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ORIGINAL PAPER

An efficient methodology to design optimal groundwater level monitoring network in Al-Buraimi region, Oman

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Abstract Designing an optimal groundwater level monitoring network (GLMN) is a major challenge and one of the primary goals of groundwater management. This paper proposes a methodology that incorporates comparative analysis of IDW, spline, ordinary kriging (OKrig), and empirical Bayesian kriging (EBK) interpolation methods with "1-fold cross-validation" technique for the regionalization and redesigning of the existing GLMN in an arid hardrock-alluvium Al-Buraimi region, Oman-UAE border. The performance indicators (weighted RMSE = 10.84 m and weighted $R^2 = 0.79$) show the superiority of the EBK interpolation method over other methods and reveal reasonably accurate results when applied in areas with sparse and scarce observation wells. A new GLMN is proposed with regard to the results of the EBK method in which the idea of a "secondary observation network" is presented to reduce time and cost needed for groundwater level measurements. The proposed GLMN consists of 14 new observation wells added to 39 existing wells in order to provide better quality data compared to the current GLMN. The procedure used herein provides a practical and straightforward method to regionalize groundwater level variations and redesign the GLMN in regions with complex hardrock-alluvium geological setting.

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Keywords Regionalization · Monitoring network · "1-fold cross-validation" technique · Groundwater · Hardrock-alluvium · Oman

Introduction

Knowledge of spatial variability of groundwater level is a crucial element in many hydrogeological and hydrological studies, including agricultural salinity management (e.g., Demir et al. 2008; Urquhart et al. 2013), landfill characterization (e.g., Eni et al. 2014), chemical seepage movement (e.g., Sophocleous et al. 1990; Denver 1993; Bailey 2012), groundwater balance (e.g., Daniels et al. 2000; Healy and cook 2002; Martin 2005; Izady et al. 2015), and water supply studies (e.g., Serrano and Serrano 1996; Foster et al. 2002; Sandwidi 2007). However, groundwater level measurements are inherently expensive and time consuming, particularly during the installation phase, which requires drilling observation wells. Hence, the number of available observation wells is often limited and a regionalization method is commonly required to map the spatial variability of groundwater level (Buchanan and Triantafilis 2009).

There are two main techniques for groundwater regionalization: deterministic and geostatistical. Deterministic regionalization techniques create surfaces from measured points based on either the extent of similarity (e.g., inverse distance weighted, IDW) or the degree of smoothing (e.g., radial basis functions) (Johnston et al. 2003). There are five different basic functions consisting of thin-plate spline, spline with tension, completely regularized spline, multi-quadric function, and inverse multi-quadric spline (Kamińska and Grzywna 2014). Geostatistical regionalization techniques (e.g., kriging) are based on statistical properties of the measured points. The geostatistical techniques quantify the spatial autocorrelation among measured points with a variogram as the quantitative measure of spatial correlation and account for the spatial configuration of the sample points around the prediction location (Goovaerts 1997).

Various geostatistical techniques (Sophocleous et al. 1982; Murashige and Pucci 1987; Hoeksema et al. 1989; Ahmed 2002; Desbarats et al. 2002; Ahmadi and sedghamiz 2008; Nikroo et al. 2009; Machiwal et al. 2012; Sadat Noori et al. 2013; Yao et al. 2013; Mini et al. 2014) along with deterministic techniques such as IDW and spline methods (Caruso and Quarta 1998; Salah 2009; Sun et al. 2009; Kambhammettu et al. 2011; Burns 2013; Kamińska and Grzywna 2014; Zedek 2014) have been used for groundwater level regionalization. Several interpolation methods have been comprehensively reviewed for groundwater level regionalization by Sun et al. (2009), Fahid et al. (2011), Ahmadian and chavoshian (2012), Burns (2013), Zedek (2014).

Groundwater in the border region of the Sultanate of Oman and the United Arab Emirates (UAE), near Al-Buraimi area, is an utmost important resource for the sustainable agricultural and urban developments. The knowledge about spatial variability of the groundwater level is the first important step for many hydrogeological and hydrological studies. The study area is characterized by the sophisticated unevenly scattered hardrock-alluvium geological setting and the available observation wells are sparse and irregularly distributed over the study area.

Therefore, the main objective of this study was to assess different interpolation methods for groundwater level regionalization for the Al-Buraimi region to obtain accurate groundwater level contour line map as a base map for the hydrogeological studies. Spline, IDW, ordinary kriging (OKrig), and empirical Bayesian kriging (EBK) methods were evaluated for monthly groundwater level regionalization. Also, the existing GLMN for the study area was redesigned using “1-fold cross-validation” technique to recommend the number and locations of new monitoring wells that will provide better quality data compared to the current monitoring network.

Material and methods

Study area

The study area is the Al-Buraimi region which is bounded to the east by the north Oman mountains (NOMs) and to the west by the border with the United Arab Emirates (UAE) (Fig. 1). The study area covers about 1604 km^2 that lies between 24° 2′ N to 24° 38′ N latitude and 55° 44′ E to 56° 14′ E longitude in the northwest of Oman. The area has an arid to semi-arid climate with low humidity and long period of below-average rainfall. Rainfall is highest in the mountains to the east and lowest in the plains to the west. Average annual rainfall ranges from 30 to 178 mm, with an average of 82 mm. Maximum daytime temperature may reach 50 °C in the summer months. The long-term annual evapotranspiration is about 2700 mm. As a result of arid to semi-arid climate, the natural vegetation tends to be fairly sparse, consisting predominantly of acacias and spiny bushes growing in the wadi, name for the ephemeral, beds (Turner et al. 1986; Kaczmarek et al. 1993b; MRMWR 2004).

The geology of the study area is divided into three principal zones that include the Semail Nappes (Ophiolite), the Hawasina Nappes, and the post-nappe strata units (Aruma group, Tertiary and Quaternary Alluvium) (Fig. 1). The term “ophiolite” refers collectively to igneous rock that crops out in the study area with various dark, colored, crystalline, and microcrystalline characteristics. The Hawasina Nappe exposures mainly occur as broken hills in the eastern piedmont zone and they are elongated in a north-south direction. The past-nappe strata consist of the Cretaceous Aruma Group and Tertiary bedrock that were deposited in a foredeep basin downfolded along the frontal margin of the nappes. Folding associated with mountain building in the Late Tertiary turned over the nappes and Tertiary strata into their present structural configurations. Afterwards, erosive processes associated with flowing water led to the deposition of alluvium (collectively to sand, gravel, silt, and clay) throughout the piedmont and alluvial fan zones to the west of the mountains (for more details about mountainous, piedmonts, and alluvial fan zones, refer to the electronic supplementary material, ESM). In terms of regional hydrogeological significance, surface waters running off the mountainous portion of the study area recharge the piedmont and alluvial fan zones. Groundwater recharged into the fractures of the ophiolite during rainfall and runoff events gradually drains laterally and vertically downhill through the fractures towards the plains of the lower basin. Compared to other geological units, the hydrologic properties of the Hawasina Nappes are such that they are less important in terms of groundwater storage and transmission. Tertiary limestones may contain locally significant supplies of groundwater and also limited fractured characteristics. The alluvium in the piedmont and mountain front fan zones is the most important aquifer in the study area and is composed of an unconsolidated mixture of ophiolite, chert, limestone, and dolomite. The thickness of alluvium varies in different places and ranges from 27 to 77 m. Based on aquifer tests, values of hydraulic conductivity (K) for the alluvium aquifer vary from a minimum of 7.79 m/day to a maximum of 43 m/day. The specific yield ranges from 0.01 to 0.039 (Davison 1982; Turner et al. 1986; Kaczmarek 1988; Kaczmarek et al. 1993a, b, c; MRMWR 2004; Onanda et al. 2013).

Dataset and methodology

Monthly groundwater level data from 39 available observation wells were adopted for groundwater level regionalization using spline, IDW, ordinary kriging (OKrig), and empirical

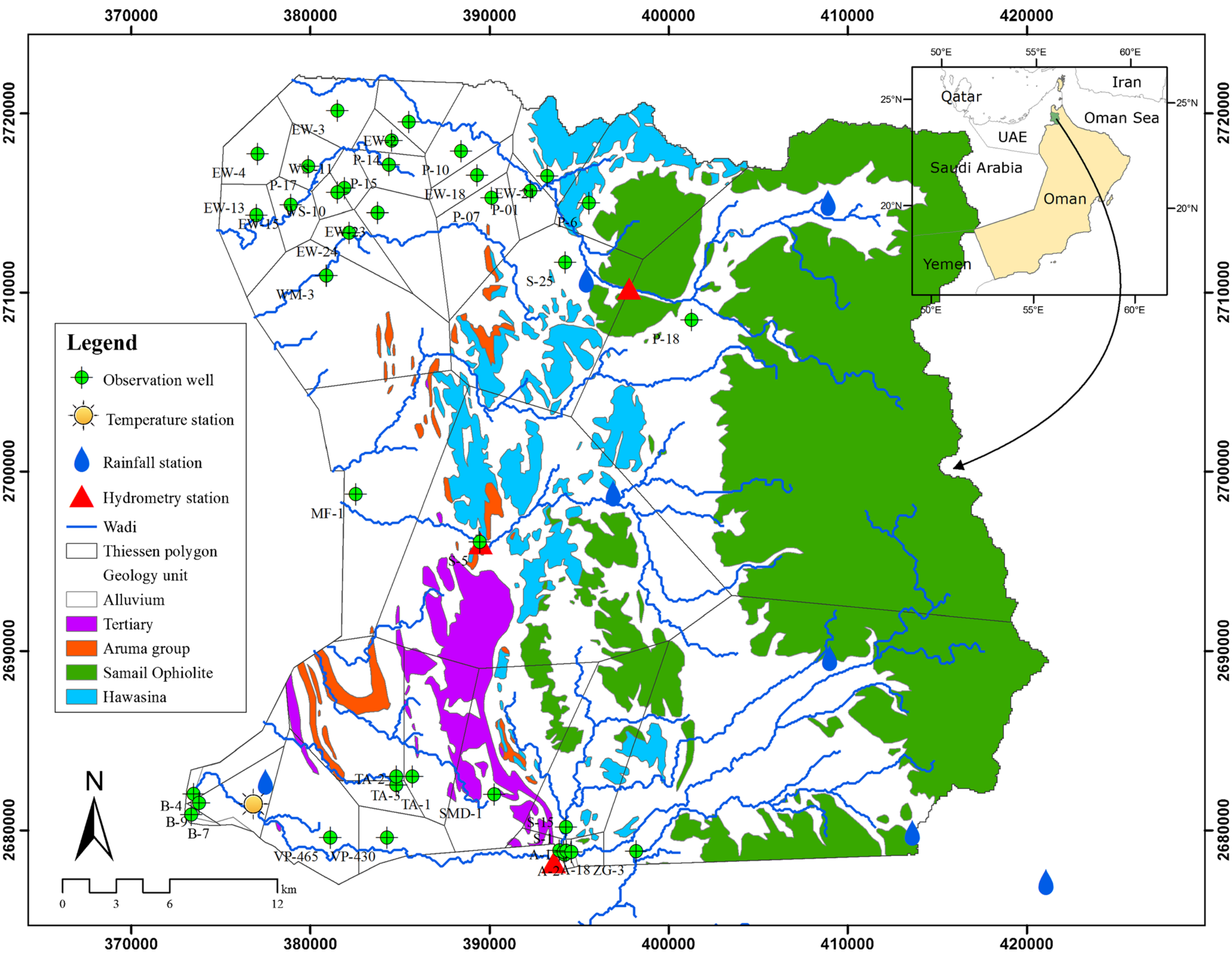

Fig. 1 Location of the study area in Al-Buraimi region, Oman-UAE border along with geological map with meteorological stations, wadi network and observation well

Bayesian kriging (EBK) methods. Six different powers and nine different weight coefficient values were used in the IDW and spline methods to find optimum method for groundwater level regionalization. Different semivariograms in major directions were examined for the OKrig method via GS$^+$ software before using for the regionalization. The following steps were considered for the EBK method: (i) a semivariogram model was estimated using groundwater level data, (ii) based on this semivariogram, a new value was simulated at each of the input data location, and (iii) the new semivariogram was estimated according to the simulated data. The semivariogram estimated in the first step was used to simulate a new set of values at the input location during the repetition of steps two and three. A new semivariogram model and its weight were produced given the simulated data. During this process, the predictions and their respective standard errors were produced at the unsampled locations. This process created a spectrum of semivariograms. The log empirical transformation method and K-Bessel semivariogram model were considered to get the most accurate results for the groundwater level regionalization as suggested by Pilz and Spock (Pilz and Spöck 2008) and Chiles and Delfner (2009).

Figure 2 shows a seven-step procedure to apply "1-fold cross-validation" technique for the monthly groundwater level regionalization for Oct. 2008 to Sep. 2013 period to redesign the existing GLMN. Step 1 is responsible to generate monthly raster maps and requires monthly groundwater level data and study area boundary. Also, a regionalization method, IDW, spline, OKrig, and EBK, is selected in this step in which desired settings are re-adjusted for the selected interpolation method (see Figs. S1 and S2 of the ESM). Monthly groundwater level value, as *dbf* format tables, was extracted in step 2 for the left-out observation well for the mentioned period from the generated raster maps (see Fig. S3 of the ESM). Step 3 is aimed at converting dbf tables to the xls tables (see Fig. S4 of the ESM). All xls tables are combined together using a written python code in IDLE (integrated development environment) python shell in step 4 to generate a single xls table. Two

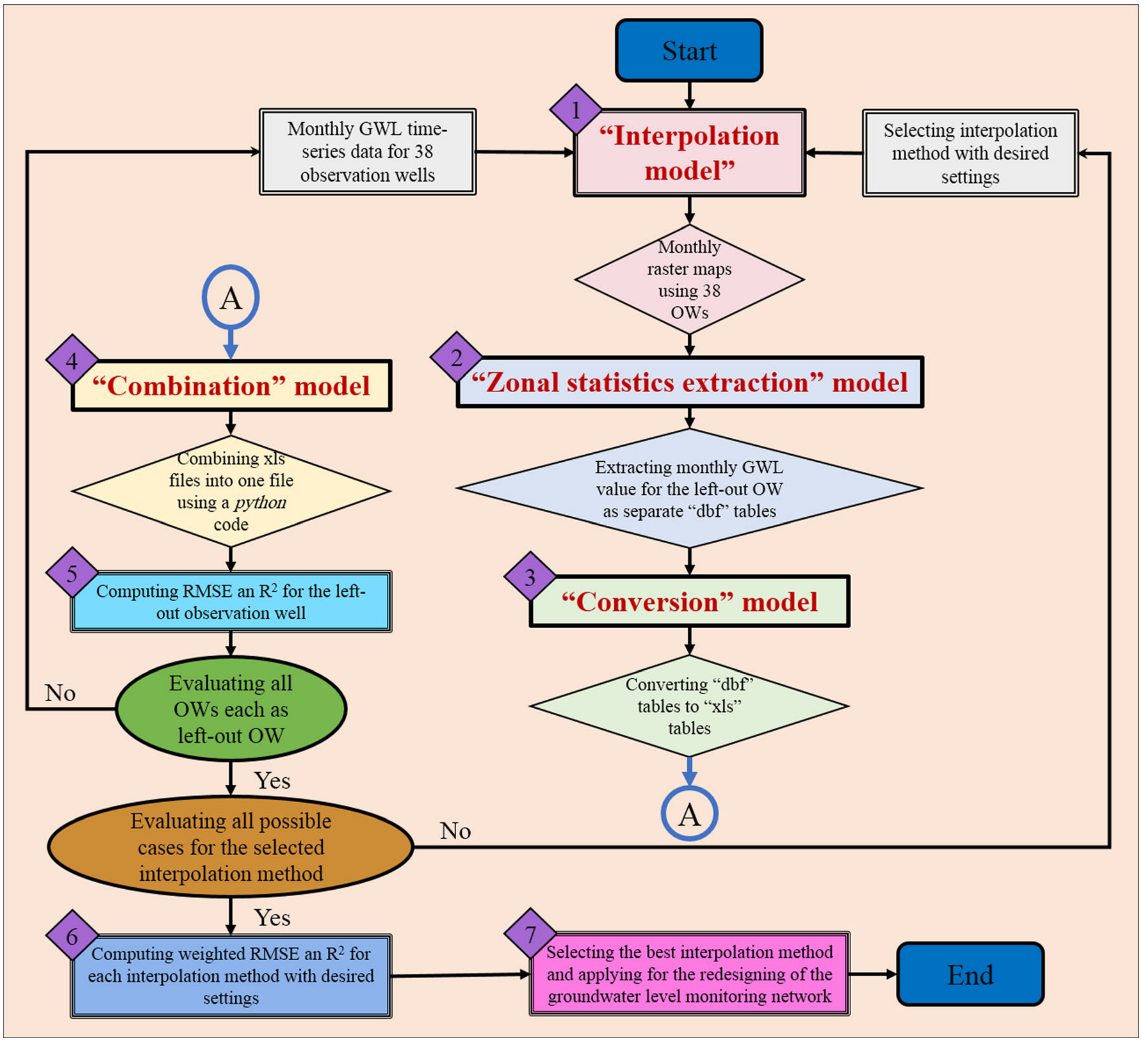

Fig. 2 Schematic diagram of the adopted procedure to apply "1-fold cross-validation" technique for the monthly groundwater level regionalization to evaluate the groundwater level monitoring network

different performance criteria consisting of coefficient of determination (R^2) and root mean square error (RMSE) are computed in step 5 with respect to observed monthly time-series groundwater level data for the left-out observation well.

Steps 1 to 5 are repeated for all 39 observation wells considering each time one left-out observation well with similar selected interpolation method with its desired settings (say, IDW with power coefficient 0.5). All steps are repeated with the same interpolation method with different settings (say, IDW with power coefficient 1.0). This process is repeated to consider all interpolation methods with desired settings for each method (say, spline and then other methods). A weighted average method is used in step 6 for the overall performance of each interpolation method with desired settings as follows:

$$\text{Weighted RMSE} = \frac{\sum_{i=1}^{n} \text{RMSE}_i \times a_i}{A} \tag{1}$$

$$\text{Weighted } R^2 = \frac{\sum_{i=1}^{n} R_i^2 \times a_i}{A} \tag{2}$$

where i refers to the Thiessen polygon (observation well), n and a are the number and area of Thiessen polygons, respectively, and A is the total area.

An interpolation method with the lowest and highest weighted RMSE and R^2 is selected in step 7 to evaluate and redesign the existing GLMN. Afterward, spatial distribution of the RMSE values is assessed for each observation well for the selected interpolation method. It is obvious that the smaller RMSE values imply the lesser importance of the specific observation well for the groundwater level regionalization. Conversely, observation wells within areas where the RMSE is considerable are critical for the groundwater level regionalization. In other words, observation wells within areas of small RMSE values can be excluded from the existing GLMN, whereas areas of large RMSE values are in need of a denser GLMN.

Regionalization methods

Kriging is a linear unbiased method to estimate the value of regionalized variables at an unsampled location based on the available data of regionalized variables and structural features of a variogram. The main tool in kriging is the variogram, which expresses the spatial dependence between neighboring observations. The variogram can be defined as one half of the variance of the difference between the attribute values at all points separated by distance *h* (Goovaerts 1997). Prior to kriging estimation, a model is required to compute a variogram value for any possible sampling interval. The most commonly used models are the spherical, exponential, Gaussian, and pure nugget effect.

Empirical Bayesian kriging (EBK) is a geostatistical interpolation method that automates the most difficult aspects of building a valid kriging model. In addition to accounting for the uncertainty in the underlying semivariogram parameters, the other main redeeming feature of EBK is the parameters in the EBK that are automatically optimized through a sub-setting and simulation process which is implemented by estimating a lot of semivariogram models instead of a single semivariogram (Chiles and Delfiner 2009; Pilz and Spöck 2008). For a given distance, *h*, EBK supports power, linear, thin plate spline, exponential, whittle, and K-Bessel semivariogram models. Among all these semivariogram models, the K-Bessel model offers most flexible and accurate transformation, although it is known to take the longest calculation time (Pilz and Spöck 2008; Chiles and Delfiner 2009).

The spline method is a well-developed technique capable of producing smooth derivatives with a minimum number of node points. There are two regularized and tension spline methods. The regularized method creates a smooth, gradually changing surface with values that may lie outside the sample data range. The tension method controls the stiffness of the surface according to the character of the modeled phenomenon. It creates a less smooth surface with values more closely constrained by the sample data range (Franke 1982; Mitas and Mitasova 1988).

Inverse distance weighted (IDW) method is based on the assumption that the value of an attribute at an unsampled point can be approximated by a weighted average of measured values within a circular search neighborhood (Munch 2004) (for more details about the theory of the adopted interpolation methods, refer to the ESM).

Results and discussion

Ordinary kriging method

Regarding the "1-fold cross-validation" technique and 39 different monthly groundwater level datasets, different semivariograms were tested in different directions for each dataset to check the anisotropy for the OKrig method before using for the groundwater level regionalization. Table 1 shows the range of semivariogram parameters fitted to the 39 different monthly groundwater level datasets. After analyzing different models in different angles, it is found that the exponential model with the angle range of 2.21° to 12.12° is the best for the 39 different monthly groundwater level datasets because of high RSS (root mean square standardized) and R^2 performance criteria (Table 1). The parameters of the best-fit exponential model for all 39 different monthly groundwater level datasets are also given for more analysis (see Table S1 in the ESM). Nugget shows no change for the different months during the period Oct. 2008 to Sep. 2013. Also, lag and range parameters have similar trend, ranging from 2705 to 2759 and 32,468 to 33,112, respectively, except for June 2011 to August 2011. The sill parameter ranges from 0.027 to 0.030. The experimental semivariograms for some groundwater level datasets are shown in Fig. 3.

OKrig method is applied for the groundwater level regionalization with respect to the best-fit exponential semivariogram parameters (Fig. 4). It is observed that groundwater flow direction is from east to west. Groundwater recharged into the hardrock fractures, located at the east, during precipitation and runoff events gradually drains downhill through the fractures towards the plains of the basin. In fact, lateral groundwater flow from the hardrock fractures in the mountain basins is the recharge source for the alluvial fan aquifer. The average groundwater gradient is 0.008 m/m from east to west. The gradient starts to decrease in the middle part and becomes least in the western part of the study area.

Spatial distribution of the RMSE for the left-out observation wells based on "1-fold cross-validation" technique is shown in Fig. 4 for the Oct. 2008 to Sep. 2013 period. It can be seen that wells MF-1, P-6, ZG-3, P-18, and TA-3 show highest RMSE when they were not considered in the raster generation process. Most of these observation wells (P-18, P-6, and ZG-3) are located at the piedmont alluvium zone between mountainous and alluvial fan zones. The piedmont alluvium zone at the mountain front is hydrologically important in that it acts as a transition zone for both surface water and groundwater that provides the alluvium downstream with adequate groundwater recharge and storage. Therefore, these wells should be taken into account for the groundwater level regionalization and GLMN needs to be denser around these wells based on the OKrig method results. The weighted RMSE for the whole area based on "1-fold cross-validation" technique is 14.87 m. The variance of RMSE for the left-out observation wells is 81.45 m^2 (Table 2).

Empirical Bayesian kriging method

As stated earlier, empirical Bayesian kriging (EBK) is a geostatistical interpolation method that automates finding

Table 1 Properties of the different fitted semivariograms for the ordinary kriging method

Model	Nugget	Lag (m)	Sill	Range (m)	R^2 (%)	RSS[a]
Exponential	0	(2688–2814)	(0.0260–0.0304)	(32,256–33,769)	(85–91)	(0.47–0.50)
Gaussian	0.0001	(2627–2907)	(0.0300–0.0378)	(21,850–34,893)	(57–66)	(1.30–1.60)
Spherical	0.0009	2770	(0.0955–0.1674)	(33,244)	(92)	(0.47)
Circular	0	(2723–2814)	(0.0297–0.0300)	(32,681–33,769)	(91–92)	(0.51–0.52)

[a] RSS is acronym for root mean square standardized

optimal semivariogram parameters by estimating a lot of semivariogram models instead of a single semivariogram. The K-Bessel semivariogram model, suggested by Chiles and Delfiner (2009) and Pilz and Spöck (2008), was considered to get the most accurate results for the groundwater level regionalization. Figure 5 shows the experimental semivariograms for some groundwater level datasets. The EBK creates several semivariograms for each dataset and the distribution of semivariograms are shaded by density in which the darker the blue color, the more semivariograms pass through that region. Also, the median of the distribution is colored with a solid red line and the 25th and 75th percentiles are colored with red dashed lines.

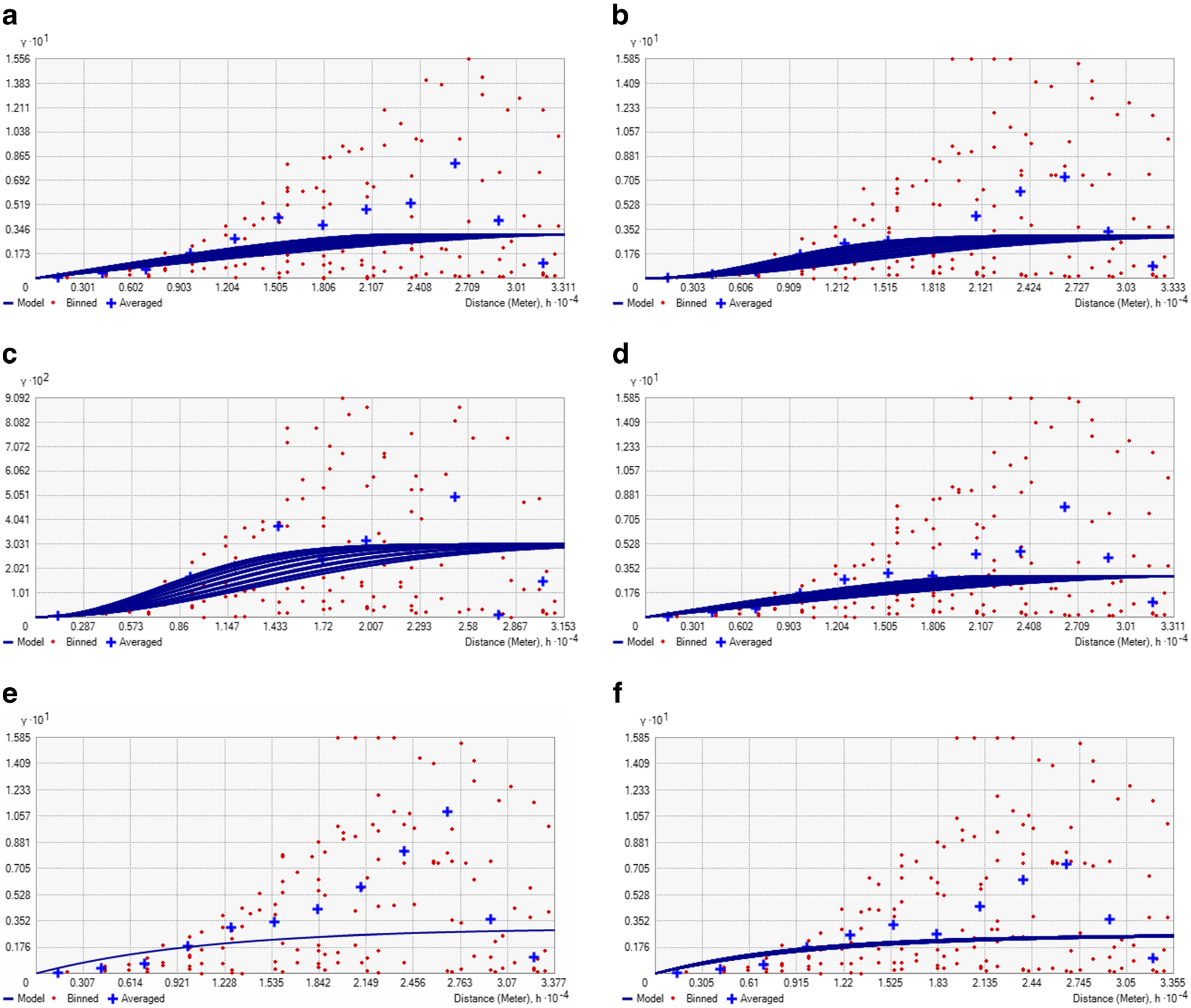

Fig. 3 Experimental and fitted semivariogram for different data sets, **a** without MF-1 OW, **b** without P-6 OW, **c** without P-18 OW, **d** without ZG-3 OW, **e** without S-5 OW, and **f** without S-25 OW, respectively. *OW* is the acronym for the observation well

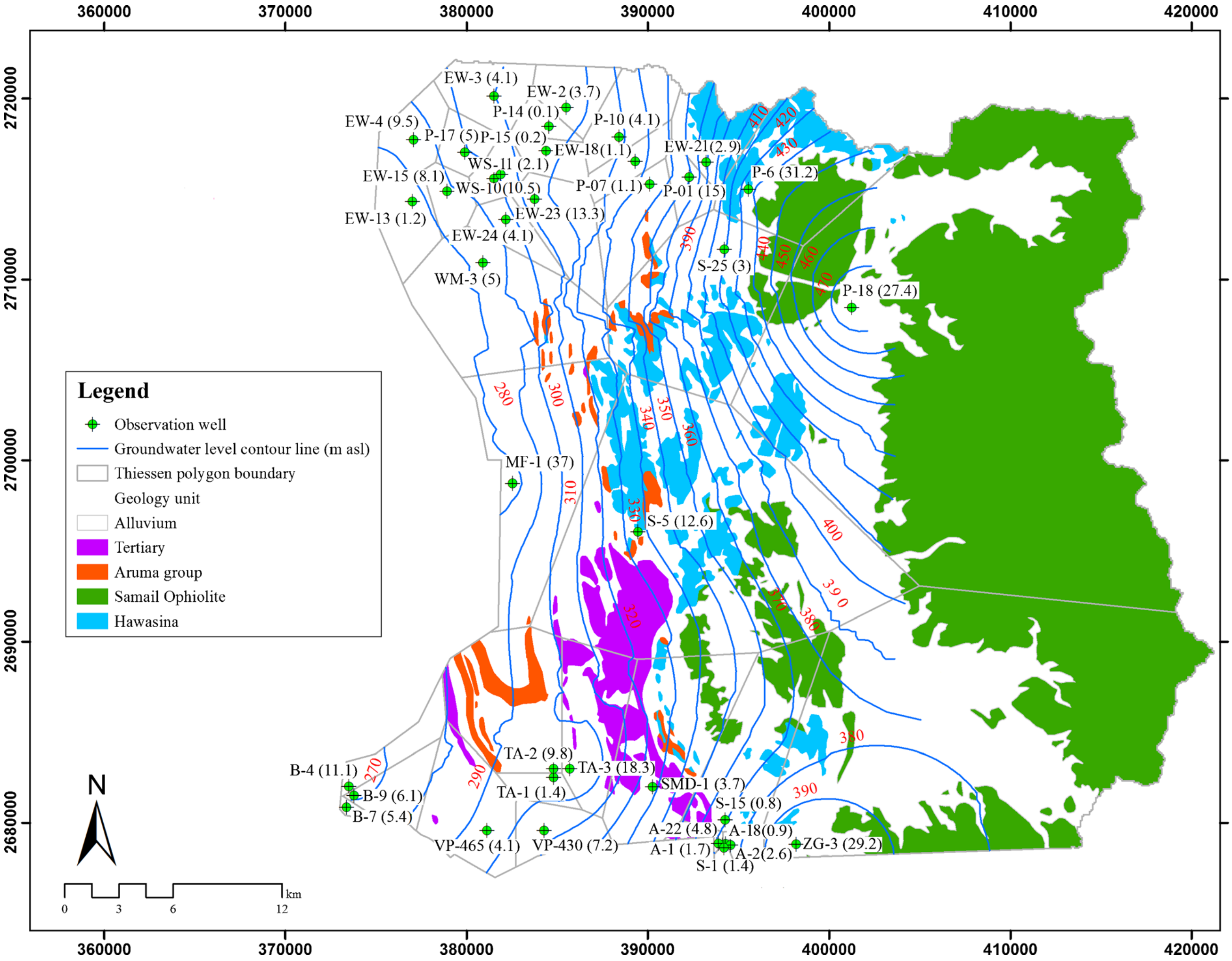

Fig. 4 Groundwater level regionalization using ordinary kriging method with best-fit exponential semivariogram parameters along with spatial distribution of the RMSE for each left-out observation wells based on "1-fold cross-validation" technique. *Numbers in the parenthesis* beside observation well's name are the RMSE performance criteria (unit in meter)

The EBK method is used for the groundwater level regionalization regarding the best-fit K-Bessel semivariogram parameters (Fig. 6). The comparison of EBK map with the map obtained by OKrig indicates that EBK produces smoother map for the whole area. The contour lines vary sharply in central part of the study area based on OKrig map (Fig. 4), while there is a smooth variation for the whole area in the EBK-generated contour lines (Fig. 6). Also, groundwater flow direction is clearly observed from east to west indicating that the NOMs are the source of the recharge to the alluvial fan zone aquifer. The weighted RMSE for the whole area based on "1-fold cross-validation" technique is 10.84 m that shows decreasing trend for the similar observation wells using the OKrig method (Table 2). The variance of RMSE values for the left-out observation wells was evaluated (Table 2). This quantity indicates less variation (45.56 m^2) in comparison with the OKrig method (81.45 m^2). Spatial distribution of the RMSE for the left-out observation wells based on "1-fold cross-validation" technique is shown in Fig. 6. It is observed that wells MF-1, P-6, P-18, and TA-3 show the highest RMSE;

Table 2 Performance statistics for the different best selected interpolation methods based on "1-fold cross-validation" technique

Model	Weighted R^2 (%)	Weighted RMSE (m)	RMSE variance (m^2)
Ordinary Kriging	76	14.87	81.45
Empirical Bayesian Kriging	79	10.84	45.56
Tension Spline Weight 1.0	65	11.79	57.47
IDW Power 3.0	75	43.82	339.14

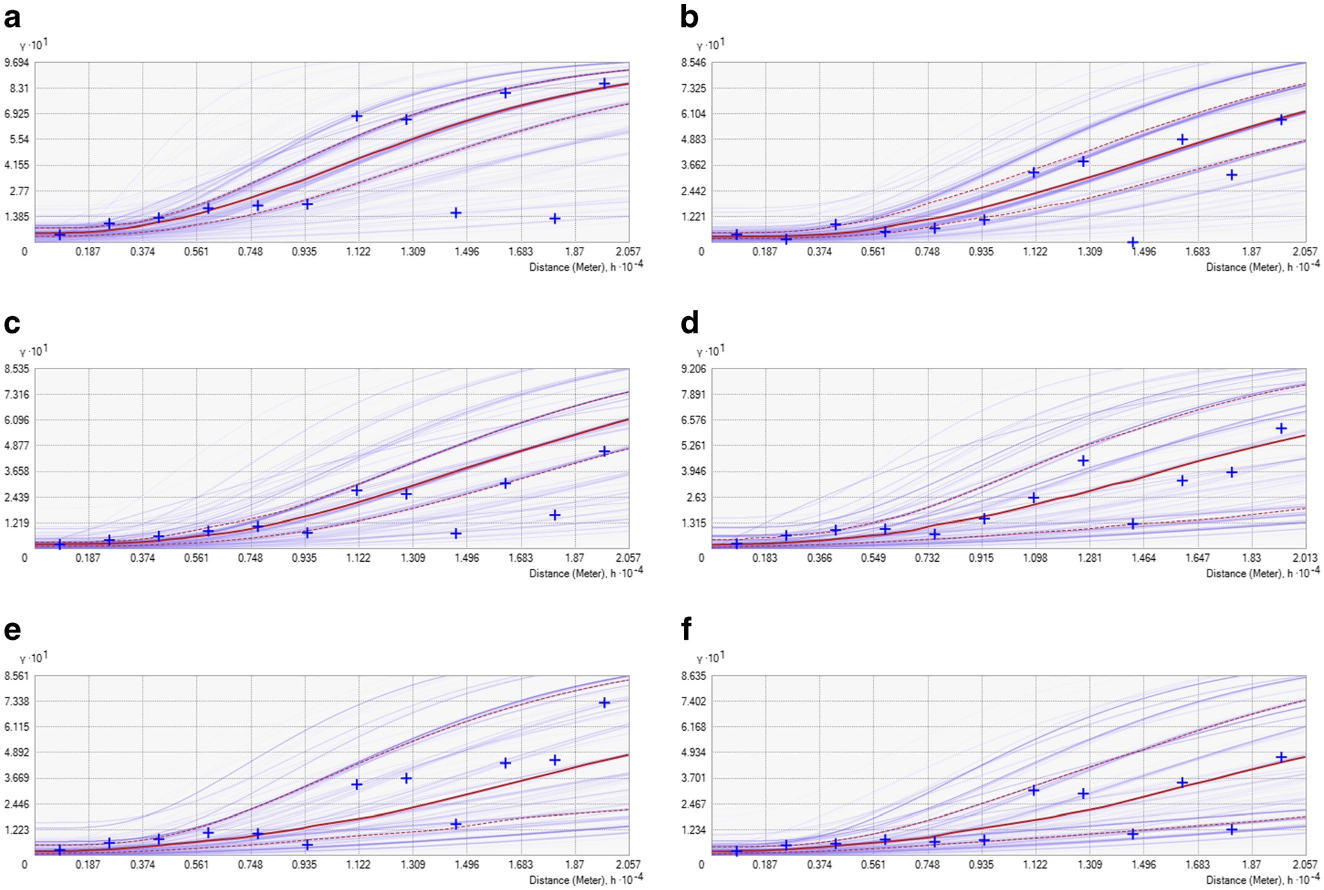

Fig. 5 Experimental (*blue cross*) and several fitted (*blue line*) semivariogram for **a** without MF-1 OW, **b** without P-6 OW, **c** without P-18 OW, **d** without ZG-3 OW, **e** without S-5 OW, and **f** without S-25 OW data sets, respectively . Note that the median of the distribution is colored with a *solid red line*, and the 25th and 75th percentiles are colored with *red dashed lines*

however, their RMSE values are decreased in comparison with the OKrig method. Hence, the EBK method confirms that these wells also must be considered for the groundwater level regionalization.

Spline method

With respect to the "1-fold cross-validation" technique and two different regularized and tension spline methods with different weight coefficients, 21,060 groundwater level raster maps were generated to find the best condition for the groundwater regionalization. Table 3 shows performance statistics of different *1-fold cross-validated* models based on various weight coefficients for two different spline methods. The tension spline method with weight coefficient 1.0 is superior among the others as it led to the minimum RMSE.

Figure 7 shows generated groundwater contour lines using tension spline method with weight coefficient 1.0 for the September 2013. The patterns of spatial variation of groundwater level are similar to the OKrig and EBK methods. However, there is an isolated point around TA series observation wells in the south. The weighted RMSE for the whole area based on "1-fold cross-validation" technique is almost similar to the EBK method (10.84 m). However, the RMSE value is increased for the same observation wells (MF-1, P-6, P-18, and TA-3) with the highest RMSE in the EBK method (Fig. 7). Similar to the OKrig and EBK methods, this method also confirms the importance of MF-1, P-6, P-18, and TA-3 observation wells in the generating groundwater contour line for the study area.

Inverse distance weighted method

Table 3 shows weighted performance statistics for the left-out observation wells based on "1-fold cross-validation" technique for the different power coefficients in the IDW method. The IDW with power coefficient 3.0 has the best performance among the other coefficients. However, the accuracy of the best selected IDW method for the groundwater level regionalization is poor in comparison with the three adopted methods. Figure 8 shows the generated groundwater level contour lines using IDW with power coefficient 3.0 along with spatial distribution of the RMSE for the left-out observation wells. There are several isolated points in different parts

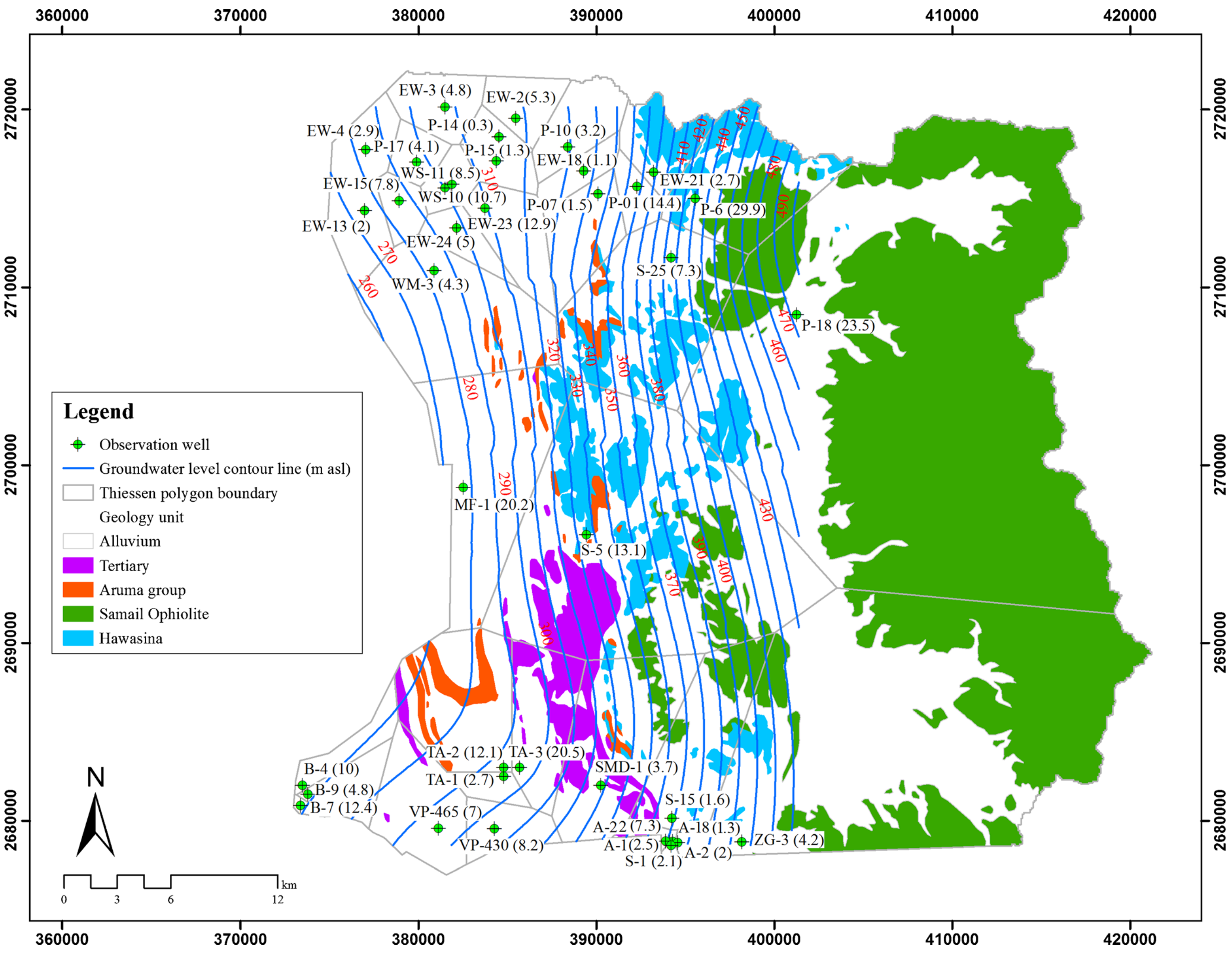

Fig. 6 Groundwater level regionalization using empirical Bayesian kriging (EBK) method with best-fit K-Bessel semivariogram parameters along with spatial distribution of the RMSE for each left-out observation wells based on "1-fold cross-validation" technique. *Numbers in the parenthesis* beside observation well's name are the RMSE performance criteria (unit in meter)

Table 3 Performance statistics of two type spline and IDW interpolation methods based on "*1-fold cross-validation*" technique

Model	Weighted R^2 (%)	Weighted RMSE (m)
Regularized Spline Weight 0.0	59	20.69
Regularized Spline Weight 0.001	54	29.31
Regularized Spline Weight 0.01	48	50.83
Regularized Spline Weight 0.1	47	77.61
Regularized Spline Weight 0.5	45	57.21
Tension Spline Weight 0.0	52	18.09
Tension Spline Weight 1.0	65	11.79
Tension Spline Weight 5.0	62	19.82
Tension Spline Weight 10.0	63	23.93
IDW Power 0.5	69	55.54
IDW Power 1.0	72	51.10
IDW Power 1.5	73	48.07
IDW Power 2.0	74	46.05
IDW Power 2.5	74	45.09
IDW Power 3.0	75	43.82

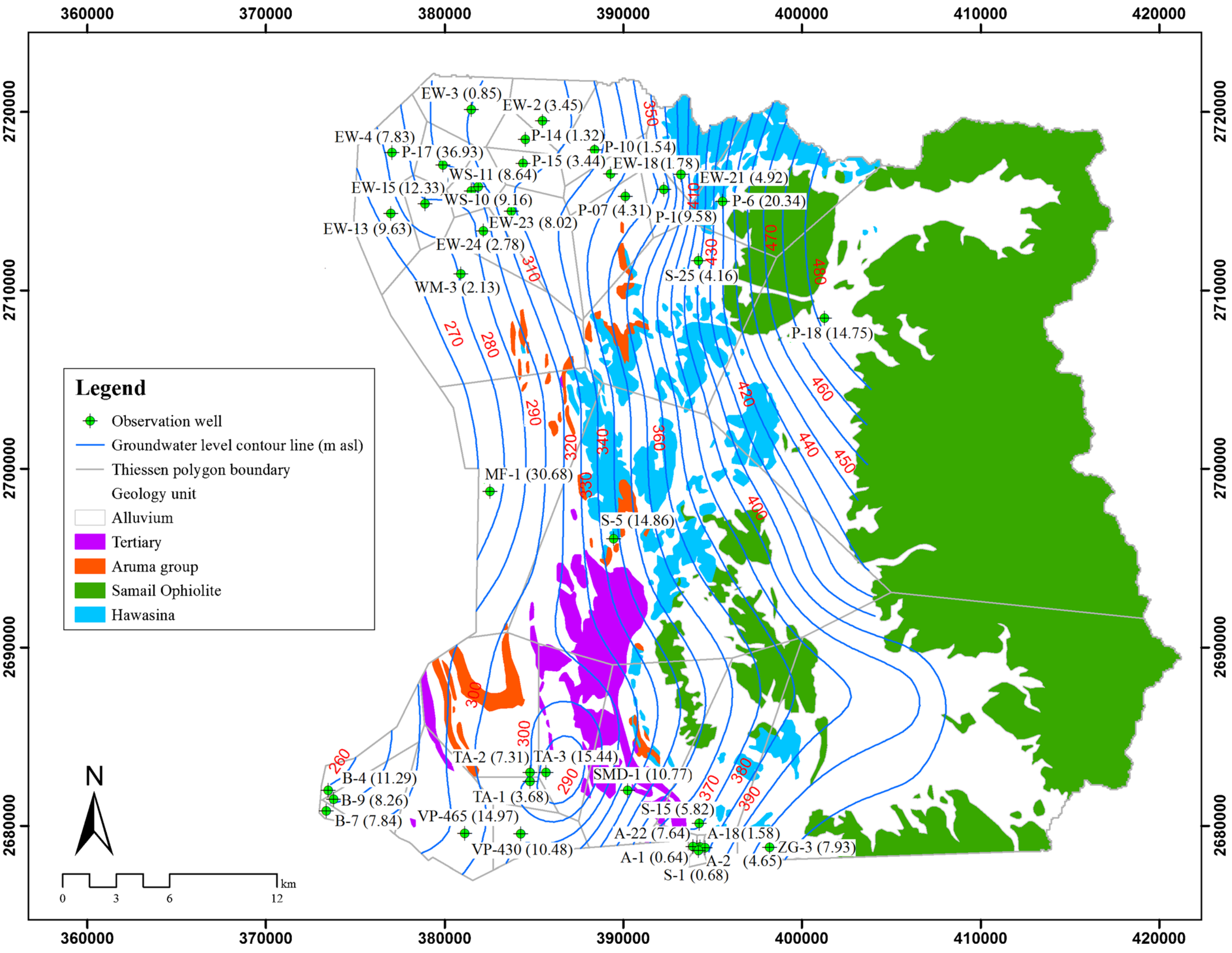

Fig. 7 Groundwater level regionalization using tension spline method with weight coefficient 1.0 along with spatial distribution of the RMSE for each left-out observation wells based on "1-fold cross-validation" technique. *Numbers in the parenthesis* beside observation well's name are the RMSE performance criteria (unit in meter)

of the study area in which the RMSE value is very high especially for the wells P-18, P-6, MF-1, P-17, ZG-3, S-5, and S-25. Also, the variance of RMSE is considerable (Table 2) that means exclusion of some observation wells significantly affects the groundwater level regionalization using IDW method.

Evaluation of groundwater monitoring network

Table 2 shows performance statistics of all interpolation methods for the groundwater level regionalization. It shows that the application of IDW method for the groundwater level regionalization might not be suitable for the area under investigation that is characterized by geological diversity. The EBK method is selected as the most reliable method to evaluate and redesign the existing GLMN. This finding confirms the results of Burns (2013) and Zedek (2014) and indicates that geostatistical methods have a higher general accuracy when utilizing the EBK method. Table 4 shows the descended RMSE values for all observation wells as the left-out observation well based on "1-fold cross-validation" technique (See Table S2 and Fig. S5 of the ESM). Analyzing results in Table 4, areas that need installment of additional observation wells can be easily identified on the basis of high RMSE. However, low RMSE indicates areas with dense observation wells. In such case, a "secondary observation network" may be considered, which means groundwater levels are infrequently measured instead of regularly. In the areas of higher RMSE, wells MF-1, P-6, ZG-3, and P-18, the GLMN needs to become denser by including more observation wells. In areas of lower RMSE, wells P-14 and P-15, the observation well can be excluded from the GLMN or considered the option of infrequently measuring groundwater level (e.g., seasonally). Obviously considering the "secondary observation network" can significantly reduce

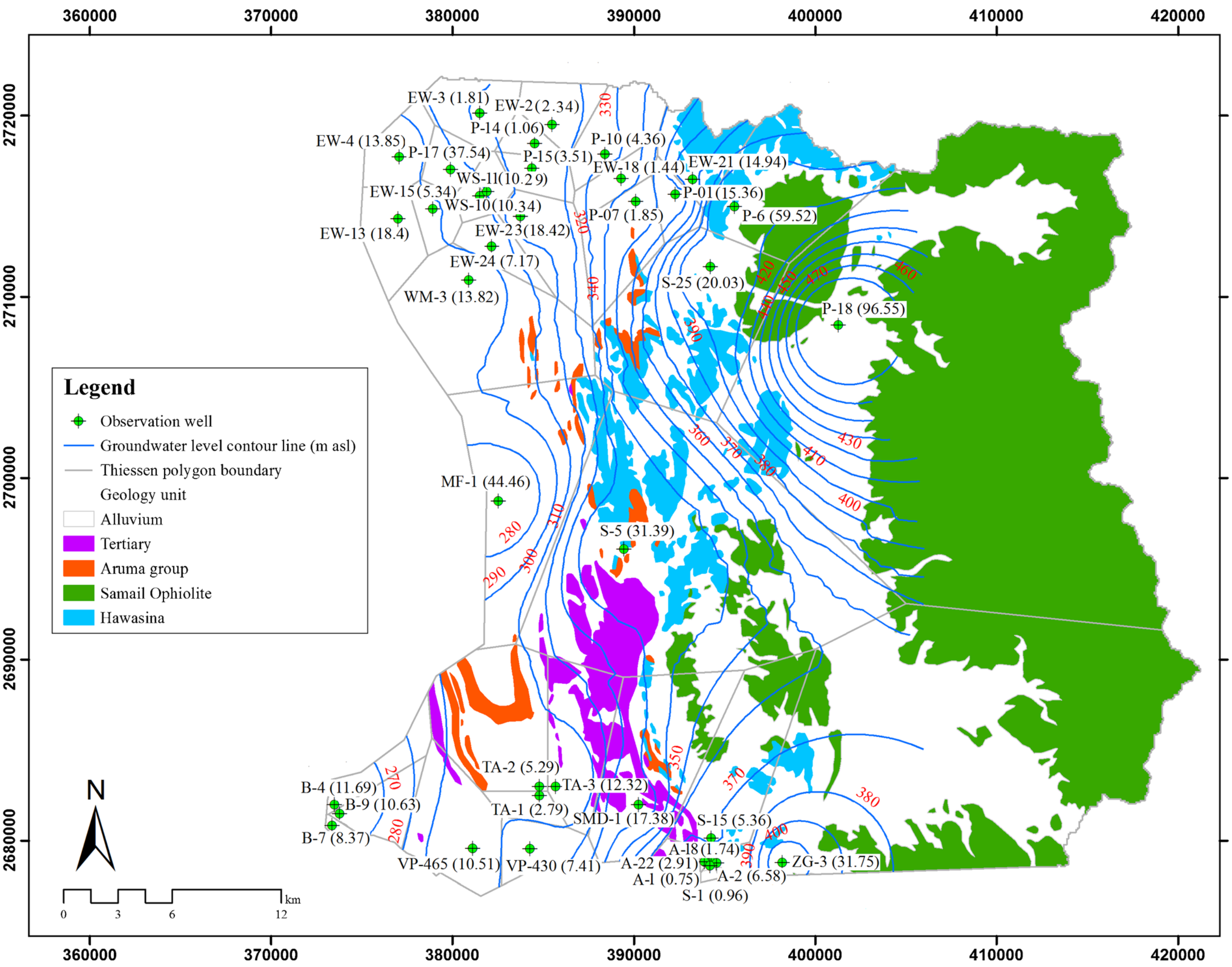

Fig. 8 Groundwater level regionalization using IDW method with power coefficient 3.0 along with spatial distribution of the RMSE for each left-out observation wells based on "1-fold cross-validation" technique. *Numbers in the parenthesis* beside observation well's name are the RMSE performance criteria (unit in meter)

Table 4 The descended RMSE value of all observation wells as left-out observation well using EBK interpolation method based on "1-fold cross-validation" technique

OW name	RMSE (m)	OW name	RMSE (m)	OW name	RMSE (m)
MF-1	37	VP-430	7.2	EW-21	2.9
P-6	31.2	B-9	6.1	A-2	2.6
ZG-3	29.2	B-7	5.4	WS-11	2.1
P-18	27.4	P-17	5.0	A-1	1.7
TA-3	18.3	WM-3	5.0	S-1	1.4
P-01	15	A-22	4.8	TA-1	1.4
EW-23	13.3	EW-24	4.1	EW-13	1.2
S-5	12.6	EW-3	4.1	EW-18	1.1
B-4	11.1	P-10	4.1	P-07	1.1
WS-10	10.5	VP-465	4.1	A-18	0.9
TA-2	9.8	EW-2	3.7	S-15	0.8
EW-4	9.5	SMD-1	3.7	P-15	0.2
EW-15	8.1	S-25	3	P-14	0.1

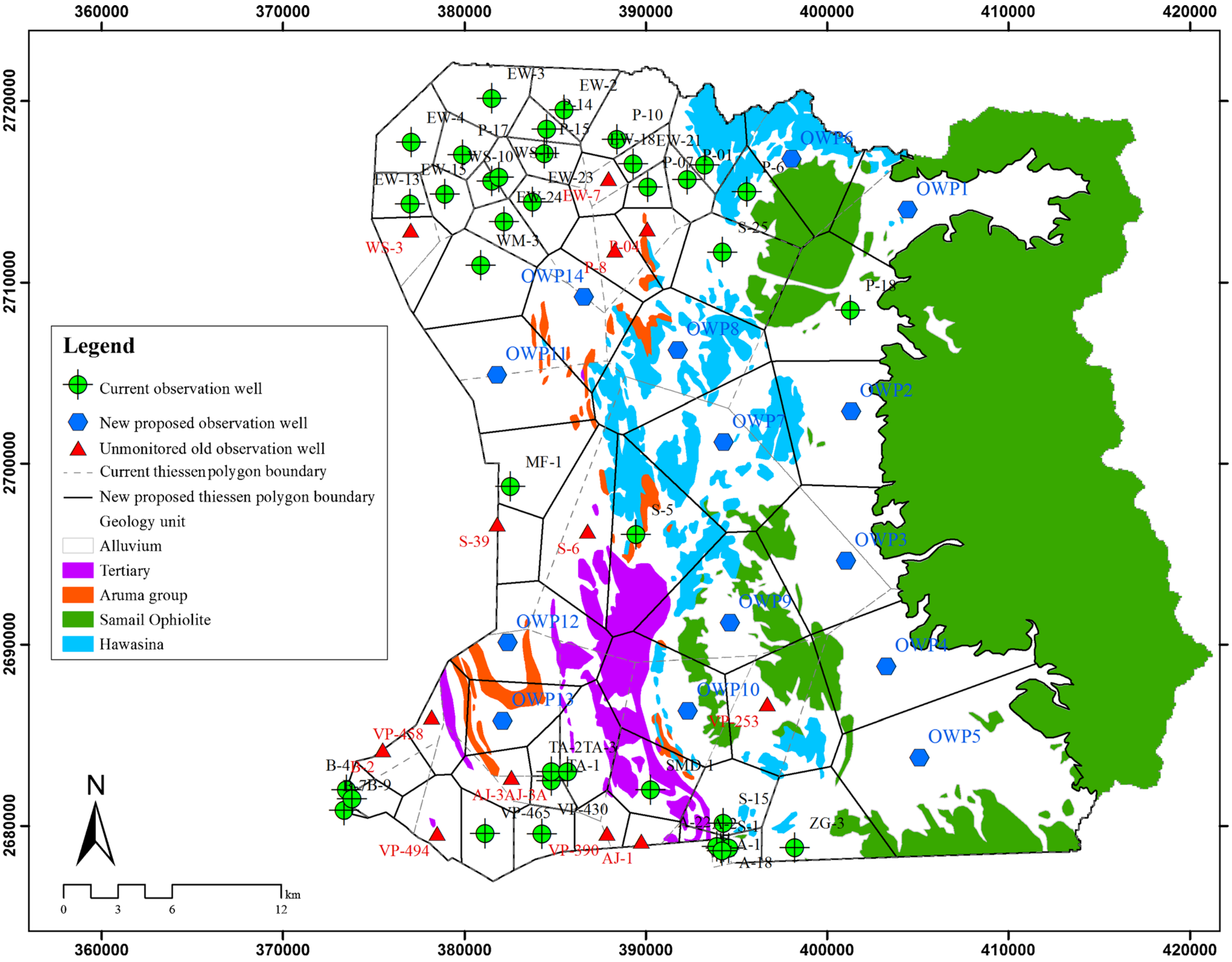

Fig. 9 The new proposed groundwater level monitoring network based on 1-fold cross-validated empirical Bayesian kriging (EBK) method

both time and cost. Optimally, before fully installing observation network, one should go for preliminary assessment through drilling a few wells. The application of current method is beneficial to cut drilling cost, optimize well locations, and, later, help in designing monitoring programs.

As mentioned earlier, most of the observation wells are clustered in groups and their distribution is not even over the study area. This is probably due to the fact that no distinctive program was considered for the installation of observation wells so far and the main focus of previous studies was to drill in areas where maximum yield was expected. Figure 9 shows the proposed GLMN consisting of current observation wells (green points), new proposed observation wells (blue points), and unmonitored old observation wells (red points). The unmonitored old observation wells need rehabilitation and maintenance before use. Nonetheless, this is cost effective compared to drilling new wells. Subsurface inflow from the eastern ophiolite mountainous part to the downstream alluvial aquifer is the source of groundwater recharge into the piedmont and alluvial fan zone aquifers. A dense GLMN near to the NOMs boundary is required to estimate the subsurface inflow. Therefore, observation wells P1 to P5 are proposed to understand spatial variations of groundwater level in this part of study area to better assess such recharge and assist in future plans. The observation well P-6 shows the second highest RMSE area and the new well OWP6 is proposed to enhance the GLMN. There is no information about the behavior of groundwater in Hawasina formation. Hence, observation wells P7 and P8 are suggested in pure Hawasina formation part to obtain more valuable information about the interaction between alluvium and Hawasina as well as the variation of groundwater level. Similarly, observation wells P9 and P10 and also P13 are considered to achieve information about the crustal sequence ophiolite and upper Cretaceous Aruma group formations, respectively. The west part of the study area is located at the border of Oman-UAE and observation wells P11 to P12 are proposed to estimate groundwater outflow from Oman-UAE border towards the UAE side. Groundwater flow crossing the border is the main natural discharge and apparently has greater influence as indicated by the highest RMSE reported in well MF-1.

Conclusion

A comparative analysis of IDW, spline, OKrig, and EBK interpolation methods was investigated for the groundwater level regionalization in an arid hardrock-alluvium Al-Buraimi region, Oman-UAE border. The "1-fold cross-validation" technique was adopted to regionalize the groundwater level in which single observation well was left-out each time and 38 observation wells were used for the regionalization. The weighted RMSE and R^2 criteria indicate that the overall performance of the EBK interpolation method is better than other methods. The current GLMN is optimized and redesigned and then new additional observation wells are proposed. It is determined that adding new wells in areas where no monitoring wells currently exist would result in a spatial distribution of wells that would better define the regional potentiometric surface of the study area. Also, the better spatial distribution and increased number of wells would improve the quality of groundwater level data measured over time. The idea of a "secondary observation network" is presented in which both time and cost needed to each groundwater level measurement can be properly utilized without significant loss of information. In fact, it is recommended that groundwater levels can be measured frequently (e.g., seasonally) at wells P-14 and P-15. The recommended optimum monitoring network consists of 14 new wells and 14 unmonitored old wells added to 39 existing wells, which would result in a network of 67 wells that would improve the quality of collected groundwater level data needed for the groundwater flow modeling.

It is important to highlight that the success of any groundwater flow modeling is strictly related to the accuracy of the groundwater level data as a base map for starting head. Therefore, the proposed approach in this study can be used not only for the comparison of different interpolation methods to find the accurate one but also for the evaluation and optimization of the existing GLMN. It is safely applicable for existing or newly designed networks and can lead to the optimization of the GLMN by integrating (or adding) absolutely necessary observation well locations' and measurements' frequency. This will enhance the understanding of groundwater system behavior and water balance assessments leading to better decision-making.

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