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Analysis of Geostatistical and Deterministic Techniques in the Spatial Variation of Groundwater Depth in the North-western part of Bangladesh

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ABSTRACT:*Various geostatistical and deterministic techniques were used to analyse the spatial variations of groundwater depths. Two different geostatistical methods of ordinary kriging and co-kriging with four semi-variogram models, spherical, exponential, circular, Gaussian, and four deterministic methods which are inverse distance weighted (IDW), global polynomial interpolation (GPI), local Polynomial Interpolation (LPI), radial basis function (RBF) were used for the estimation of groundwater depths. The study area is in the three North-western districts of Bangladesh. Groundwater depth data were recorded from 132 observation wells in the study area over a period of 6 years (2004 to 2009) was considered for the analysis. The spatial interpolation of groundwater depths was then performed using the best-fit model which is geostatistical model selected by comparing the observed RMSE values predicted by the geostatistical and deterministic models and the empirical semi-variogram models. Out of the four semi-variogram models, spherical semi-variogram with co-kriging model was considered as the best fitted model for the study area. Result of sensitivity analysis conducted on the input parameters shows that inputs have a strong influence on groundwater levels and the statistical indicators of RMSE and ME suggest that the Co-kriging work best with percolation in predicting the average groundwater table of the study area.*

Keywords *-Groundwater level prediction, spatial interpolation, Semi-variograms, Ordinary Kriging, Co-kriging and GIS.*

I. INTRODUCTION

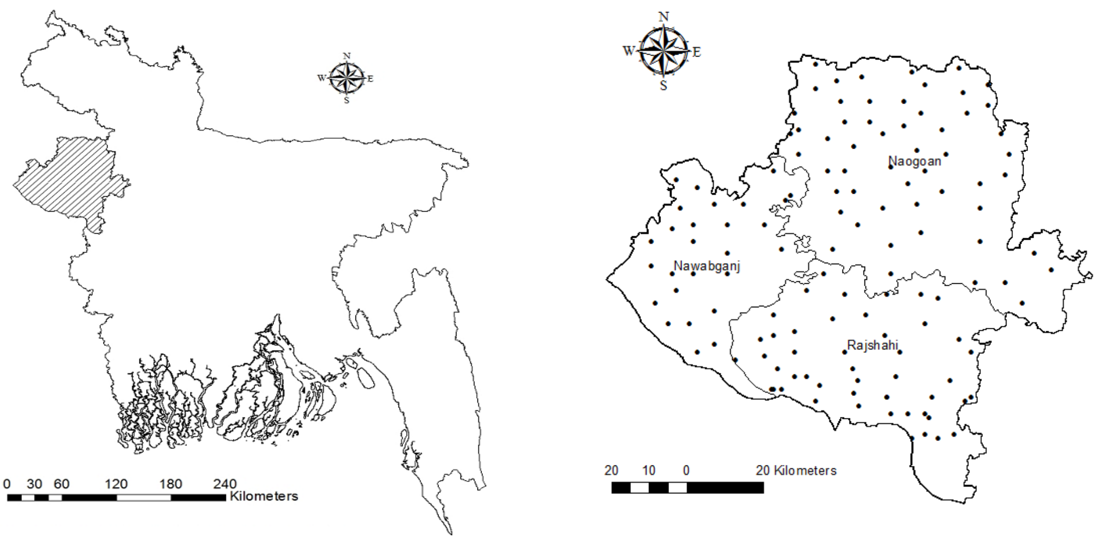
Geostatistical and deterministic techniques play an important role in sustainable management of groundwater systems. These methods provide a set of statistical tools for analysing the spatial variability and interpolation as well as predictingthe model input parameters at regular spots from their measurements at random locations (Kitanidis, 1997). Geostatistics is a collection of techniques for solving estimation problems involving spatial variables, which provides a mixture of tools including interpolation, integration and differentiation of hydro-geologic parameters to make the prediction surface and other derived characteristics from measurements at known positions (Journel and Huijbregts, 1978). The semi-variogram used to describe the structure of spatialvariability, which plays a key role in the analysis of geostatistical data using the kriging and co-kriging methods.

In the past, a number of studies havebeen carried out on the comparison of interpolations methods on groundwater table elevation in different regions.Geostatistical analysis was performed on water table elevation of some 70 wells in Kansas by Christakos (2000). Kumar and Ahmed (2003) monitored the groundwater level during 12 months of the year and used kriging method to estimate groundwater level for unmeasured points and wells for each month. Another study by Reghunath et al. (2005) revealed that geostatistical methods are efficient instruments for water resources management and can effectively be used to gain the long term drifts of the groundwater. Stahl et al. (2006) used regression-based and weighted-average approaches for daily maximum and minimum temperatures over British Columbia, Canada. Benavides et al. (2007) compared ordinary kriging, ordinary kriging with external drift, and universal kriging and regression models for mapping air temperature in northern Spain. Zhang and Srinivasan (2009) incorporated nearest neighborhood, inverse distance weighted, simple kriging, ordinary kriging, simple kriging with local means, and kriging with external drift for mapping precipitation over Luohe River, China. Eldrandaly and Abu-Zaid (2011) compared six GIS interpolation methods for estimating air temperature in western parts of Saudi Arabia. Bostan et al. (2012) compared multiple linear regression, ordinary kriging, regression kriging, universal kriging and geographically weighted regression for mapping average annual precipitation over Turkey. Mutua and Kuria (2013) compared inverse distance method, global polynomial interpolation and kriging and cokriging for rainfall estimation in Nyando river basin, Kenya. Delbari et al. (2013) compared univariate (inverse distance weighing and ordinary kriging) and multivariate (linear regression, ordinary cokriging, simple kriging with varying local mean and krigingwith an external drift) interpolation methods for mapping monthly and annual rainfall over Golistan province, Iran. The above studies emphasized that the application of single interpolation method may produce unrealistic results. Therefore, it is better to choose the best model by comparing different methods.

The major objectives of this study are to compare various deterministic and geostatistical interpolation methods available in ArcGIS 9.3 for mapping and analysis of spatial variations of groundwater depths, to find the best fit of semi-variogram model viz; spherical, exponential, circular and Gaussian models, with kriging and co-kriging of geostatistical technique to develop spatial predictions of groundwater depths, and to consider all variables which have significant effect on the groundwater-based irrigation in the North-western region of Bangladesh.

II. DESCRIPTION OF THE STUDY AREA

Thesubject area of this research comprises three North-western districts of Bangladeshnamely, Rajshahi, Naogaon and Nawabganj which are geographically placed at a latitude ranging from 24°08'N to 25°13'N and a longitude ranging from 88°01'E to 89°10'E, which encompasses an area of 7587 km^2. The placements of these regions, as considerably as the positioning of water-wells used for picking up the groundwater data are presented in Figure 1 (a) and (b).



(a) **(b)**

Figure 1;(a) Location of study area in Bangladesh; (b) location of groundwater sampling points used for the study

The topography of the study area contains mainly of a flat earth with an average height of 25 m above the mean sea level and comprise of a mild surface gradient towards southeast. The surface geology in the major part of the area comprises of uplifted terraces of Pleistocene sediments called Barind Tracts. Barind tract is an uplifted land formed over the Madhupur Clay (an older alluvium of Pleistocene age). Barind Tract sediments can be grounded at depths ranging between 150–200 m and more in the areas with concentration of alluvial. Hydro-geological surveys have been carried out in the area (Jahan et al., 1994; Ahmed and Burgess, 1995; Shwets et al., 1995; Jahan and Ahmed, 1997; Begum et al., 1997; Haque et al., 2000; Azad and Bashar, 2000; Rahman and Shahid, 2004; Islam and Kanungoe, 2005; Faisal et al., 2005; Asaduzzaman and Rushton, 2006). These studies show that upper aquifers in the region are unconfined or semi-confined in nature. The thickness of the exploitable aquifer ranges from 10 to 40 m. Jahan et al. (1994) worked out the specific output of the aquifer in the area vary from 8 to 32% with a general decreasing trend from north towards central portion.

Climatically, the study area belongs to dry, humid zone with annual average rainfall, which varies between 1400 to 1650 mm, among which about 83% of the rainfall occur in monsoon (June to October). Rainfall in the region varies widely from year to year.

III. DATA AND METHODOLOGY

Thecriteria used for selecting sites for this study were the availability and continuity of long-term daily water table data at individual sites. Based on these criteria, data from 132 different observation wells across 25 different Upazillas were selected for the simulation of water table fluctuations for 2004-2009 periods by using Geostatistical and Deterministic techniques. Before developing the models, the groundwater level data were checked for the presence of spatial trends and found suitable for geostatistical modelling due to lack of spatial trends. Then, four deterministic models, viz; inverse distance weighted (IDW), global polynomial interpolation (GPI), local polynomial interpolation (LPI), radial basis function (RBF) and the two geostatistical models viz; kriging and co-kriging with their four semi-variogram models, viz., spherical, exponential, circular and Gaussian models were developed. Finally, the best-fit model for the groundwater depths was selected based on goodness-of-fit criteria. The best-fit geostatistical model thus obtained was used to generate spatial maps of groundwater depths by using ArcGIS9.3 software. The goodness-of-fit criteria used in this study are root mean square error (RMSE), the coefficient of determination (R^2) and mean error (ME) for evaluating the performance of the models.

3.1 Deterministic methods

The deterministic methods available in ArcMap 9.3 are inverse distance weighted (IDW), global polynomial interpolation (GPI), local Polynomial Interpolation (LPI), radial basis function (RBF). They employ the use of mathematical functions based on the degree of similarity or smoothing. Deterministic interpolation techniques can be either exact or inexact interpolators. Exact interpolators include Inverse Distance Weighted Interpolation and Radial Basis Functions which are used to generate a surface that passes through the control points. Inexact interpolators which are Global and Local Polynomial are used to predict a value at a point or location that differs from its known value (Johnston et al., 2003; Eldrandaly and Abu-Zaid, 2011). All the deterministic methods available in ArcMap 9.3 are used in this study.

3.2 Geostatistical methods

Geostatistical processes use both mathematical and statistical functions based on the spatial autocorrelation of the data. The techniques of Geostatistical interpolation create surfaces incorporating the statistical properties of the measured data by developing not only prediction surfaces, but also error or uncertainty surfaces, which turns over the analysis as an indication of how good the predictions are. There are many geostatistical methods under Kriging. The different kriging methods available in the Geostatistical Analysis for spatial interpolation are Ordinary, Simple, Universal, Probability, Indicator, and Disjunctive Kriging (Johnston et al., 2003; Eldrandaly and Abu-Zaid, 2011). In this study ordinary, simple, universal and disjunctive kriging were used. Detail theories about geostatistical models can be found in (Isaaks and Srivastava, 1989; Johnston et al., 2003; Webster and Oliver, 2008).

3.2.1 Semi-variogram

The semi-variogram is a geostatistical function which describes the spatial variability of the values of a variable. It relates the semi-variance with the spatial separation, providing a concise and unbiased description of the scale and the pattern of spatial variability (Curran, 1988). There are many types of semi-variograms viz; circular, exponential, Gaussian, whole effect, J-Bessel K-Bessel, penta-spherical, rational quadratic, spherical, stable, tetra-spherical, etc. In this study, four popular semi-variogram models namely, Circular, Exponential, Gaussian and Spherical models were compared and the best fit model was proposed based on least observed error after simulation.

IV. RESULTS AND DISCUSSION

4.1 Comparison of Deterministic models

In the interpolation of the four deterministic models, viz; inverse distance weighted (IDW), global polynomial interpolation (GPI), local polynomial Interpolation (LPI), radial basis function (RBF),the selection of power value and neighbourhood search is important for the proper interpolation. In this study, power values between 1 and 3 were used and the smooth function was used for neighbourhood search to produce smoother surfaces by assigning smoothing factor values. The accuracy of interpolations was assessed by considering the lowest root mean square error (RMSE). The RMSE values were found to vary with the power and neighbourhood search parameters. The radial basis function (RBF) model gave the best deterministic model with the lowest RMSE value of 2.154 while the global polynomial interpolation (GPI) gave the poorest result with the highest RMSE value of 2.930.

4.2 Comparison of Geostatistical models

Ordinary kriging and co-kriging methods of interpolation were used to interpolate the average water table using Circular, Spherical, and Exponential and Gaussian semi-variograms. The goodness-of-fit statistics results are shown in Table 1, and the residual analysis results are shown in figure 2. The performance of the semi-variogram models showed that spherical semi-variogram with co-kriging yielded the lowest RMSE value of 2.105 and circular semi-variogram with co-kriging yielded the highest error of 2.491, respectively.

Table 1; Results of Semi-variograms Models

Model	Kriging	Co-Kriging
Semi-Variogram	**RMSE**	**RMSE**
Circular	2.186	2.491
Spherical	2.222	2.105
Exponential	2.252	2.145
Gausian	2.222	2.141

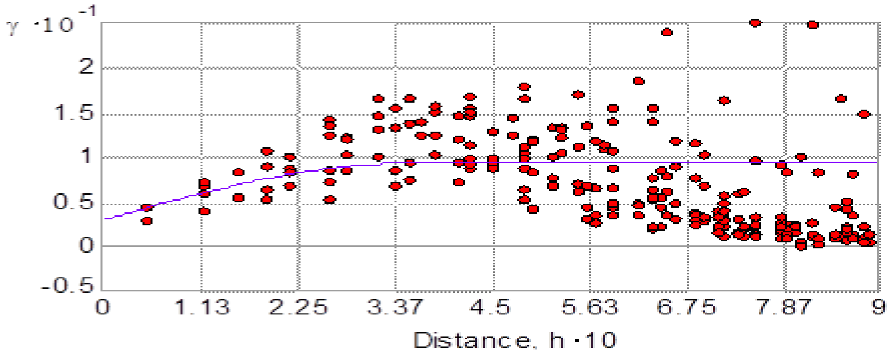


Figure 2: Fitted semi-variogram of Spherical model for groundwater depths with co-kriging

The overall performance of co-kriging was outstanding with Spherical, Exponential and Gaussian semi-variogram which gave lowest error in all the cases. In case of kriging, circular semi-variogram gave lowest error while Spherical, Exponential and Gaussian semi-variograms gave approximately the same error.

4.3 Comparison of Geostatistical and Deterministic models

Finally, the best model from deterministic and geostatistical methods are compared to find the most suitable spatial interpolation method for the region. The results obtained are shown in Table 2. Co-kriging with Circular semi-variogram gave lowest error among all geostatistical methods, while the radius basis function gave best results among the deterministic methods. Overall, the performance of geostatistical methods was superior compared to deterministic method. Performance of co-kriging was found to be the best among all the methods.

Table 2: Comparison of the Results of deterministic and geostatistical methods

Models	RMSE	Mean Error
IDW	2.180	0.036
GPI	2.930	0.031
LPI	2.251	-0.314
RBF	2.154	0.022
Kriging	2.186	-0.051
Co-kriging	2.105	0.010

4.4 Results of Sensitivity analysis

On investigating the influence of the input parameters on the average groundwater table using the best interpolation methods with the best semi-variogram model, results of the sensitivity analysis as depicted in table 3; below indicates that all the inputs have a strong influence on groundwater levels in the study area. Looking at the general performance of the input variables, it can be seen that percolation has the highest influence on the average water table while the geology of the area has the lowest influence on the average water table. Assessment of the general results; it was deduced that the statistical indicators suggests that Co-kriging with percolation is inferior for interpolating the average water table in the study area.

Input Parameters	**Ordinary Co-Kriging**	
	RMSE	**AIC**
R, P, G	2.45	4.21
R, MC, G	2.37	4.27
R, A, G	2.34	4.30
P, A	2.13	4.49
R, P, MC	2.44	4.22
R, MC, A	2.26	4.37
R, P, A	2.35	4.29
P, MC, A	2.04	4.57
R	2.49	0.18
P	2.11	0.51
MC	2.10	0.52
A	2.16	0.46
G	2.49	0.17

Where;

R = Rainfall, P = Percolation, MC = Soil moisture content, A = Altitude, and G = Geology of the area.

4.4 Spatial Variation of Groundwater Depth in the Study Area

The contour map of 6-year (2004-2009) average groundwater depth was generated by co-kriging technique (Spherical geostatistical model) which reveals that the mean pre-monsoon groundwater depth in the area generally varies from 2.4 to 15.72 m belowground surface (m bgs) with a major portion of the area having 2.4 to 7.05m bgs depth (Figure 3).

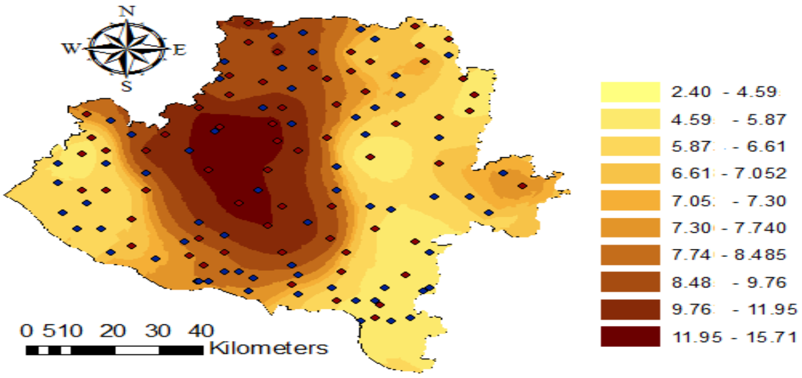


Figure 3: Maps of average Groundwater level of the study area obtained by ordinary co-kriging methods with Spherical semi-variogram

V. CONCLUSION

In this paper, the spatial analysis of groundwater depth was performed using geostatistical and deterministic models of GIS. The analysis of results indicated that geostatistic models are more suitable for spartial interpolation than the deterministic models and that the geostatistcal model can reveal stochastic structure of groundwater level variations in the study area. The co-kriging model with spherical semi-variogram was found to be the best-fit geostatistical model for the study area, which were used for developing contour maps for spatial analysis to show a significant groundwater fluctuation in the study area. On investigating the influence of the input parameters on the average groundwater table using the best interpolation methods with the best semi-variogram model, satistical indicators also indicates that co-kriging works best with percolation. The results obtained suggest the usefulness of applying geostatistic techniques in investigating the spatial variations of groundwater depths in the study area.

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