yield with existing pumping values in the aquifer using the Hill method

In this section, the Hill method was applied to the initial pumping values of the aquifer to obtain a linear graph and equation. The results indicate that the line equation obtained from pumping 494.8 million m^3 results in a zero water level change. This number is considered the safe yield that maintains the optimal condition of the aquifer’ s water level.

This section applies the Hill method to the initial pumping values of the aquifer to obtain a linear graph and equation. The results show that the line equation obtained from pumping 494.8 million m^3 results in a zero water level. This number is con-

Table 3 Determination of safe yield from the obtained curve equation

Water year	Annual pumping (million m^3)	Annual water level change (m)
2000–2001	680.42	−0.90
2001–2002	671.82	−1.10
2002–2003	662.63	−0.93
2003–2004	655.39	−0.84
2005–2004	644.76	−0.72
2005–2006	635.54	−0.78
2006–2007	626.10	−0.66
2007–2008	616.36	−0.68
2008–2009	609.83	−0.62
2009–2010	611.46	−0.65
2010–2011	611.52	−0.64
2011–2012	547.29	−0.45
From the curve equation to zero water level drop	494.8	0

sidered the safe yield that maintains the optimal condition of the aquifer's water level.

Fig. 3 displays the curve for determining safe yield through initial pumping rates. The estimated safe yield from the curve equation is found along the curve obtained from the points but it exceeds the annual recharge rate of the aquifer. This implies that the safe yield obtained from this step is not satisfactory and a more accurate safe yield is obtained by reducing the initial pumping rates.

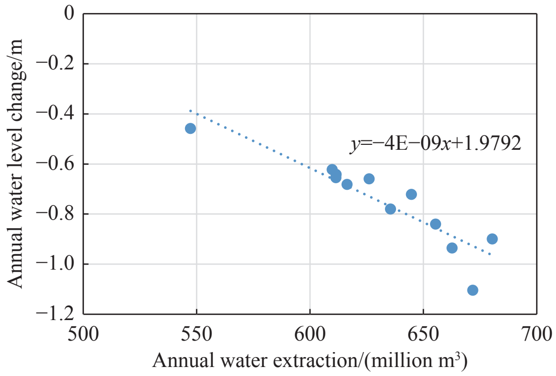

Fig. 3 The Hill method and determination of safe yield using initial pumping values

3.2 Implementation of the Hill method on modified pumping values

As described in Materials and Methods, the initial pumping rates in the aquifer were reduced by various percentages. Then, water level changes were plotted against time for each pumping change.

For each change in pumping of the targeted wells, the average annual abstraction was also calculated during the study period. Additionally, the average annual waterlevel change was computed during the same period. Finally, a graph was plotted showing these two values against each other, and the pumping at which the aquifer level drop was zero was identified as a safe yield.

The results of the water level-time change diagrams in the aquifer indicate that appropriate pumping rate are approximately 60% lower than the initial pumping rates during the study period, which can maintain the water level drop at around zero in the aquifer. Furthermore, the estmiated safe yield obtained from this section is 257.20 million m^3 in the aquifer. Fig. 4.1 to Fig. 4.6 show the graphs of water table changes related to various stages of pumping percentage reductions in in the aquifer.

As shown in Fig. 4.6, the water level drop in the aquifer has almost reached zero with a 60%

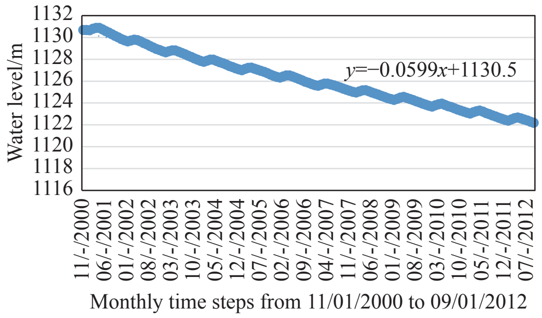

Fig. 4. 1 Modelled water level with 10% pumping reduction

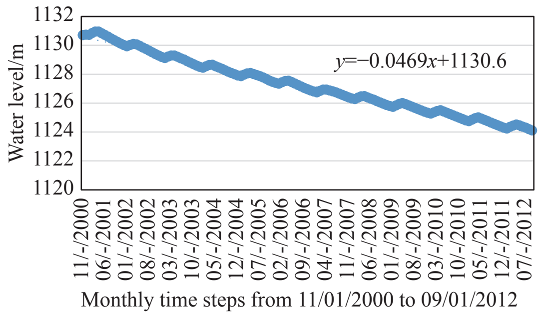

Fig. 4. 2 Modelled water level with 20% pumping reduction

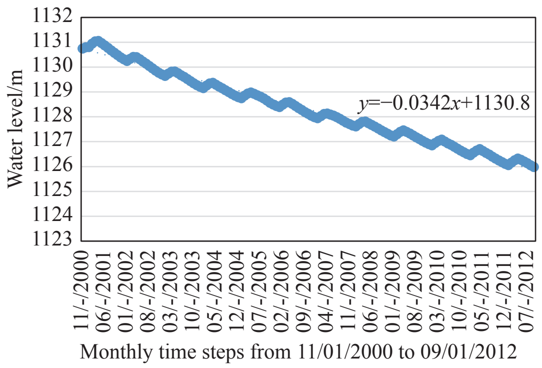

Fig. 4. 3 Modelled water level with 30% pumping reduction

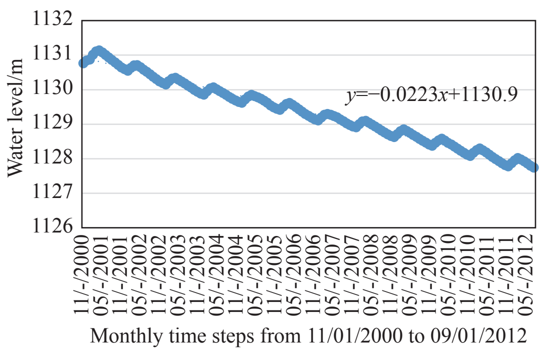

Fig. 4. 4 Modelled water level with 40% pumping reduction

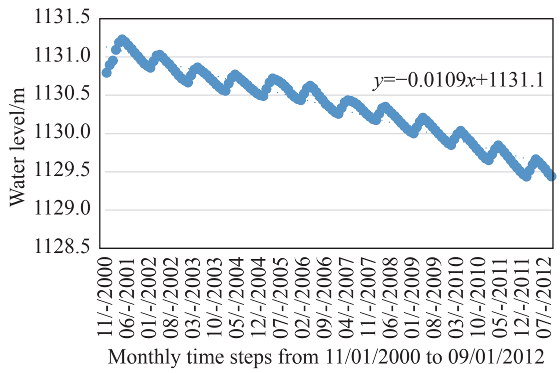

Fig. 4. 5 Modelled water level with 50% pumping reduction

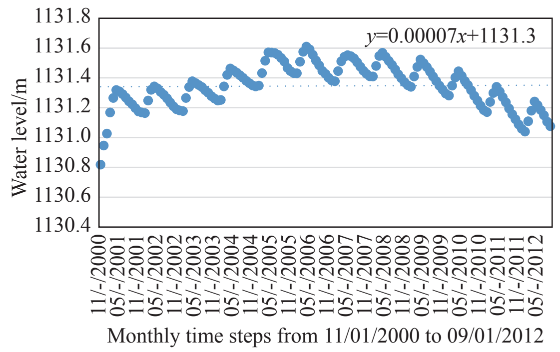

Fig. 4. 6 Modelled water level with 60% pumping reduction

reduction in initial pumping rates. The water table in the aquifer has a positive slope in its changes. During this period, the average monthly water level was 1 131.35 m in this case. Table 4 reports the results of determining the average annual pumping and the average annual changes in water level in the period for each pumping percentage reduction. Lastly, Fig. 5 displays the graph used to determine the safe yield of the aquifer.

Table 4 Determining the safe yield from the obtained line equation

The percentage of Pumping reduction compared to existing (initial) values (%)	Average annual pumping values of the period (million m^3)	Average annual water level changes of the period (m)
−10	557.99	−0.70
−20	495.83	−0.54
−30	433.99	−0.39
−40	371.99	−0.25
−50	315.45	−0.11
−60	245.84	+0.02
From the curve equation to zero water level drop	257.2	0

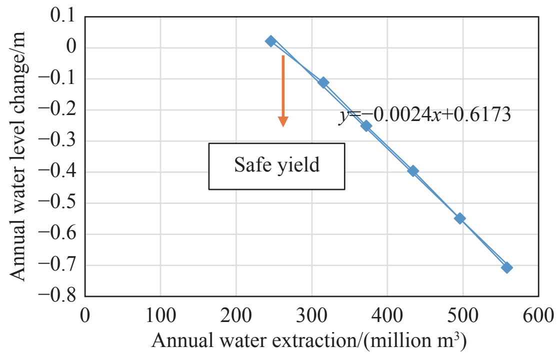

Fig. 5 The Hill method and determination of safe yield after changing pumping values

By plotting the average annual pumping of wells against the annual average water level changes in the aquifer (the Hill method), a safe yield value of 257.20 million m^3 was estimated for the Neishabour aquifer. With the current annual pumping rate (about 617 million m^3/a) of the aquifer during the study period at approximately 617 million m^3/a (Izadi, 2013), it can be concluded that there is an overdraft of approximately 360 million m^3 per year compared to the estimated safe yield. This overdraft can lead to serious water crises and depletion of the groundwater aquifer in the Neishabour plain.

3.3 Examination of water level zoning maps in the plain

Water level zoning maps in the Neishabour aquifer were created and compared at the end of the study period in two scenarios, using appropriate pumping rates (a 60% reduction compared to initial pumping values) and the second scenario with no changes to initial) pumping rates. The results are displayed in Fig. 6 and Fig. 7.

From the analysis of the maps, it can be concluded that in the second scenario, with proper pumping rate applied in the aquifer, the water level is generally higher in all areas of the aquifer, compared to the the initial pumping conditions. As a result, the average water level in various classes is higher in the second scenario.

From the analysis of the maps, it can be deduced that in the second scenario, with proper pumping in the aquifer, the water level is generally higher in all areas of the aquifer compared to the initial pumping conditions. As a result, the average water level in various categories is higher in the second scenario.

4 Conclusion

In this study, the safe yield rate was determined by

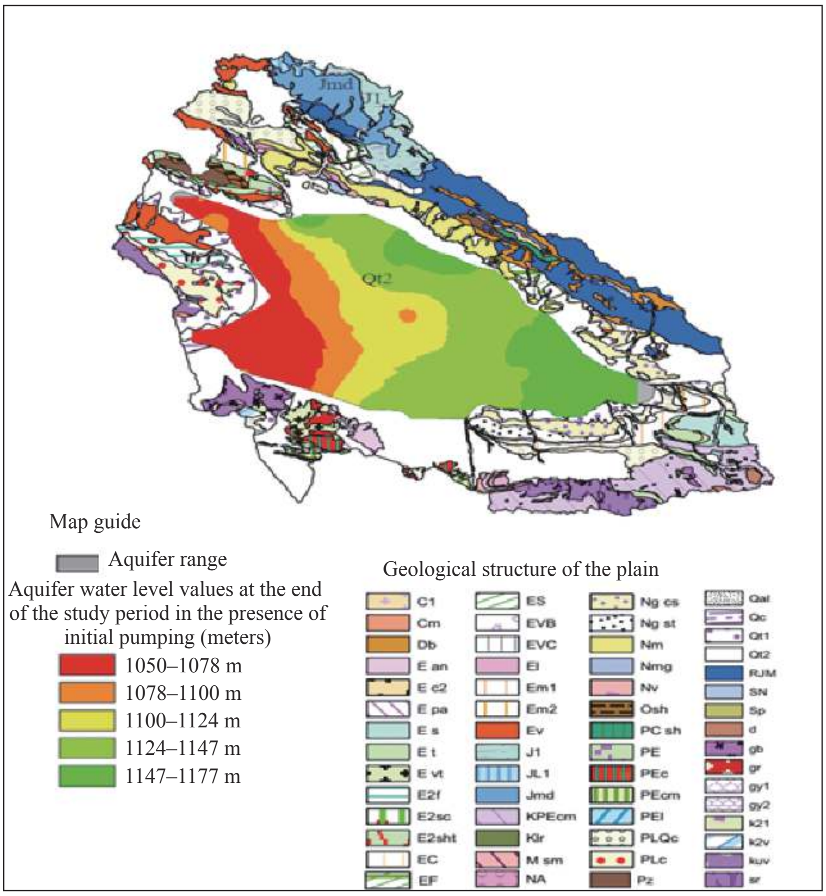

Fig. 6 The zoning map of the aquifer water level in the initial pumping condition

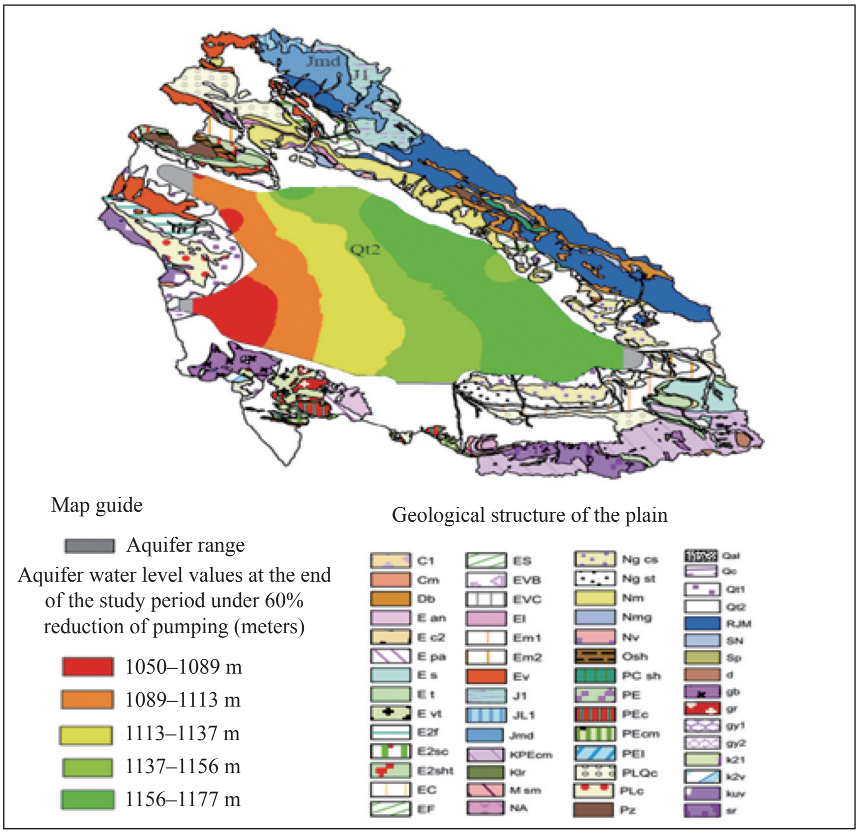

Fig. 7 The zoning map of aquifer water level in the appropriate pumping condition

changing pumping rates (at different percentages) using the Hill method for the water years 2000–2012. A safe yield rate was also obtained using the initial pumping data of the aquifer through the Hill method, but the results indicated that the estimate was not reasonable in this scenario because the estimated safe yield exceeded the annual recharge rate of the aquifer. Thus, it can be concluded that the safe yield estimated from reducing the initial pumping values provides a more precise estimate.

The results of water table changes in different scenarios of reducing pumping rate indicated that reducing pumping percentages from the aquifer by 60% can result in appropriate pumping that maintains the water level and prevents the aquifer from depletion during the period.

The safe yield rate from the aquifer is approximately 257.20 million m^3/a. Based on the average actual discharge rate of the aquifer during the study period, there is an annual overdraft of around 360 million m^3 of compared to safe yield.

The safe yield rate from the aquifer is approximately 257.20 million m^3/a. Based on the average actual discharge rate of the aquifer during the study period, there is an annual overdraft of around 360 million m^3 compared to the safe yield.

References

Akbari B, Hejazi A. 2017. The importance of water resources management in Iran with emphasis on groundwater. The 7th National Conference on Agriculture and Sustainable Natural Resources.

Alizadeh A, Izadi A, Davari K, et al. 2013. Estimation of actual evapotranspiration on a year-basin scale using SWAT. Iranian Journal of Irrigation and Drainage, 2: 243−258. https://www.sid.ir/paper/131662/fa

Alley William M, Stanley AL. 2004. The journey from safe yield to sustainability. Groundwater, 42(1): 12−16. DOI：10.1111/j.1745-6584.2004.tb02446.x.

Bredehoeft J. 1997. Safe yield and the water budget myth. Groundwater, 35(6): 929. DOI：10.1111/j.1745-6584.1997.tb00162.x.

Izadi A. 2013. Application and evaluation of a developed integrated model of groundwater-surface water in the Neishabour Basin. Ph. D. Dissertation in Water Science and Engineering, Faculty of Agriculture, Ferdowsi University of Mashhad.

Kalf FR, Woolley DR. 2005. Applicability and methodology of determining sustainable yield in groundwater systems. Hydrogeology Journal, 13: 295−312. DOI：10.1007/s10040-004-0401-x.

Kamran KV, Khorrami B, Roostaei S. 2018. Assessment of groundwater-level susceptibility to degradation based on analytical network process (ANP). International Journal of Environment and Geoinformatics, 5(3): 314−324. DOI：10.30897/ijegeo.451067.

Meyland SJ. 2011. Examining safe yield and sustainable yield for groundwater supplies and moving to managed yield as water resource limits become a reality. Department of Environmental Technology, New York Institute of Technology, USA, water resource management, 1: 813.

Meinzer E. 1923. Outline of groundwater hydrology, with definitions. Geological Survey, Water Supply: 494. https://doi.org/10.3133/wsp494

Naik P, Awasthi A. 2003. Groundwater resources assessment of the Koyna River basin, India. Hydrogeology Journal, 11: 582−594. DOI：10.1007/s10040-003-0273-5.

Nazarieh F. 2017. Development and evaluation of an integrated simulation model of surface flow, unsaturated, and saturated areas in the Neishabour plain. Ph. D. Dissertation in Water Science and Engineering, Faculty of Agriculture, Ferdowsi University of Mashhad. https://ganj.irandoc.ac.ir/#/articles/b8f1157641ec90c37f3a108914a1f435

Panahi Gh, Hassanzadeh Eskafi M, Faridhosseini A, et al. 2021 Physical–chemical evaluation of groundwater quality in semi-arid areas: Case study—Sabzevar plain, Iran. Sustainable Water Resources Management, 7: 99. https://doi.org/10.1007/s40899-021-00576-y

Sharp J. 2016. Sustainability of groundwater resources: Conceptual evolution, opportunities, & challenges. Session I: 2. DOI：10.1130/abs/2017SC-288962.

Wilson E. 2005. Safe Yield of an Aquifer. Water Encyclopedia, 5: 575−576. DOI：10.1002/047147844X.gw1006.

Yazdani, Mansoorian H. 2014. Zoning the exploitation potential of groundwater resources using quantitative and qualitative data of the Neishabour plain aquifer. Journal of Irrigation and Water Engineering, 15: 118. http://www.waterjournal.ir/article_70951.