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RESEARCH PAPER

Delineating capture zone of the production wells in Abarkooh aquifer (central Iran) using WhAEM model and statistical method of multivariate regression

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Abstract
Groundwater is the most common source of water in many places especially arid regions. The quality of this valuable resource is highly important for human health. One of the essential topics in groundwater management is the area surrounding a pumping well from which groundwater is extracted. The extent of this area namely as capture zone or wellhead protection area, generally depends on factors such as the pumping rate, hydraulic conductivity, and well depth. In this research, the capture zones of 575 production wells in Abarkooh plain, located in Yazd province at central Iran, are calculated using WhAEM model for a travel time of 10-year, considering groundwater hydraulic gradient, hydraulic conductivity, recharge and aquifer thickness parameters. Furthermore, for the first time, a general equation of capture zone was developed using multivariate statistical regression method, which is based on the results obtained from WhAEM. The capture zones calculated by the new developed equation are relatively correlated with the results simulated by the WhAEM model with the correlation coefficient of about 51%. As the input parameters for the capture zone analysis are changing over time, the new developed equation by multivariate regression method can help to calculate the capture zone more effective and quicker. The calculated capture zones are essential for protecting groundwater resources, applying in remediation actions in the case of groundwater pollution.

Keywords: Multivariate Regression Method, Whaem, Capture Zone, Abarkooh.

Introduction

Humans use groundwater for drinking, irrigation, and industry, so the quality and quantity of groundwater affect human life in most areas (Goodarzi et al., 2015). In light of the importance of the issue, human is expected to protect the groundwater against a range of pollution (Sadeghi et al., 2015). Generally, groundwater protection takes two forms including 1) Protecting the groundwater pumping area, and 2) controlling the sources of pollution (Siarkos et al., 2012). Remediation of polluted groundwater resources can be a very expensive and time-consuming process, so delineating the capture zone is most important to protecting valuable water resources. It is best to identify vulnerable areas of groundwater systems in order to achieve this objective (Akbarpour et al., 2011; Naseri & Gharemahmoodlo, 2004). Identifying the capture zone of a production well, which is surrounding area of the well that supply water for pumping, is one of the best ways to protect groundwater resources. Typically, several factors determine the size of the capture zone, including the hydraulic gradient, effective porosity, the thickness

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of the saturated layer, the transmissivity of the aquifer, and the rate of groundwater pumping (Ferreira et al., 2004). There are methods for calculating the capture zone including mathematical equations and numerical methods (Siarkos et al, 2012).

Based on special hydrological conditions of Mile River, (Fadlelmawla, 2006) combined two methods of simplified shapes, and a numerical model to determine capture zone or protection area of the wells. The author used the hydraulic gradient, clay layer thickness, and hydraulic conductivity to test the model's sensitivity, and the results showed a strong relationship between the variables. Other studies, such as (Sadeghi et al., 2015: Delkhahi et al., 2011, 2013), (Badv et al., 2005), (Akbarpour et al., 2011), and (Ferrante et al., 2015) also investigated the capture zone or protection area of the discharging wells.

In this study WhAEM software used to model Abarkouh aquifer in Yazd Province (central Iran). The aquifer is one of the most important water resources in the region that supply water for drinking, agricultural and industrial uses. The aim was to delineate the capture zones of the production wells. The results of the WhAEM have been also analyzed by multivariate statistical regression method to obtain a general equation of the capture zone in the study plain considering affective parameters.

Materials and method

Area of Study

Abarkooh plain has an area of about 929 Km^2. The plain is located between 52° 58′ N to 53° 30′ N latitude and 31° 14′ W to 30° 50′ W longitude. Located 140 km south-southeast of Yazd, the plain is bounded by the Shoor River to the north and the Abarkooh desert at the east. The most important Quaternary unit is Qt2 which includes young terraces of alluvial sediments in the plain center. Limestone and dolomite formations border the plain in the west and the fine-grained sediments of Abarkooh desert at the west Abarkooh aquifer which is located in alluvial sediments is vital for drinking water and agricultural uses. Based on the iso-potential map of the aquifer, the main recharge zone of the Abarkooh aquifer is likely from the elevations in the west (Fig 1). The main groundwater flow directions are from west to the east of the plain. Reverse groundwater flow direction from Abarkooh desert (east to the west) is also created in the eastern boundary of the aquifer where the pumping wells are highly concentrated. The combined over-draft of the aquifer in this area caused reverse flow direction from deserts into the alluvial aquifer which threaten and degrade the groundwater quality in this valuable and important aquifer.

Methodology

In order to clarify all processes, several methodological frameworks are proposed. In this study, two steps were involved which have been summarized as: Step 1) Calculation of the capture zone with WhAEM model, Step 2) developing the equation of the capture zone with the Multivariate regression method (Fig 2).

WhAEM model

In this study, WhAEM software is used for solving groundwater flow. WhAEM software uses the analytical element model for simulation of groundwater flow (Swadeshi et al., 2015; Badv and Deriszadeh 2005; Kraemer et al., 2007). One of the key performances of WhAEM is simulating capture zones, which has been applied for the Abarkooh aquifer considering local hydrogeological conditions.

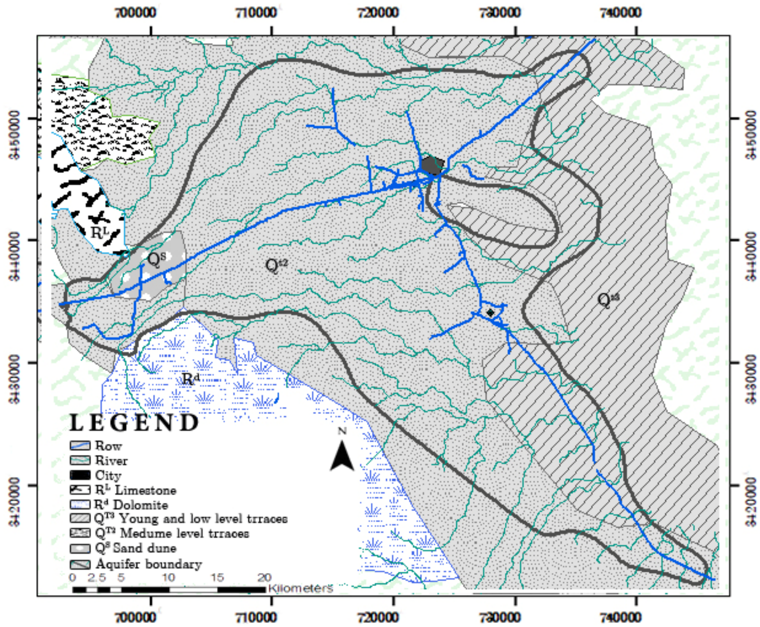

Figure 1. Geological map of the Abarkooh plain in which Iso-potential lines and groundwater flow directions are also depicted

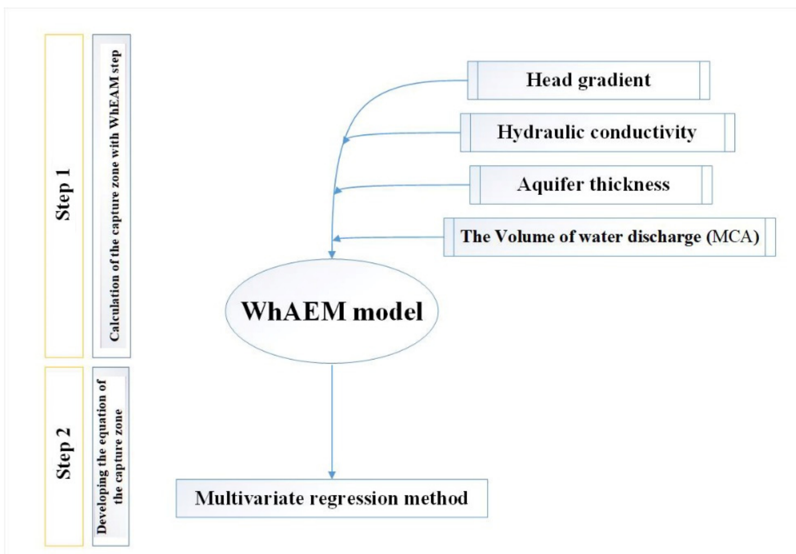

Figure 2. An overview of the methodology used in this study (research flowchart)

The WhAEM model provides many tools such as line-sink option for simulating lakes and drains, areal recharge option for recharge, well function for the operating wells, Inhomogeneity function for hydraulic conductivity changes, and horizontal barrier function for impermeable boundaries (Kraemer et al., 2007). Determination of capture zone by WhAEM model is done through the following four steps (Godarzy, 2019):

1) Preparing maps and thematic layers (conceptual model of aquifer)
2) Transform data into information that can be used in the model
3) Select an analytic function
4) Calibration of the developed model to delineate the capture zones of the wells

After doing simulation, the results were analyzed by the geographic information system software (Arc GIS) and other softwares like Excel and SPSS.

It must be mentioned that all data necessary to perform WhEAM model, including hydraulic conductivity, aquifer thickness, and groundwater heads in the Abarkooh aquifer were provided by the Yazd regional water authority.

Multivariate regression method

One of the models which can be used to forecast events is the multivariate regression. The purpose of the multivariate regression models is to explain the behavior of many response variables according to other variables. In this study, there is one independent variable (responses) and many dependent variables (predictors), which are linearly related. Using this method, it is possible to predict response behavior based on the change in predictors values. The difference between simple linear regression and multiple regression is that the multiple regression model theoretically includes more predictors, so the general form of the model becomes for k predictors is as the following equation:

$$\mathbf{y_i = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} ... + \beta_k x_{ki} + \varepsilon_i} \tag{1}$$

α is the population intercept of the line and β is the population slope, and y_i is the predicted value. The values of ε_i are the predication errors.

Results and discussion

WhAEM - Capture zones

To calculate the capture zone using WhAEM software, the required data, including groundwater head gradient, hydraulic conductivity, aquifer thickness, and discharge rate of the wells, entered into the software (Fig. 3). After simulating water table heads using WhAEM, the calibration process was performed and then, the capture zone of the wells was delineated. The capture zone has been calculated and delineated for 575 wells in the study aquifer. The result is illustrated in Fig 4. Based on the results the capture zones are mostly aligned toward the west where the recharge areas of the aquifer are located. The surface area of the capture zones vary in the range of 0.006 to 0.613 with the mean of 0.22 km^2.

Simulating capture zone by multivariate regression method

The responder and predictor variables were included in the multivariate regression method, as was previously explained. The capture zone surface area delineated by the WhAEM model and calculated by ARC GIS (Fig. 4), were employed as a response component in the multivariate linear regression. The predictor variables are included as annual discharge of the well in million cubic meter (MCA), hydraulic conductivity, thickness, and head gradient.

The initial report is shown in Table 1 based on calculating multivariate regression by SPSS software. The table1 reveals the slightly condensed output from the sequence of the multivariate regression.

Overall, while the t value is between 2.3 and 10.6, which is shown as a high value, the sign value is less than 0.01. Among the coefficients and constants for the linear regression equation, gradient has the highest value at 70%, while aquifer thickness has the lowest value at 0%.

The following equation was determined by multivariate regression analysis for simulating area of the capture zone in Abarkooh aquifer

$$\text{Capture zone area of the wells in Abarkooh aquifer } (Km^2) = -0.054 + 0.43a + 0.025b + 70.5c \tag{2}$$

In which a stands for MCA, b hydraulic conductivity and c hydraulic gradient.

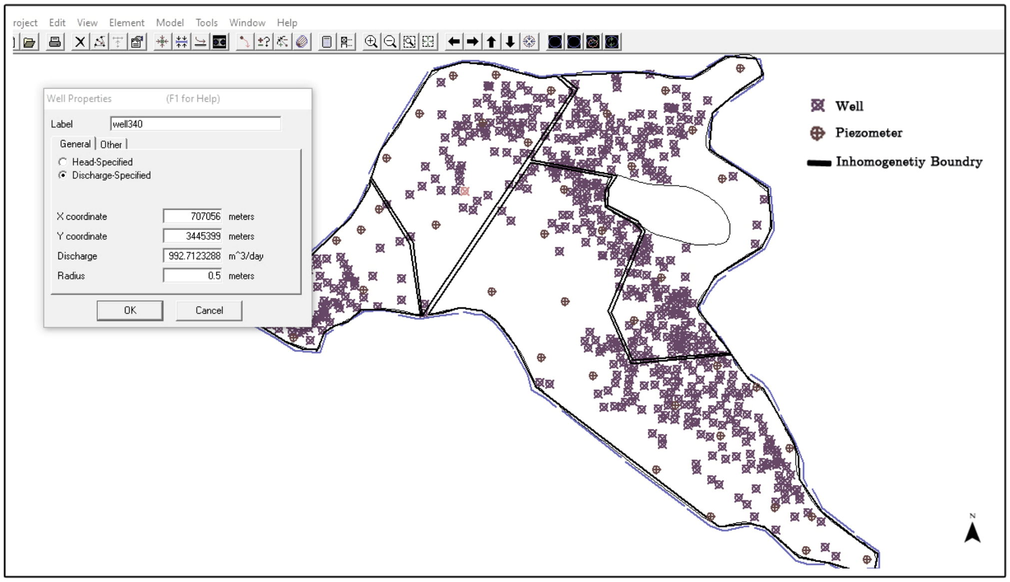

Figure 3. The WhAEM model for the estimating capture zone of the wells in the study area

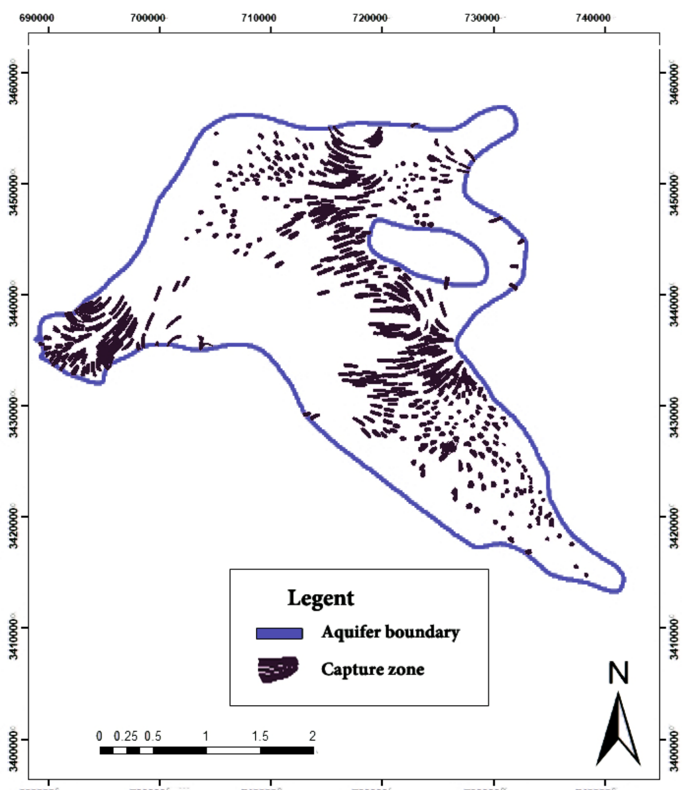

Figure 4. The capture zone of the production wells in Abarkooh aquifer based on the results of the WhAEM calibrated model

The comparison of the surface area calculated by the WhAEM software and proposed multivariate regression equation is shown in Fig 5. The relative similarity of the results confirms the validity of the proposed equation. The calculated surface areas of the capture zone by the two methods are compared in a bivariate graph (Fig. 6) and correlation coefficient was calculated about 0.51. It more confirms the validity of the proposed equation for calculating surface area of the capture zone for production wells.

Table 1. Constant value and coefficients of the multivariate regression equation developed for Abarkooh aquifer

			Standardized Coefficients		
Model	B[a]	Std. Error [b]	Beta [c]	t	Sig [d]
(Constant)	-0.054	0.023	-	-2.346	0.01
MCA	0.437	0.044	0.379	10.036	0
Hydraulic conductivity	0.025	0.002	0.407	10.622	0
Hydraulic gradient	70.528	9.745	0.268	7.237	0
Aquifer Thickness	0	0	-0.086	-2.37	0.01

[a] coefficient and constant for the linear regression equation
[b] a measure of the stability or sampling error of the B values
[c] likelihood that this result could occur by chance
[d] the standardized regression coefficient

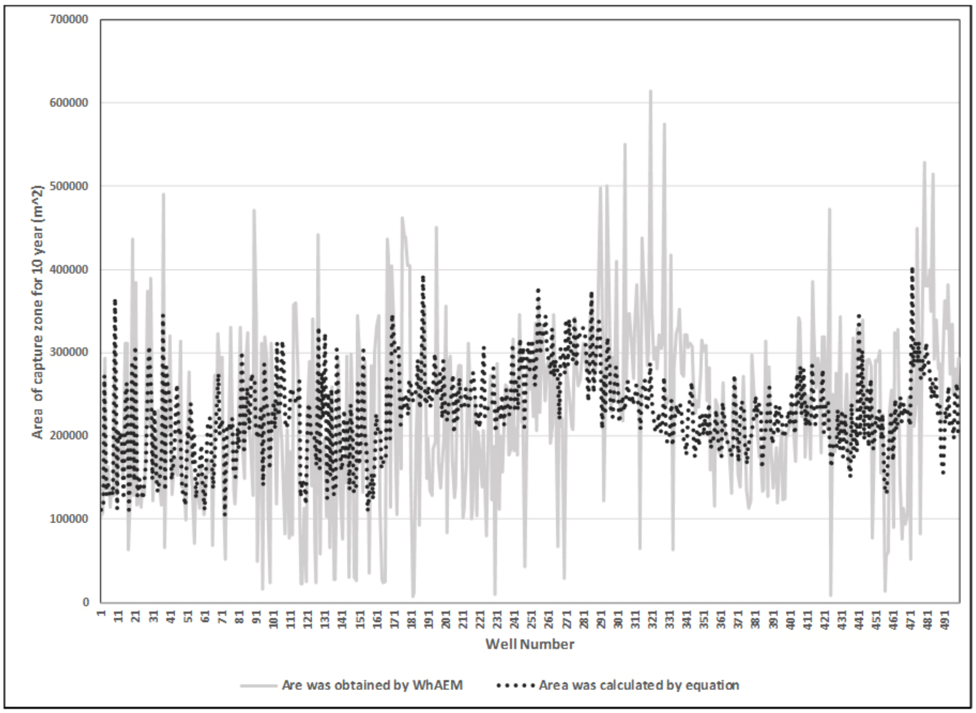

Figure 5. Comparing the area of the capture zone calculated by the WhAEM software and proposed equation derived by multivariate regression method

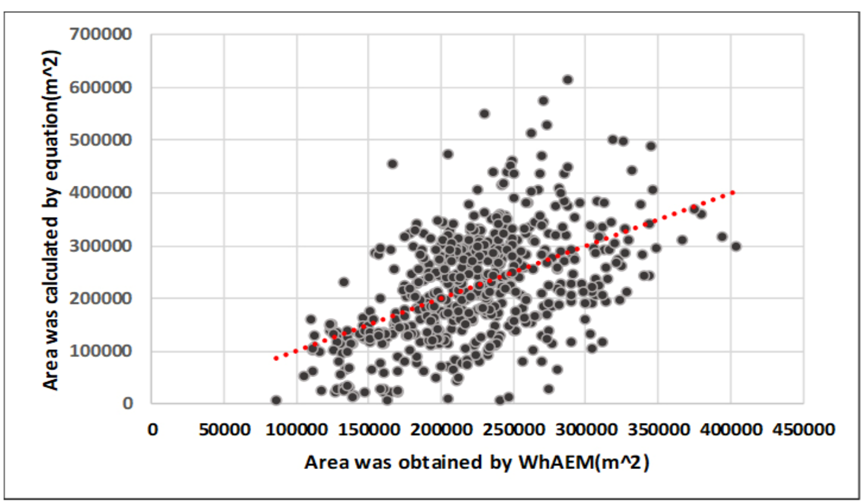

Figure 6. The correlation between the capture zone area calculated by WhAEM and multi-variate regression

Conclusion

The goal of this research was to determine the surface area of the capture zone for production wells in Abarkooh aquifer, located in central Iran. To achieve this, WhAEM software was used to calculate the capture zone for all production wells in the aquifer. After analyzing the data from WhAEM, a formula was developed using the multivariate regression method, which took into account several influencing factors, such as annual discharge of the well in million cubic meter (MCA), hydraulic conductivity, thickness, and head gradient, as predictors. The results show that there is a strong correlation (R=0.51) between the results of the WhAEM model and the proposed equation. By using this new equation, which can calculate the capture zone more efficiently and quickly, variations in input parameters for capture zone analysis over time can be accounted. Accurate capture zones are crucial in preserving groundwater resources and for taking effective remediation measures in case of groundwater pollution.

References

Akbarpour, A., Etebari, B. and Barzoni, S., 2011. Groundwater modeling to determine the protection zone of drinking wells (A Case Study of Birjand). In Fourth Water Resources Management Conference, Amirkabir University of Technology, Tehran, Iran.

Badv, K., Deriszadeh, M., 2005. Wellhead protection area delineation using the analytic element method. Water, Air, and Soil Pollution, 161(1): 39-54.

Delkhahi, b., asadian, f., khodaei, k., 2013. a comparison of calculated fixed radius and numerical model methods to delineate drinking water wellheads protection area in yaft abad dis-trict, tehran.

Delkhahi, b., Asadian, f., 2011. review of effective factors on drinking wellhead protection area using numerical mathe-matical model (case study: yaftabad district, city of tehran), technical note.

Denis, D.J., 2018. SPSS data analysis for univariate, bivariate, and multivariate statis- tics. John Wiley and son.

Fadlelmawla, A.A., Dawoud, M.A., 2006. An approach for delineating drinking water wellhead protection areas at the Nile Delta, Egypt. Journal of environmental manage-ment, 79(2): 140-149.

Ferrante, M., Mazzetti, E., Fiori, A., Burini, M., Fioriti, B., Mazzoni, A., Schir`o, G., Vacca, G., Brunone, B., Meniconi, S. and Capponi, C., 2015. Delineation of wellhead protection areas in the Umbria region. 1. A simplified procedure. Procedia Environmen-tal Sciences, 25: 90-95.

Goodarzi, M., Eslamian, S.S., 2019. Evaluation of WhAEM and MODFLOW models to determine the protection zone of drinking wells. Environmental Earth Sciences, 78(6): 1-8.

Kraemer, S.R., Haitjema, H.M. and Kelson, V.A., 2007. Working with WhAEM2000 capture zone delineation for a city wellfield in a valley fill glacial outwash aquifer sup-porting wellhead protection. Office of Research and Development US Environmental Protection Agency, Washington, DC.

Sadeghi, Z., Esmaili, K. and Kaboli, A.R., 2015. Evaluation and comparison of methods for determining the protection zone of wells using a mathematical model (case study of Golestan aquifer). Iranian Journal of Irrigation and Drainage, 9(2): 335-344.

Naseri H, Gharemahmoodlo M (2004) Determining the protection zone of drinking wells, (Case Study: Sari). In: Eighth Iranian Geological Society Conference

Siarkos, I. and Latinopoulos, P., 2012. Delineation of wellhead protection zones for the control of point pollution sources in the aquifer of N. Moudania, Greece. Eur Water, 40: 3-17.

Siarkos, I. and Latinopoulos, P., 2012. Delineation of wellhead protection zones for the control of point pollution sources in the aquifer of N. Moudania, Greece. Eur Water, 40: 3-17.