Hydraulic conductivity estimation by using groundwater modelling system program for upper zone of Iraqi aquifers

T S Khayyun¹ and H H Mahdi²

¹Civil Engineering Department, University of Technology, Baghdad, Iraq. Email: thshkhma@yahoo.com
²Civil Engineering Department, University of Technology, Baghdad, Iraq. Email: Hasan.hadi3@gmail.com

Abstract. Estimating of soil hydraulic conductivity was so important and essential parameter for designing systems. Hydraulic conductivity measurements need many activities beginning from extract samples. Therefore it has been found costly and time-consuming. At the present time, geo-statistical ways were used to estimate the hydraulic conductivity on the basis of restricted data. The aim of this research is to characterize hydraulic conductivity for the upper zone of Iraqi aquifers using groundwater modelling system (GMS) software and to build two dimensions geo-statistical analysis model depending on the application of 868 wells. These wells were divided into 778 wells for building the model and 90 wells for the verification. The hydraulic conductivity parameter which was obtained from the geo-statistical analysis model results indicated that the best fitted theoretical model was the inverse distance weighted (IDW) model with a coefficient of determination (R²) equal to 87.43% and root mean square error (RMSE) equal to 1.853. Also, by conducting many trails, it was found that the optimal distance range for estimating the hydraulic conductivity was 3800 to 5000 meters. A comparison between the kriging and IDW interpolation methods indicated that both methods could estimate the hydraulic conductivity with good accuracy and less error.

1. Introduction

In general, estimating reliable hydraulic conductivity value is one of the fundamental challenges in groundwater modelling applications. Hydraulic conductivity parameter often varies intensely and exhibits spatial variations at an extent range of spatial scales. It is the most important factor for modelling soil hydraulic properties in saturated and unsaturated soils as in [37]. At the level of national scales of tens to hundreds of kilometres and at depths greater than one kilometre, the field information on hydraulic conductivities is relatively scarce as in [11]. Maps of Hydraulic conductivity at such scales of extent areas and depths are usually generated through numerical models that attempt to reflect the geological structure of the region and are simultaneously calibrated on both, natural tracer concentrations and hydraulic heads as in [9]. In a popular of hydrologic cycle models, soil hydraulic conductivity can be considered as constant (homogeneous) within an area of 100 to 10,000 km² and, this may lead to inappropriate results as in [8]. References [6], [10], [11], [12], [13], [28], [29], [30], [31], [32], [33], [34], [38], [41], [42] and [43] studied hydraulic conductivity variability in heterogeneous aquifers. They were used interpolation estimation procedures such as co-kriging, Inverse Distance Weighted (IDW), Local Polynomial Interpolation (LPI), Global Polynomial Interpolation (GPI), Radial Basis Functions (RBF) and spatial kriging. The results showed that the use of these interpolation methods yields best assessments and a good agree with the results of experimental pumping test, therefore this agreement proves that the distribution of hydraulic conductivity can be estimated economically and
efficiently in a difficult and wide area. The aim of this study is to characterize hydraulic conductivity for upper zone of Iraqi aquifers within the thickness of one hundred meters by using GMS software to build two dimensions geo-statistical analysis model depending on available actual field data obtaining from the investigation of drilled wells.

![Figure 1. Iraq location map.](image1)

![Figure 2. Iraq main topographical areas map.](image2)

2. Study area
The Republic of Iraq is located in the Middle East at the northernmost extent of the Arabian Gulf, west of Iran, east of Syria, north of Saudi Arabia, and south of Turkey, (figure 1). The total area of Iraq catchment is 437,072 square kilometres, containing 432,162 square kilometres of the land surface as in [48] and [49]. Iraq has four foremost topographical areas: desert region, uplands region, northern highlands, and the alluvial plain (Mesopotamia), (figure 2), as in [48]. The climate in Iraq is mainly of the continental, subtropical semi-arid type, except the north and north-eastern mountainous areas having a Mediterranean climate as in [45], [46], and [47].

3. Material and methods
3.1 Hydrogeology of Iraq
Geologists divide Iraq into six geologic regions: Al-Jazeera area, Mesopotamia plain, Southern Desert, Western Desert, Low Folded Zone, and High Folded Zone, (figure 3). Each of these regions includes a system of formations, aquifers and characterized with specific features. (Table 1) indicates type of formations, transmissivity (T, m²/d), and hydraulic conductivity (K, m/d) according to the available data from the performed pumping tests of the drilled wells as in [1, 2, 3, 4, 5, 7, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 35, 39, and 40].
Table 1. Hydro-geologic characteristics of study area, [16], [17], [18], [19], [20], and [21].

| Region                        | Formations                                      | T (m²/d) from | to   | K (m/d) from | to   |
|-------------------------------|-------------------------------------------------|---------------|------|--------------|------|
| Jazira area                   | Fat'ha                                          | 2             | 246  | 0.1          | 6.3  |
|                               | Injana                                          | 2             | 1274 | 0.1          | 20   |
|                               | Quaternary Sediments                            | 5             | 257  | 0.2          | 24.  |
|                               | Euphrates                                       | -             | -    | -            | -    |
| Mesopotamian plain            | Northern part (Injana, Mukdadiya, Bai Hassan    | 4             | 503  | 0.1          | 47   |
|                               | formations, in addition to Quaternary sediments |               |      |              |      |
|                               | Northern part (Mukdadiya aquifer within the    | 3             | 774  | 0.1          | 55.  |
|                               | vicinity of Samara)                             |               |      |              |      |
|                               | Northern part (Bai Hassan aquifer within the    | 4             | 829  | 0.1          | 43   |
|                               | vicinity of Samara)                             |               |      |              |      |
|                               | Northern part (Quaternary sediments aquifer    | 21            | 555  | 1.5          | 29.  |
|                               | within the vicinity of Samara)                  |               |      |              |      |
|                               | Northern part (Quaternary sediments aquifer    | 6             | 1089 | 0.5          | 126  |
|                               | within the vicinity of Baghdad)                 |               |      |              |      |
|                               | Northern part (Quaternary sediments aquifer    | 4             | 1382 | 0.1          | 374  |
|                               | within the vicinity of Mandali vicinity)        |               |      |              |      |
|                               | Central Part (within the vicinity of Karbala    | 10            | 165  | 1            | 27   |
|                               | city)                                           |               |      |              |      |
|                               | Central Part (within the vicinities of Kut and  | 13            | 742  | 0.8          | 72   |
|                               | Ali Al-Gharbi)                                  |               |      |              |      |
|                               | Southern Part                                   | 36            | 439  | 1.1          | 36.  |
|                               |                                                  |               |      |              |      |
| Southern Desert               | Hartha                                          | -             | 163.3| -            | -    |
|                               | Tayarat                                         | 0.5           | 1800 | Very low     | 20.  |
|                               | Umm ErRadhuma                                   | 3             | 2100 | 0.1          | 21.  |
|                               | Dammam                                          | 3.1           | 4752 | 0.1          | 100  |
|                               | Ghar – Euphrates                                | 21            | 246  | 1.3          | 14   |
|                               | Dibdibba                                        | 15            | 265  | 0.3          | 25.  |
|                               | Quaternary Sediments                            | 14            | 964  | 2.9          | 74   |
| Western Desert                | Suffi                                          | 36            | 350  | -            | -    |
|                               | Ga`ara (unconfined)                             | 0.5           | 620  | 0.1          | 13.  |
|                               | Ga`ara (confined)                               | 10            | 250  | 0.1          | 19   |
|                               | Mulussa                                         | 0.8           | 397  | 0.03         | 4.4  |
|                               | Ubaid                                          | 7             | 200  | 0.1          | 4    |
|                               | Muhaiwir                                        | 9             | 1243 | 0.1          | 9.3  |
|                               | Rutbah                                         | 2             | 7000 | 0.2          | 19.  |
|                               | Ms`ad                                          | 15            | 104  | 0.2          | 1.1  |
|                               | Hartha                                         | 2             | 588  | 0.1          | 9.2  |
|                               | Tayararat                                       | 202           | 1552 | 0.2          | 25.  |
|                               |                                                  |               |      |              | 9    |
|                               |                                                  |               |      |              | 6    |
| Location                        | Depth | Irregularities | Lithology | Comment                                      |
|--------------------------------|-------|----------------|-----------|----------------------------------------------|
| Umm ErRadhuma                  | 2     | 1550           | 0.1       | 21.                                          |
| Akashat                        | 2     | 620            | 0.1       | 5.2                                          |
| Dammam                         | 6     | 5000           | 0.1       | 16.                                          |
| Euphrates                      | 3     | 1750           | 0.2       | 29.                                          |
| Injana                         | 21    | 927            | 0.8       | 40.                                          |
| **Low Folded Zone**            |       |                |           |                                              |
| Injana                         | 2     | 1274           | 0.1       | 18.                                          |
| Mukdadiya and Bai Hassan       | 3     | 2800           | 0.1       | 24.                                          |
| Quaternary sediments           | 5     | 539            | 0.1       | 47.                                          |
| carbonate (within Sinjar area)  | 4     | 337            | 0.1       | 6.8                                          |
| Injana (within Sinjar area)     | 2     | 1274           | 0.1       | 11.                                          |
| Quaternary sediments (within Sinjar area) | 15  | 91             | 1.4       | 6.7                                          |
| Fatha (within Tigris River Sub Province) | 8  | 360            | 0.1       | 8                                            |
| Injana (within Tigris River Sub Province) | 3  | 626            | 0.1       | 18.                                          |
| Khazir – Gomel Sub Province    | 100   | 7000           | 0.00      | 0.2                                          |
| Injana (within Dohuk – Alqosh Sub Province) | 6.5 | 622            | 0.1       | 16.                                          |
| carbonate (mainly PilaSpi) (within Dohuk – Alqosh Sub Province) | 4  | 375            | 0.1       | 5.1                                          |
| Mukdadiya and Bai Hassan (within Erbil Sub Province) | 3  | 1296           | 0.1       | 30.                                          |
| Quaternary sediments (within Erbil Sub Province) | 10 | 1225           | 0.4       | 35.                                          |
| AltunKupri Sub Province         | 4     | 1738           | 0.1       | 47.                                          |
| Mukdadiya and Bai Hassan (within Dibiga Sub Province) | 5  | 1650           | 0.1       | 28.                                          |
| Mukdadiya and Bai Hassan (within Makhmour Sub Province) | 6  | 1350           | 0.1       | 25.                                          |
| Mukdadiya and Bai Hassan (within Kirkuk – Hawija – TuzKhurmatu Sub Province) | 3  | 2775           | 0.1       | 57.                                          |
| Mukdadiya and Bai Hassan (within Cham Chamal – QadirKaram – Qara Too Sub Province) | 3  | 1950           | 0.1       | 42.                                          |
| Mukdadiya and Bai Hassan (within Kalar – Khanaqeen Sub Province) | 15 | 1170           | 0.1       | 24.                                          |
| Quaternary sediments (within Kalar – Khanaqeen Sub Province) | 20 | 540            | 0.4       | 35.                                          |
| Mukdadiya and Bai Hassan (within QaraTappa – Al-Sa'adiyah Sub Province) | 10 | 1120           | 0.1       | 23.                                          |
| Quaternary sediments (within QaraTappa – Al-Sa'adiyah Sub Province) | 12 | 510            | 0.3       | 25.                                          |
| Mukdadiya and Bai Hassan (within Mandili town and its vicinities - Mandili – Zurbatiya – Teeb Sub Province) | 3  | 445            | 0.1       | 12.                                          |
3.2. Division of data

In this study, 868 well information was used to build geo-statistical model including (x, y, and z) coordinates after processing in order to exchange it to UTM coordinate system, as well as the hydraulic conductivity (k) in (meter per day) unit. The data are randomly separated into two sets (778 for building...
the geo-statistical model) and (90 for verification) depending on available data within the areas and as possible as covering all of the catchment areas of Iraq. The selection of two data sets was completed by using statistical criteria after many trials in order to meet optimum statistical distribution. (Table 2) summarizes ranges and statistical criteria for both sets. (figures 4 and 5) illustrate the hydraulic conductivity values for both data sets.

| Hydraulic conductivity sets                  | Min. m/d | Max. m/d | Range m/d | Mean m/d | Median | Standard deviation |
|-----------------------------------------------|----------|----------|-----------|----------|--------|--------------------|
| All data (868)                                | 0        | 24.7     | 24.7      | 3.1637   | 0.9    | 5.0180             |
| Building model data (778)                     | 0        | 24.7     | 24.7      | 3.1829   | 0.9    | 5.00081            |
| Verification data (90)                        | 0.01     | 24.7     | 24.69     | 2.9973   | 0.9    | 5.19052            |

3.3. GMS software
In this research, the 2D Scatter Point Module integrated with The Groundwater Modeling System (GMS) software was used in order to build the geo-statistical model. GMS represent a comprehensive graphical user environment for conducting groundwater simulations. The entire GMS system contains a graphical user interface and a sum of analysis codes. The two dimensional (2D) Scatter Point module is implemented to interpolate from sets of 2D scattered data to (Triangulated Irregular Network (TIN), meshes and grids). Several interpolation techniques are supported, including IDW and kriging as in [50].

![Figure 4. Building geo-statistical model.](image1)

![Figure 5. Verification data.](image2)

3.4. Interpolation techniques
One of the best commonly used interpolation techniques for point data is inverse distance weighted (IDW). Inverse distance weighted methods are depended on the assumption that the interpolating surface should be most influenced by the nearby points and less influenced by the more distant points. The result of the interpolated surface is a weighted average of the point data; at the interpolated surface, the weight assigned to each point reduces as the distance to the interpolation position increases. In this research, the simplest form of inverse distance weighted technique (constant nodal function) or occasionally called the "Shepard's method" was used as in [51].

Over the past several decades, the kriging technique has become an essential tool in the field of geostatistics. Kriging is depended on the assumption of treated the parameter as a regionalized variable. A regionalized variable defined as variable intermediate between a completely deterministic variable and a truly random variable that it varies in a continuous way from one location to the next and thus, points that are neighboring each other have a certain degree of spatial correlation, but points that are generally separated are statistically independent. Kriging is a set of linear regression procedures which minimize assessment variance from a predefined covariance model.

GMS program offers two kriging methods (simple and ordinary kriging). In this research, ordinary method was used as an efficient method which recommended by previous researchers work in the same
field. The first step in ordinary kriging is to create a variogram from the scatter point set to be interpolated. A variogram involves two parts: an experimental variogram and a model variogram, Figure (6). If the value to be interpolated \( f \) is assumed, the experimental variogram is constructed by calculating the variance \( g \) of every point in the set concerning every one of the other points and plotting distance \( h \) between the points versus the variances. There are many formulas can be used to calculate the variance, but it is typically calculated as one half the difference in \( f \) squared.

![Figure 6. Experimental and model variogram.](image)

A model variogram represents a simple mathematical function that models the style in the experimental variogram. Once the model variogram is created, it was used to calculate the weights which were used in kriging as in [43].

In order to conclude the accuracy of any given method of spatial interpolation, Root Mean Square Error value (RMSE) was used as in [32]. The techniques of spatial interpolation estimate values of the variables at unobserved places in geographic space depended on the values at observed places. RMSE is a commonly used measure of the differences between model predicted values, and the actually values observed from what is being estimated or modeled. The technique which gave the lowest RMSE value was considered to be the most appropriate technique as in [32].

3.5. Triangulated Irregular Network (TIN)

The TIN technique represents a surface as a set of connecting, non-overlapping triangles, where within each triangle the surface created as a plane. In order to construct a TIN in GMS program, it should be available a set of points called TIN vertices. In this research, GMS program was used to construct TIN, (figure 7) and (figure 8).

![Figure 7. TIN was used for the geo-statistics model.](image)

4. Results and discussion

The geo-statistical interpolation methods (IDW and Kriging) were applied based on hydraulic conductivity data of observed spaces in order to estimate this parameter for unobserved spaces. By using each of these methods, a total of 21,277 hydraulic conductivity points were estimated in wholly areas of Iraq, (figure 9) and (Table 3).
As can be seen, the two methods indicated well accuracy distribution for hydraulic conductivity values, (figure10). The convergence in results of both methods reflects the appropriate selection for model data building and verification data. For the available used data, the values of hydraulic conductivity over 24.7 m/d, were excluded because it was very little values and to obtain reliable results. There is high convergence in results of two methods in the west desert region, particularly in Al-Anbar governorate while a clear difference in results was shown in the north part of the high folded region particularly in Erbil governorate. Also, results indicated that the high values were found in south desert particularly in al Basra governorate and in many parts of Mesopotamia plain particularly in Baghdad, Babylon, and east of Thi-Qar governorates while the low values were found in west desert region, al- Jazeera region, parts of high folded region, and parts of low folded region.

Table 3. Ranges and statistical criteria for estimated Hydraulic conductivity (m/d).

| STATISTICAL DETAILS | IDW           | Kriging       |
|---------------------|---------------|---------------|
| Min.                | 0.02574564    | 0             |
| Max.                | 23.6914       | 22.99957      |
| range               | 23.66566      | 22.99957      |
| Mean                | 3.768914      | 3.672453      |
| Median              | 2.75598       | 2.399603      |
| Standard deviation  | 3.557749      | 3.647328      |
| RMSE                | 1.852755      | 1.993618      |
| MAE                 | 0.879478      | 0.827022      |
| MBE                 | -0.12692      | -0.33804      |
| R²                  | 87.43%        | 85.97%        |

Figure 10. Comparison between actual and calculated values.
5. Conclusions and Recommendations

Hydraulic conductivity parameter (K) is one of the parameters governing both the direction and the magnitude of groundwater velocity, and therefore, is one of the most key parameters affecting groundwater flow and pollutants transport. Geo-statistics interpolation methods proved a very interesting tool modeling for estimating hydraulic conductivity. The purpose of this research was to confirm the possibility to use IDW and kriging techniques as reliable tools for estimating the hydraulic conductivity parameter. The scaves of field data influence the results and restricted the confirmation of the accuracy in the verification process. The accuracy of the results increases with minimizing study area and as possible as available more information and data. The hydraulic conductivity parameter which obtained from geo-statistical analysis model results indicated that the best fitted theoretical model was the inverse distance weighted (IDW) model with R² equal to 87.43%. Also, by conducting many trails, it was found that the optimal distance for estimating the hydraulic conductivity was 4800 meters. A comparison between the kriging and IDW interpolation methods indicated that both methods could estimate hydraulic conductivity with good accuracy and less error. The methods were used in this study can still be significantly improved, mainly by refining the kriging and IDW strategy of hydraulic conductivity parameter and distribution of samples. By improving the methods, the obtained assessment will be more precise and more reliable, which will allow for extend estimation uses.

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