THE UNCERTAINTY OF GIS-BASED INTERPOLATION METHODS IN CONSTRUCTING SHALLOW GROUNDWATER DISTRIBUTION MAP: A CASE STUDY AT PLEIKU CITY, GIA LAI PROVINCE

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Abstract - Four interpolation methods are applied to interpolate shallow groundwater level in Pleiku city, including inverse distance weighted, tension spline, universal kriging, and ordinary kriging. The cross-validation results record that the ordinary kriging is the best interpolation method which is shown by the lowest RMSE value, the highest R² value. It is selected to assess the shallow groundwater level in spatial and seasonal change. Based on the groundwater level interpolated by the ordinary kriging, the groundwater level is divided into the northern and southern parts of the study area. The distribution of groundwater level is shallower than that in the southern part wheret groundwater depth is around less than 15m while in the southern part, most of the groundwater level is higher than 18m. The elevation of groundwater level is found in rainy season; the elevated area accounts for 72.6% of natural area. Additionally, the groundwater level also declines in the rainy season at some region, focusing on Bien Ho lake region and two regions in the southern part of the city whose area accounts for 27.4% of the natural area.

Key words - Interpolation; groundwater level; rainy season; dry season; ordinary kriging

1. Introduction

Groundwater is not only an important component of water resources but also a major source in many regions around the world. Over time, the increasing freshwater demand for development activities and human needs has severely influenced groundwater storage because domestic use and irrigation largely use groundwater. Globally, irrigated agriculture is the largest groundwater use sector, especially in arid and semi-arid regions such as Pakistan, Saudi Arabia, Syria and Iran, groundwater supply is respectively 94%, 92%, 90% and 87% for irrigation [1, 2]. The abstraction of groundwater in specific aquifers exceeded potential recharge from 100% to 200% in Saudi Arabia, Yemen, Jordan, Morocco and India; overall groundwater level has declined from 0.5 to 5 m/year worldwide [3]. In groundwater systems, shallow groundwater level usually fluctuates than deep groundwater level because it occurs nearest to the earth's surface, flexible in both short - term and long - term of precipitation change, extreme events of climate and withdrawal [4, 5]. The shallow groundwater level is a good indicator of trend changes on surface, including precipitation, overexploitation, changes in surface water [5, 6]. The understanding of shallow groundwater level is therefore required for managing, utilizing and planning in a suitable manner of groundwater.

Of the various methods approached, GIS - based interpolation methods have succeeded in evaluating spatial and temporal variability of precipitation, evapotranspiration, temperature, and groundwater level. The common interpolation techniques consist of inverse distance weighted; Tension spline; Ordinary kriging; And universal kriging [7-10]. In principle, these techniques estimate values for a variable in a given geographic space (unknown locations from variable values collected at the sampling sites (known point) [11]. There is not a general agreement on which constitutes the best interpolation method, each interpolation method has some drawbacks, and its reliability strongly depends on external factors such as the amount of available input data, the spatial and temporal coverage, the groundwater characteristics, the kind of spatial model desired and the like [7, 12]. Hence, the optimal interpolation method should be evaluated before applying it in a specific region. Many studies proved that GIS – based interpolation methods are successful for groundwater level monitoring, Ahmadi and Sedghami [10] reported a potential of kriging interpolation in spatial and temporal variations of groundwater level in Darab plain (Iran); Sun et al. [13] evaluated three interpolation methods (IDW, simple kriging, and radial basis function), the simple kriging was the best method for interpolating depth to groundwater in their study area; Yao et al. [7] showed the eight interpolation methods, including IDW, global polynomial interpolation, local polynomial interpolation, regularized spline, tension spline, ordinary kriging, simple kriging, and universal kriging but only the universal kriging method was selected for assessing groundwater level in the Wuwei oasis (China).

This study aims to select an optimal interpolation method from four interpolation methods, including inverse distance weighted (IDW); Tension spline (TS); Ordinary kriging (OK); Universal kriging (UK), to assess seasonal and spatial change of shallow groundwater level in Pleiku city, Gia Lai province (Vietnam).

2. Methodology

2.1. Study area

Pleiku city is the economic and social center of Gia Lai province where a mountainous province is located in the Central Highlands of Vietnam (Figure 1). Its natural land area is 260.77 km² and its average population is 231,387 persons (in 2016) increasing about 30,000 persons in the last ten years. Climatically, Pleiku city has a tropical monsoon climate with the rainy season from May to October and the dry season from November to April; the average of annual rainfall and temperature are 2,861 mm and 22°C respectively. Ferralsols account for 79.71% of the natural land area, these soils are apposite to cultivate both annual and perennial crops. With congruous climate conditions and soil, Pleiku city has dominantly developed in cultivation with crop area of 63.71% of the natural land area. The perennial crops include coffee, tea, rubber, pepper that is still continuously increasing in planted area, keeping an important role in the socio-economic life of Pleiku city [14]. The rapid expansion of population and agriculture production can cause large pressure to freshwater resources consisting of groundwater. Groundwater in Pleiku city underlies the Pleiku plateau consisting of the aquifer in Holocene sediments; aquifer in the middle Pleistocene basalt and aquifer in Pliocene -Pleistocene basalt. Among these aquifers, those in middle Pleistocene and Pliocene - Pleistocene basalt have a large distribution and good reserves of groundwater, they keep an important role in water supply in the study area [15].



Figure 1. Map of study area

2.2. Method

The spatial and the non-spatial database were collected to conduct groundwater status, which include dug well location, well depth. They were practiced by field surveys, direct measurements.

The field survey was conducted on all 23 communes and wards in Pleiku city, the 170 dug wells of households which characterize shallow groundwater, were selected to study (Figure 1). At the dug well sites, the spatial coordinates were taken by a global positioning system (GPS). The groundwater level is influenced by recharge, discharge, and withdrawal, which are dominated by seasonal variation. This research, therefore focuses on measuring well depth in 2/2016 and 7/2016 which represent the dry and rainy season in Pleiku city.

To select an optimal interpolation method in this study, four methods were evaluated, including the geo-statistical method (OK, UK) and the deterministic method (IDW, TS). Estimations of nearly all interpolation methods can be represented as weighted averages of sampled data. They all share the same general estimation formula [16, 17], as follows:

$$Z(x_0) = \sum_{i=1}^n \lambda_i Z(x_i)$$

Where, $Z(x_0)$ is the value that tries to predict for location x_0 ; n is the number of measure sample points surrounding the predicted location that will be used in the prediction; λ_i are the weight assigned to each measured point; $Z(x_i)$ is

the observed value at location x_i.

Kriging method assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. It fits a function to a specified number of points or all points within a specified radius to determine the output value for each location [18]. OK and UK are two common kriging methods to calculate $Z(x_0)$ value; the primary difference between these two methods is how they characterize the mean of the data value used in interpolation which OK assumes a constant, unknown mean value and estimates the mean in the prediction neighborhood while UK models local means using polynomial equations [19]. IDW and TS create surfaces from measured points, respectively based on either the extent of similarity or the degree of smoothing. Therein, IDW estimates a continuous surface of values through the weighted averaging of values relevant to values at a known location. Those known values closest to the prediction location will have more influence on predicted value [18]. For TS (also called radial basis functions under tension), it creates surfaces that pass through measurement locations with the minimum amount of curvature. The interpolation surface goes through every sample location, which is suitable for a large amount of interpolation data [18].

Each interpolation technique has advantages and disadvantages, based on surface interpolation could not give the most accurate method, hence the cross-validation was adopted to assess which method gave the best interpolation effect. In a cross-validation technique, the sample locations were temporarily divided into two datasets, with one used to train an interpolation method and the other used to validate the interpolation method. The Root mean squared error (RMSE) was selected as the main criterion for crossvalidation; the smaller RMSE value is considered as better performance [7, 13, 20-22]. Another criterion to assess the interpolation method was the coefficient of determination (\mathbf{R}^2) which is a measure of the correlation between the measured and estimated values. It ranges from 0 to 1 and the high R^2 values are thus preferable, but its value above 0.6 is accepted in many studies [7, 13, 23].

ArcGIS 10.3 software was applied for interpolating, mapping, changing assessment of groundwater level; the UTM Zone 49N coordinates used for all spatial data. RMSE and R² were computed in Microsoft Excel 2010.

3. Results

3.1. Optimal interpolation method

The original dataset of dug well depth was classified into the training set and the validation set. The 134 dug wells of train set were used to interpolate the groundwater level, while the validation set used 36 remaining sites to test the confidence of the interpolation methods by computing the value of RMSE and R^2 .

Table 1 shows the cross-validation results of the groundwater observation data in the rainy and dry season. The RMSE values are calculated from 5.612 to 8.126 and from 6.132 to 7.341 in the dry and rainy season respectively. Based on RMSE value, the order is OK < UK < IDW < TS in both seasons. The lowest RMSE value

indicates that OK is the best interpolation method in four approached methods. On the other hand, R² values are recorded from 0.341 to 0.635 that are sorted as OK > UK> IDW > TS, the highest R^2 value obtained from OK estimations. By aggregating of RMSE and R² value, TS is the poorest interpolation method while OK is the best method, it is considered as the optimal for interpolating groundwater level in the study area. This result is similar to that of the study of Yao et al. [7]. The study accepted that OK was the best effect for the interpolating groundwater level when comparing eight interpolation methods in The Wuwei oasis (China); Hua et al. [24] showed that the OK was better than the IDW in for groundwater depth in the Shule River basin (China). Oppositely, UK technique had given the best prediction for spatial variation of groundwater depth comparing with OK and IDW in the National Capital Territory of Delhi [21].

Interpolation method	Dry season		Rainy season		
	RMSE	R ²	RMSE	R ²	
IDW	6.863	0.396	6.537	0.601	
TS	8.126	0.341	7.341	0.423	
OK	5.612	0.552	6.132	0.635	
UK	5.868	0.508	6.452	0.614	

Table 1. Cross-validation result of interpolation methods

TS is the poorest method in this study, which may be affected by the spatial distribution of observed dug well (Figure 1), The highest and lowest value estimated from TS did not fit with the observed dataset (Figure 2b). According to Li and Heap [16], TS performed much better when dense, regularly-spaced spatial data was available, but not for irregular-spaced spatial data. For irregularly-spaced spatial data, the interpolated map was more variable where the sample density was higher than where it was low, which may result in structures that are pure artefacts of the data configuration. In contrast, OK assumes that sample locations are independent of the data values basing on a concept of random functions; it is hence less affected by regularly-spaced spatial data and also estimates better following the data fluctuations than TS method [16, 25].

Basing on generated maps (Figure 2), the effect of the interpolation approach clearly is indicated. First, there is the appearance of the buphthalmos phenomenon (also called bulls eye) generated by IDW method (Figure 2a), caused by those overestimated or underestimated values from the depth distribution extreme and uneven of data [7, 20]. Extreme depth data that is over or under in the dataset, is interpolated by using a linear-weighted combination set of sample locations. The weight assigned is a function of the distance of the measured location from the predicted location, hence observed value closest to the prediction location will have more influence on predicted values than those farther away which produce local extremely estimated values [18]. Second, the surface is smoothest based on TS method (Figure 2b). In principle, TS method estimates values using a mathematical function that minimizes overall surface curvature. This results in a smooth surface that passes exactly through the input locations [18]. However, estimated values may excessively high or low values compared with measured data (Figure 2b). Third, UK and OK create a fairly smooth surface (Figure 2c and Figure 2d), but a lot of sharp corners are produced by UK method. OK is more approximate to the real situation and more flexible to deal with extreme data than UK method.



Figure 2. Interpolation effect of groundwater level in rainy season in Pleiku city (classified by geometric interval)

Although OK interpolation method is shown as the best estimation of groundwater level, there are some differences between the measured values and OK interpolation results. The real values are above the interpolated results in minimum and mean, the interpolated mean values are quite close to the real mean values. The maximum and standard deviation values are lower than interpolated values, out of which the real maximum values are recorded much higher than interpolated results (Table 2). Thus, OK interpolation method still consists of uncertain estimated results that may be due to the non-uniform distribution of measured dug wells or the amount of measured groundwater level [10].

 Table 2. Statistical summary of groundwater level from measured data and OK interpolation method

Groundwater level data		Range	Min.	Max.	Mean	SD
Measured data	Dry season	33.4	1	34.6	14.2	7.7
	Rainy season	30.3	0.5	30.8	13.2	7.9
OK interpolation	Dry season	21.9	3.7	25.6	16.4	5.3
	Rainy season	22	2.6	24.6	15.7	5.6

3.2. The status of groundwater level change

The groundwater level experiences seasonal fluctuations or show declines at times of drought even when they are not exploited or are modestly used. If groundwater is exploited consistently at rates above the average annual net recharge, its levels will decline. Also, the groundwater level is fluctuated by spatial variation and the assessment of groundwater level should be included in spatial analysis and temporary analysis. Based on the measured data, the groundwater level is higher than in the rainy season, showed by range, minimum, mean, median and maximum values. In Table 2 and Figure 3, there are 33 per 170 dug wells recorded decline depth. However, to clearly evaluate the spatial variation of groundwater level, constructing distribution maps and spatial analysis are necessary. In the study, the cross-validation results have shown that OK interpolation is the best effect compared among UK, IDW, and TS, it hence is used for spatial and seasonal assessing of groundwater level.



Figure 3. Boxplot of measured groundwater level in the dry and rainy season



Figure 4. Groundwater level in the dry season (a) and rainy seasonal (b)

The groundwater level has spatial variation, which is a range of 2.6 - 25.6 m. Groundwater level distributes unevenly throughout the study area. Generally, it is divided into two groups including the northern and southern parts of the study area (Figure 4). They are isolated by the narrow groundwater zone following northwest direction where stability exists around 15 m to 18 m in groundwater depth. In the northern part, the distribution of groundwater level is shallower than that in the southern part where groundwater depth is around lesser 15 m. The high levels are around 3-6 m concentrating at the western and eastern of the northern part, they are commonly connected by a widely continuous layer groundwater whose depth is around 6 - 12 m. Toward to the north boundary of the city, groundwater level tends to be deeper (from 12 to 18 m). In the southern part, the most of groundwater level is higher than 18 m, only a small area consists of 12 - 18 m in depth which mainly focuses on at the western tail of the bottom city. The low groundwater levels (> 21 m) almost occupy the whole western region of the northern part. The groundwater depth is influenced by the hydrogeological setting. There are two groups of aquifer in Pleiku city including interstitial (aquifer in Holocene sediments) and fissure aquifers (aquifer in middle Pleistocene basalt and aquifer in Pliocene - Pleistocene basalt). Groundwater in Holocene sediments obtains the high level distribution in the western and eastern of the northern part, while the groundwater level in middle Pleistocene basalt and aquifer in Pliocene - Pleistocene basalt is deeper and fluctuates, widely distributed in the study area [15].



Figure 5. Groundwater level change by season

For seasonal change, the average elevation of depth is calculated by 0.7 m in rainy season; the values of minimum, maximum and mean of the groundwater level are respectively 24.6m, 2.6m, and 15.7 ± 5.6 m in the rainy season while in the dry season they are higher and their values are 25.6m, 3.7m, and 16.4 ± 5.3 m, respectively. Figure 5 shows the groundwater level change between rainy and dry season; the negative values represent the decline of the groundwater level, whereas the positive values represent the elevation of the groundwater level. Overall, the groundwater level tends to rise in the rainy season across the study area, but some local area drops in rainy season. The elevated area of depth accounts for 72.6%. It is dominantly found by from higher 0m to 2m and is distributed in most of the study area. The highest elevations concentrate at both the top (adjacent to Bien Ho Lake) and the central city, they fluctuate around 2 - 6.1m accounting for 14% of the natural area. The elevation of the groundwater level has not reached the peak value yet at the time of the study, which is recorded by both respondents and previous studies. According to Tu et al. [15] and Hoc et al. [26], the change of groundwater level in basalt is usually slower than the rainfall change; it gains peak value only about 1-3 months after the rainy season. On the other hand, the dropped groundwater level also appears in the rainy season, its area accounts for 27.4% of the natural area. The declining level is around from 0 to 3.8m, but it dominantly drops around 0 - 2m. Overally, the groundwater level of the study is divided into three drop local regions. The first region focuses on adjacent to the Bien Ho lake, the one is near to the narrow groundwater zone, and the other region is located toward the bottom city. The decline regions of groundwater level do not disperse sparsely but they aggregate a large area with the highest drop in the central core and decrease in depth by distance from the central core.

Commonly in the natural condition, the groundwater level will elevate in the rainy season by direct and indirect recharging from precipitation or surface water while groundwater occurring nearer to the earth's surface, usually fluctuates than deep groundwater experiences [4, 5]. The water can percolate into shallow groundwater then moving down into the deep groundwater (the saturated zone). In the rainy season, the shallow groundwater level, therefore has increased in most of the study area during the rainy season. Additionally, the declining trend of groundwater level also occurs in the rainy season which may be related that the groundwater experienced a long drought period (about six months) and its level decreased significantly by withdrawing and discharging. The rainfall seeps downward shallow groundwater becoming a discharge source for surface water, deeper groundwater, or near shallow groundwater controlled by gradient or gravity. Hence, in some regions of the study area, the recharge is not enough to raise the groundwater level at the study time. The discharge process will end when the equilibrium stage of water level is reached [27]. The peak groundwater level reaches after the rainy season around 1 - 3 months [15]. Those explanations are based on the hypothesis which may be true in some cases. Practically the groundwater level change is also influenced strongly by human activities. Therefore, there are deeper researches relating groundwater level variations in the study area.

4. Conclusions

There are a lot of interpolation methods for interpolating the groundwater level; each interpolation method comes with some drawbacks. Therefore, it is necessary to develop an appropriate interpolation method before applying. In the study, OK method has the lowest value of RMSE and the highest value of R² compared with IDW, TS and UK method. It is suitable for interpolating shallow groundwater level in Pleiku city. The groundwater level is divided into two parts whose value is high in the northern part and low in the southern part; it tends to increase across the study area in rainy season. On the other hand, the three local regions occur with the drop of groundwater level, including adjacent to Bien Ho lake, near to the narrow groundwater zone, and towards the bottom of the city. The drop in groundwater level in the rainy season needs to be more deeply researched to well support suitable planning and managing.

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