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ESTIMATION OF HYDRAULIC PARAMETERS FOR KAROON RIVER BY COKRIGING AND RESIDUAL KRIGING*

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Abstract – The determination of hydraulic properties of open-channels and rivers is very important in water resources management and engineering. Geostatistical estimation methods in comparison with direct measurements and/or using mathematical models can be more cost and time effective. The objective of this study is to evaluate the possibility of applying cokriging and residual kriging methods to estimate some hydraulic parameters of rivers or open-channels. The results indicate that cokriging can be used to estimate flow cross-sectional area, flow velocity and hydraulic radius, while residual kriging can be used to estimate flow cross-sectional area, flow velocity and water surface level elevation. It is concluded that water surface width is preferable to water depth as an auxiliary variable in the cokriging method. The relative error of estimation for geostatistical estimators was about 0.87 to 22%. Thus, these methods can be considered appropriate and the user's expected accuracy is important in choosing the geostatistical estimators for estimation of hydraulic parameters in open-channels or rivers. In general, cokriging and residual kriging can be used to estimate open-channel hydraulic parameters by using 25% (29 data) of measured data instead of 115 measured cross-sections along the channel or river with minimal cost and the least amount of time.

Keywords – Cokriging, residual kriging, river hydraulics, Karoon river, geostatistical interpolation

1. INTRODUCTION

The evaluation of open-channel and river hydraulic parameters is an important element of water resources management. For this evaluation, flow parameters such as water surface elevation, flow velocity and hydraulic radius should be assessed. Direct measurement of parameters by suitable equipment and their estimation by mathematical models are two possible methods. The first method is very difficult and is not cost nor time effective for large canals or rivers, and for this reason we prefer computerized mathematical models which have only minor difficulties. This approach is, however, limited by programming complexity, expense and the necessity of numerous data for canal or river cross-sections. As previously mentioned, canal or river cross-section measurements are costly and time consuming. Therefore, statistical or geostatistical systems may be used to estimate the cross-section and hydraulic parameters along the canal or river based on scarce measured data. These procedures are both useful and cost effective in the estimation of hydraulic parameters along the canals or rivers at locations with no measured data.

Increasing the flow rate or water depth in open-channels increases flow area, flow velocity and water surface width. A mathematical relationship can be assumed between water depth or water surface width, and other hydraulic properties such as flow area and flow velocity. This mathematical relationship is the primary assumption and is required in geostatistical estimators such as cokriging and residual kriging which were used in this research.

There are several research reports on the use of geostatistical methods for the estimation of unknown parameters, most of which are applied to soil, environment and mining, but there are few published works on geostatistics in the field of water resources engineering. Desbarats *et al*. [1] used geostatistical estimation

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for water table elevations of an unconfined aquifer near Toronto, Canada. Haberlandt *et al*. [2] applied geostatistical methods to the base flow index in a large river basin. Wang *et al*. [3] studied the surface water leakage into groundwater by geostatistics.

MIKE 11 is a software developed at the Danish Hydraulic Institute (DHI) for the simulation of water flow, sediment transport and water quality in estuaries, rivers, irrigation systems and similar water bodies. The MIKE 11 hydrodynamic module (HD) uses an implicit finite difference scheme for the computation of unsteady flows [4].

In this research, the results of a calibrated MIKE 11 mathematical model for the Karoon river in Khuzestan Province, I.R. of Iran, were used to estimate some of the hydraulic parameters of this river by cokriging and residual kriging methods. These parameters were flow area, flow velocity, hydraulic radius and water surface elevation at discharge rates of 2000 and 7000 m^3s^{-1}.

2. THEORY

In classical statistics, the chance occurence of samples is equal. For many natural variables however, the difference between variable values increases with distance and some order of correlation exists between sample magnitudes which are functions of distance. Such variables are called regionalized variables. The semivariogram quantifies the relationship between the semivariance and the distance between sampling pairs by the following Eq. [5, 6]:

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [Z(x_i + h) - Z(x_i)]^2 \tag{1}$$

where $\gamma(h)$ is the estimated value of the semivariance for lag(h), n(h) is the number of sample pairs separated by h , $Z(x_i+h)$ and $Z(x_i)$ are the values of variable Z at x_i+h and x_i ,respectively, and h is the distance vector between sample points.

Geostatistical estimations are based on the semivariogram or the crossvariogram (cross-semivariogram), and is a process that can be used to estimate the magnitude of a variable at a specific location by means of values of the same variable at other locations. This estimator is called kriging. Semivariogram is a requirement in kriging estimation procedure. In order to use kriging estimators (except universal kriging), it is imperative that input data not have a definite trend in order for the semivariogram to reach a constant value which is called "Sill". Semivariogram is also used in the kriging procedure for estimation of values in unsampled points, indirectly [5, 6].

a) Punctual (point) kriging

The punctual kriging can be used to estimate the unknown variable as follows [5]:

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{2}$$

where $Z(x_i)$ is the measured value at x_i , $Z(x_o)$ is the estimated value at a given location (x_o) and λ_i is the weighting coefficient related to the ith sample.

Estimated values can be obtained from an optimization procedure in which the variance of estimation becomes the minimum, while the sum of weighting coefficients (λ_i) must be equal to one. The variance of estimation can be written in the form of the following relationship:

$$\sigma_E^2 = 2\sum_{i=1}^{n} \lambda_i \gamma(x_i, v) - \gamma(v, v) - \sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i \lambda_j \gamma(x_i, x_j) \tag{3}$$

where λ_i and λ_j are the weighting coefficient of points x_i and x_j, respectively, $\gamma(x_i, v)$ is the variogram between x_i and x_0 , $\gamma(v, v)$ is the variogram between x_0, and x_0 (which is zero in punctual kriging) and $\gamma(x_i, x_j)$

is the variogram between points x_i and x_j. The weighting coefficients (λ_i) will be obtained from this optimization process. More details are given in references [5, 6].

b) Cokriging

The correlation between different variables is the basis of the cokriging estimator. In this method, by means of an auxiliary variable, the principal variable is estimated because the auxiliary variable can be easily measured and there is an existing correlation between auxiliary and principal variables. Supposing Z_1 and Z_2 are the auxiliary and principal variables, respectively, the following can be written [5]:

$$Z_2^*(x_0) = \sum_{i=1}^{N1} \lambda_{1i} Z_1(x_{1i}) + \sum_{j=1}^{N2} \lambda_{2j} Z_2(x_{2j}) \tag{4}$$

$$Z_1 = [Z_{1i}\ , i=1,2\ , \ldots, N_1] \tag{5}$$

$$Z_2 = [Z_{2j}\ , j=1,2\ , \ldots\ , N_2] \tag{6}$$

$$\phi(h) = \frac{1}{2n(h)} \sum_{j=1}^{n(h)} [Z_1(x_{2j}+h) - Z_1(x_{2j})].[Z_2(x_{2j}+h) - Z_2(x_{2j})] \tag{7}$$

where $Z^*_2(x_o)$ is the estimated principal variable, $\phi(h)$ is the cross variance and λ_{1i} and λ_{2j} are the weighting coefficient of auxiliary and principal variables, respectively. For estimating unknown values, the weighting coefficients will be obtained from minimizing the variance of estimation similar to punctual kriging. More details are given in references [5, 6].

c) Residual kriging

This method is similar to the cokriging method, but it is supposed that the mathematical relationship between principal and auxiliary variables has been defined. Thus, the errors (differences between the calculated values obtained from the mathematical relationship and measured data) can be calculated and the errors at unsampled points can be estimated by means of punctual kriging. Adding these estimated errors to the values obtained from the mathematical relationships results in the estimated value of the principal variable at unsampled points. For example, for any given river, a mathematical relationship can be fitted to the variables along the reach. In this case, the auxiliary variable is distance and principal variable is the hydraulic parameter which must be estimated. Having this fitted equation, the residuals can be calculated for known points. Punctual kriging is applied to these residuals to determine the residuals for unsampled points. The addition of these residual values to the values obtained by the fitted equation results in the value of the principal variable in the unsampled points.

3. MATERIALS AND METHODS

a) Study area

The Karoon river, which has a watershed area of 58,180 km^2 and is located in southwest of the I.R. of Iran in Khuzestan province (Fig. 1) was chosen for this study. The river lies between the city of Ahwaz (31^o 20' N, 48^o 41' E) and the Bahmanshir river (30^o 25' N, 48^o 12' E), which is about 190 km in length. The Karoon river is a meandering river which supplies water for the irrigation of sugarcane cultivation projects, as well as other agricultural lands. Near the Persian Gulf, it splits into two rivers, the Bahmanshir and the Arvand. These two rivers flow into the Persian Gulf. Low duration and high discharge are the characteristics of early rainy season floods, while high duration and low discharge floods occur in the late rainy season. The river cross-sections are not uniform at all. The river has a main channel and two floodplains. Some cross-sections of the river are shown in Fig.2.

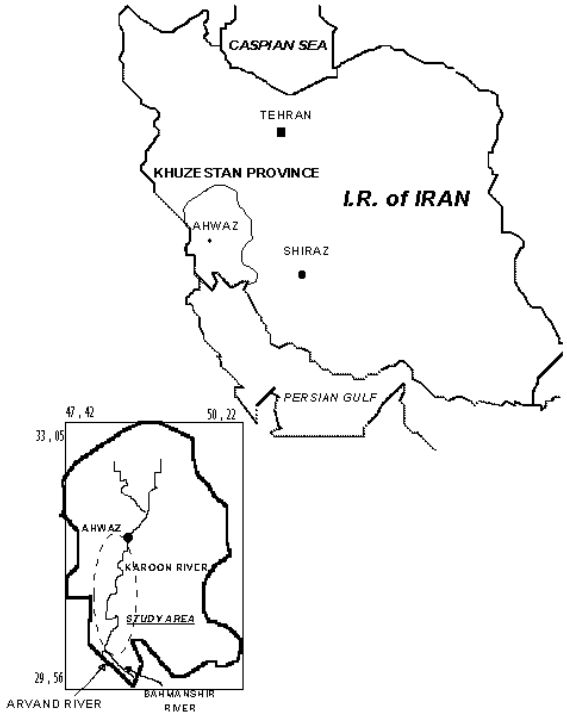

Fig. 1. Location map of the study area

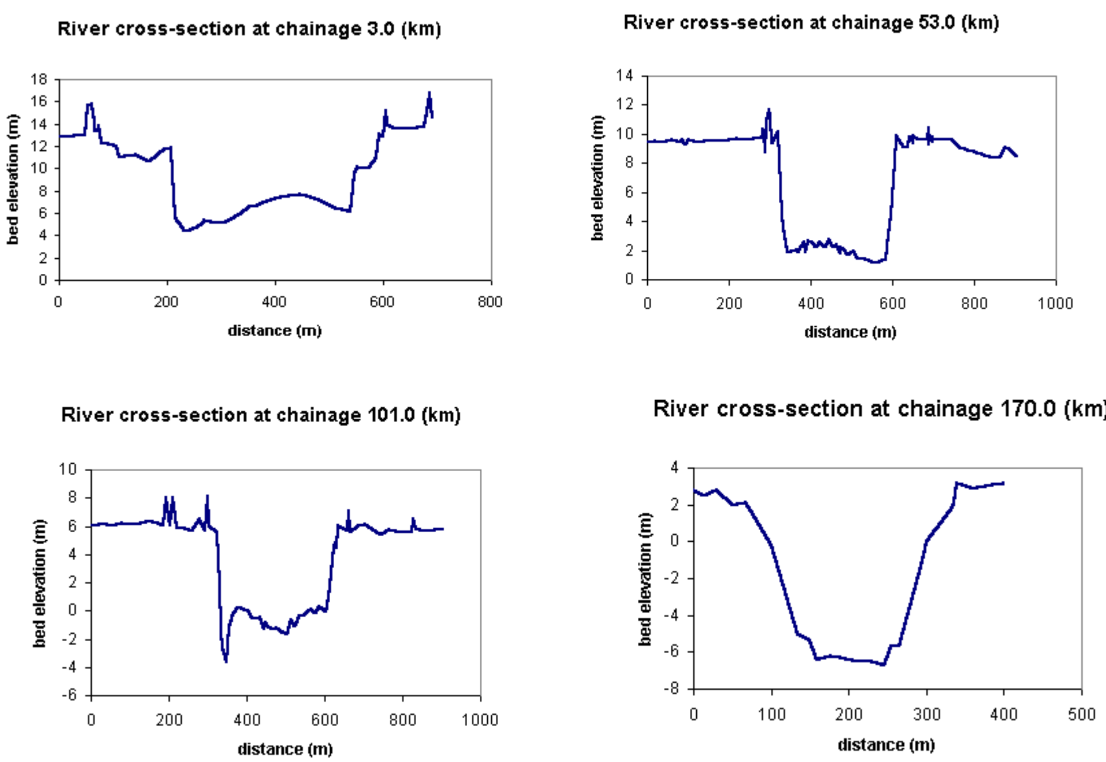

Fig. 2. Some river cross-sections along the reach

b) Procedure

The MIKE 11 model, which was developed by DHI [4], was calibrated and used to simulate the hydraulic parameters such as water surface elevation, flow velocity, hydraulic radius and flow area for two floods, with a return period of 1 and 100 years. This model was used for data generation because there is not enough measured water flow data along the river. The simulations were made in steady state conditions. The discharge rates were 2000 and 7000 m^3s^{-1}, respectively. MIKE 11 can simulate unsteady flows in channels or rivers by an implicit finite difference method. It solves the continuity and momentum equations of Saint Venant by the six-point Abbott scheme [4]. "MIKE" is the first name of Mr. Abbott who developed the six-point Abbott scheme. The number of measured cross-sections used for this simulation were 115, and the first cross-section was located at the Ahwaz stage-flow meter station. These cross-sections were located at equal distances, therefore, the hydraulic parameters for these 115 points were simulated by a calibrated MIKE 11 model [7-9].

The Cokriging method was used to estimate flow area (A), flow velocity (V) and hydraulic radius (R) as principal variables, while the auxiliary variables were water depth (D) and water surface width (T). The procedure of estimation for principal variables is as follows:

- All of the variables at discharge rates of 2000 and 7000 m^3s^{-1} were computed by a calibrated MIKE 11 model [7, 8, 9].
-Water surface width (T) was chosen as the auxiliary variable and flow velocity (V); flow area (A) and hydraulic radius (R) were the principal variables.
-25, 50 and 75 % of the principal variables computed by the model were omitted and the rest were entered to Geopack software for geostatistical estimation. Selection of 25%, 50% and 75% of omitted principal variables were arbitrary, however, the omitting pattern was done in such a way that the distance between the remaining cross-sections were equal.
-The omitted data were estimated by the cokriging method using Geopack software. (Geopack is a geostatistical software that is used for estimations using kriging and cokriging methods) [10].

Thus we had 36 cases by a composition of three series of omitted data as unknown data, two auxiliary variables (D and T), three principal variables (A, V and R) and two discharge rates. In each case, the values of principal variables, which were estimated by cokriging, were compared with the computed variables from the MIKE 11 model. In this comparison the relative average error was computed as follows:

$$E_{avg} = \frac{1}{n}\sum_{i=1}^{n} \left| \frac{z_i(x_0) - z_i(x)}{z_i(x)} \right| \tag{8}$$

where $z_i(x_0)$ is the estimated value by cokriging, $z_i(x)$ is the computed value by the model, E_{avg} is the average relative error of all estimated values and n is the number of estimations.

Variables such as water surface elevation, flow velocity and flow area were also estimated by the residual kriging method. For this purpose, 75% of the values computed by the model were omitted and the rest (25%) were used in a curve fitting software to get the best mathematical relationship describing the relationship between these variables and distance. The differences between the fitted equation and the model computed variables were considered as residuals and were used in Geopack software to estimate the residual values for omitted data using punctual kriging. Thus, the residues at other points (75% of points which were omitted before) were computed. Adding the estimated residues to values obtained from fitted equations, results in the estimated variables at unsampled points. The average relative error was also computed by Eq. (8).

4. RESULTS AND DISCUSSION

Figures 3-9 show some estimated semivariograms and crossvariograms related to different discharge rates and hydraulic variables. In all cases, the sill reached constant value and there was no trend in input data. Therefore, these variograms can be used in geostatistical estimations. Tables 1-5 show the characteristics of all the semivariograms and crossvariograms for cokriging and residual kriging methods at two discharge rates and different percentages of omitted principal variables. It is indicated that the spherical model is the best fitted model for variograms. The criterion for selecting the appropriate semivariograms is the sum of squared errors between points and fitted variograms. The variogram with a lower sum of squared error was chosen. These variograms were used in the estimation procedure of punctual kriging, cokriging and residual kriging.

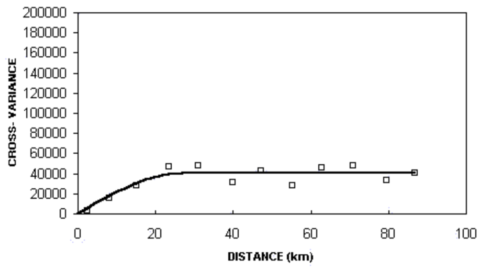

Fig. 3. Crossvariogram of flow area and water surface width with 75% omitted principal variable at discharge of 2000 m^3s^{-1}

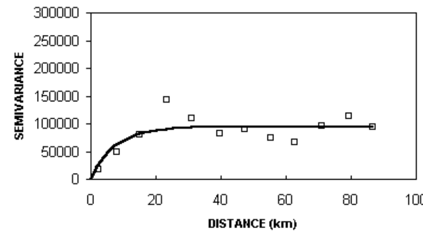

Fig. 4. Semivariogram of flow area with 75% omitted principal variable at discharge of 2000 m^3s^{-1}

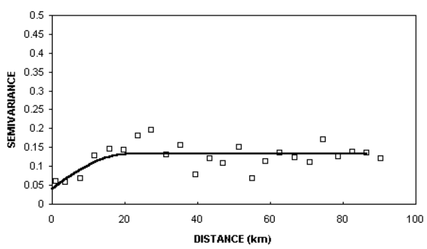

Fig. 5. Semivariogram of flow velocity with 50% omitted principal variable at discharge of 2000 m^3s^{-1}

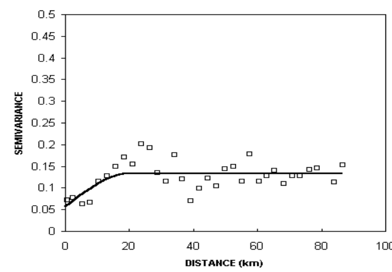

Fig. 6. Semivariogram of flow velocity with 25% omitted principal variable at discharge of 2000 m^3s^{-1}

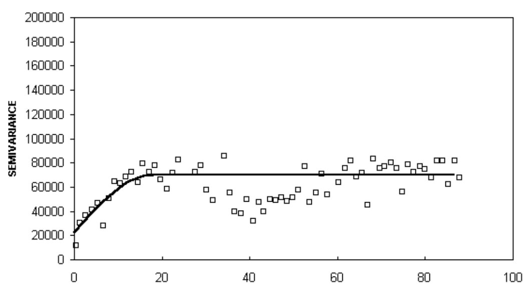

Fig. 7. Semivariogram of water surface width at discharge of 7000 m^3s^{-1}

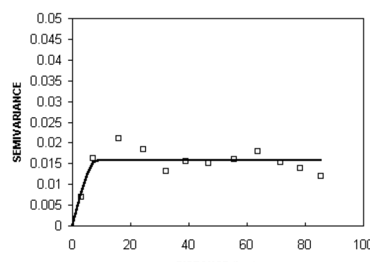

Fig. 8. Semivariogram of water surface elevation residuals with 75% omitted principal variable at discharge of 7000 m^3s^{-1}

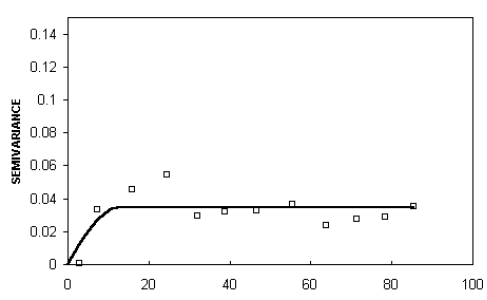

Fig. 9. Semivariogram of water surface elevation residuals with 75% omitted principal variable at discharge of 2000 m^3s^{-1}

Table 1. Characteristics of semivariograms for principal variables

Flow rate (m^3s^{-1})	Percentage of omitted principal variable	Principal variable	Range (km)	Sill (*)	Nugget (*)	Fitted model
2000	25	Flow area	18.6	186900	90600	Spherical
		Hydraulic radius	10.0	1.76	1.38	Spherical
		Flow velocity	20.1	0.134	0.0567	Spherical
	50	Flow area	18.8	187500	53500	Spherical
		Hydraulic radius	7.7	2.39	2.04	Spherical
		Flow velocity	20.3	0.133	0.0412	Spherical
	75	Flow area	7.5	94900	0.0	Exponential
		Hydraulic radius	43.2	3.19	0.58	Spherical
		Flow velocity	6.9	0.33	0.14	Exponential
7000	25	Flow area	20.5	2545210	605310	Spherical
		Hydraulic radius	41.3	1.28	0.23	Spherical
		Flow velocity	22.4	1.37	0.0753	Spherical
	50	Flow area	19.0	3012550	206150	Spherical
		Hydraulic radius	27.2	0.68	0.48	Spherical
		Flow velocity	21.6	1.49	0.0728	Spherical
	75	Flow area	19.3	2513700	1002600	Spherical
		Hydraulic radius	75.5	1.07	0.83	Linear
		Flow velocity	26.0	1.14	0.0	Spherical

(*) Hydraulic radius: $(m^2)^2$, Flow velocity: $(m/s)^2$, Hydraulic radius: $(m)^2$

Table 2. Characteristics of semivariograms for auxiliary variables

Flow rate (m^3s^{-1})	Auxiliary variable	Range (km)	Sill $(m)^2$	Nugget $(m)^2$	Fitted model
2000	Water depth	7.4	6.44	5.64	Spherical
	Water surface width	21.5	87900	34100	Spherical
7000	Water depth	13.3	7.03	4.74	Spherical
	Water surface width	17.9	70300	22900	Spherical

Table 3. Characteristics of residuals' semivariogram in residual kriging method

Flow rate (m^3s^{-1})	Principal variable	Range (km)	Sill (*)	Nugget (*)	Fitted model
2000	Flow area	4.1	130200	0.0	Exponential
	Flow velocity	3.3	0.094	0.0	Exponential
	Water surface elevation	12.3	0.034	0.0	Spherical
7000	Flow area	8.1	859800	0.0	Spherical
	Flow velocity	7.8	0.100	0.0	Spherical
	Water surface elevation	8.7	0.016	0.0	Spherical

(*) Flow area: $(m^2)^2$, Flow velocity: $(m/s)^2$, Water surface elevation: $(m)^2$

Table 4. Characteristics of crossvariograms for principal and auxiliary variables at flow rate of 7000 (m^3s^{-1})

Percentage of omitted principal variable	Principal and auxiliary variable	Range (km)	Sill	Nugget	Fitted model
25	Flow area/Water depth (m^3)	17.2	1679	289	Spherical
	Hydraulic radius/Water depth (m^2)	58.8	-0.54	0.0	Spherical
	Flow velocity/Water depth (m^2/s)	26.4	-0.85	0.0	Spherical
	Flow area/Water surface width (m^3)	20.7	382760	105820	Spherical
	Hydraulic radius/Water surface width (m^2)	27.5	-158.7	-80	Spherical
	Flow velocity/Water surface width (m^2/s)	25.3	-240.6	-22.6	Spherical
50	Flow area/Water depth	17.0	2100	447	Spherical
	Hydraulic radius/Water depth	57.9	-0.79	0.0	Exponential
	Flow velocity/Water depth	26.1	-0.77	0.0	Spherical
	Flow area/Water surface width	18.7	459500	44200	Spherical
	Hydraulic radius/Water surface width	27.7	-123.2	-50.3	Spherical
	Flow velocity/Water surface width	24.5	-274	0.0	Spherical
75	Flow area/Water depth	23.0	2642	704	Spherical
	Hydraulic radius/Water depth	38.8	-0.66	0.0	Linear
	Flow velocity/Water depth	43.3	-2.34	-0.425	Spherical
	Flow area/Water surface width	14.4	380660	184230	Spherical
	Hydraulic radius/Water surface width	76.9	-4376	-126	Spherical
	Flow velocity/Water surface width	25.3	-198.1	-19.1	Spherical

Table 5. Characteristics of crossvariograms for principal and auxiliary variables at flow rate of 2000 (m^3s^{-1})

Percentage of omitted principal variable	Principal and auxiliary variable	Range (km)	Sill	Nugget	Fitted model
25	Flow area/Water depth (m^3)	15.6	28.9	20.2	Linear
	Hydraulic radius/Water depth (m^2)	43.2	2.34	0.43	Exponential
	Flow velocity/Water depth (m^2/s)	43.3	-0.21	-0.0387	Exponential
	Flow area/Water surface width (m^3)	19.9	94100	20600	Spherical
	Hydraulic radius/Water surface width (m^2)	30.2	-236.5	-93.5	Spherical
	Flow velocity/Water surface width (m^2/s)	17.9	-63.3	-4.8	Spherical
50	Flow area/Water depth	35.7	-1.31	0.0	Exponential
	Hydraulic radius / Water depth	43.2	2.26	0.41	Spherical
	Flow velocity / Water depth	85.0	135.2	0.0	Exponential
	Flow area / Water surface width	20.7	103500	15600	Spherical
	Hydraulic radius / Water surface width	32.4	-234.7	-80.7	Spherical
	Flow velocity/Water surface width	6.2	-63.2	0.0	Exponential
75	Flow area/Water depth	43.0	420.5	76.5	Linear
	Hydraulic radius/Water depth	43.2	2.81	0.51	Spherical
	Flow velocity/Water depth	43.6	-0.57	-0.10	Spherical
	Flow area/Water surface width	26.9	40300	0.0	Spherical
	Hydraulic radius/Water surface width	32.1	-188.7	-165	Spherical
	Flow velocity/Water surface width	17.2	-63.7	0.0	Spherical

The average relative error of estimation for principal variables by cokriging is shown in Table 6. For estimating the flow area in the case of 2000 m^3s^{-1} discharge with auxiliary variable of water surface width

(T), the errors of estimation in 25%, 50% and 75% of omitted principal variables are 13.2%, 13.4% and 12.8%, respectively. These errors are very similar. In the case of 7000 m^3s^{-1} discharge, the errors of estimation for 25% and 50% of omitted principal variables are 10% and 8%, while for 75% omitted points the error is 14.6%. For the auxiliary variable of water depth (D), the error of estimation varied from 11.8% to 22.3% and 10.9% to 14.6% for the discharges of 2000 and 7000 m^3s^{-1}, respectively.

For estimation of flow velocity using water surface width (T) in the case of 2000 and 7000 m^3s^{-1} discharges, the errors of estimation varied from 12.8% to 18.9% and 7.7% to 10.9%, respectively. Using the auxiliary variable of water depth (D), these errors varied from 12.5% to 16.4% and 7.3% to 18.1%, respectively.

For hydraulic radius, the differences between errors of estimation in both auxiliary variables of water surface width (T) and water depth (D) were low. Also the variation of errors in different percentages of omitted principal variables were low.

The results showed that the method of cokriging is appropriate for estimation of some hydraulic variables such as flow area, flow velocity and hydraulic radius, and the magnitude of errors is acceptable in most cases. Using 25% (29 data) versus 50% (58 data) of the data to estimate the unknown data did not increase the relative error of estimation significantly for most of the hydraulic parameters. The auxiliary variable of water surface width (T) has a lower relative error of estimation than water depth (D).

Table 6. Relative error of estimation for principal variables in cokriging method (%)

Principal variable	Percentage of omitted principal variables	Auxiliary variable	Discharge 2000 (m^3s^{-1})	Discharge 7000 (m^3s^{-1})
Flow area (A)	25	T*	13.2	10.0
		D	11.8	10.9
	50	T	13.4	8.0
		D	13.6	10.9
	75	T	12.8	14.6
		D	22.3	14.6
Flow velocity (V)	25	T	12.8	7.7
		D	12.5	7.3
	50	T	14.8	8.4
		D	13.4	7.8
	75	T	18.9	10.9
		D	16.4	18.1
Hydraulic Radius (R)	25	T	15.5	7.0
		D	14.8	5.2
	50	T	15.3	6.4
		D	14.6	6.4
	75	T	13.7	6.9
		D	13.9	8.8

(*) T: water surface width D: water depth

The relative error of estimation at a discharge rate of 7000 m^3s^{-1} is less than that obtained at a discharge rate of 2000 m^3s^{-1}. This might be due to the small variability in the hydraulic parameters at different locations along the river at the greater discharge rate [7, 8].

Table 7 shows the relative error of estimation for flow velocity, flow area and water surface elevation obtained by the residual kriging method. In this method, the fitted equations to the principal variables were in the form of polynomials, but any other kind of equation could be used. For the sake of being brief, these equations were not shown. The residual kriging method was used only in the case of omitting 75% of the total data (using 25% of the total data), because the fitted equations did not show good agreement to the data points in the case of 25% and 50% of omitted data due to scattering of the data points. However, this is not such a serious problem, because it is more appropriate to use fewer data for estimation of unsampled points. The relative error of estimation for this estimator was about 0.87 to 18%, which is acceptable. Therefore, it can be concluded that the previously mentioned variables at unsampled locations can be estimated by residual kriging. Estimation of water surface elevation has a much lower relative error of estimation than the others. Furthermore, the relative error of estimation for flow area and flow velocity by cokriging and residual kriging was nearly the same. Figures 10-13 compare the estimated and computed values of principal variables at different conditions. It can be seen that in all cases the estimated and computed values have good agreement. According to Fig. 10, the cokriging method could estimate flow velocity using 25% of total data (29 data) accurately. Figures 11 and 12 show that residual kriging could be used for an accurate estimation of water surface elevation accurately. Figure 13 shows the agreement between computed and estimated data of flow area using cokriging method.

Table 7. Relative error of estimation in residual kriging method (%)

Variables	Discharge 2000 (m^3s^{-1})	Discharge 7000 (m^3s^{-1})
Flow area (A)	12.8	14.4
Flow velocity (V)	18.0	12.8
Water surface elevation (Y)	0.87	1.12

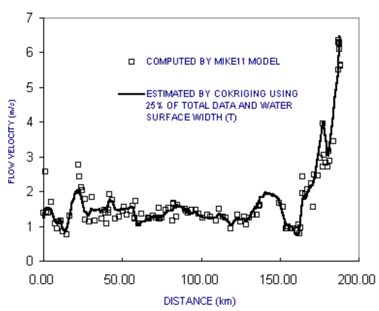

Fig. 10. Estimated and computed flow velocity at discharge of 7000 m^3s^{-1}

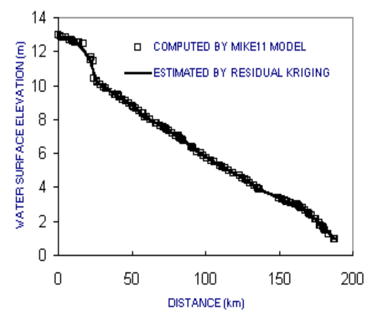

Fig. 11. Estimated and computed water surface elevations at discharge of 2000 m^3s^{-1}

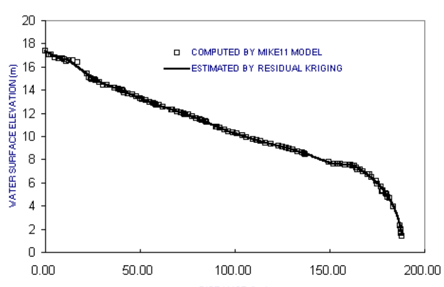

Fig. 12. Estimated and computed water surface elevations at discharge of 7000 m^3s^{-1}

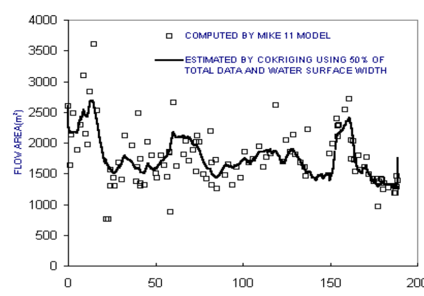

Fig. 13. Estimated and computed flow areas at discharge of 2000 m^3s^{-1}

5. CONCLUSIONS

Results showed that residual kriging is appropriate for the estimation of water surface elevation with lower errors (0.87% and 1.12% for 2000 and 7000 m^3s^{-1} discharge rates, respectively). Using 25% (29), 50% (58), or 75% (87) of total data, cokriging generated a 5 to 22 percent error in the estimation of flow velocity, flow area and hydraulic radius which can be considered acceptable and economical in most cases. Using the residual kriging method to estimate the flow area and flow velocity resulted in a relative error of 13 to 18%, which is similar to those of the cokriging method. It was also concluded that water surface width (T) as an auxiliary variable in the cokriging method is preferable to the water surface depth (D).

In general, cokriging and residual kriging methods can be used to estimate open-channel hydraulic parameters by using only 25% (29 data) or 50% (58 data) of measured data instead of 115 measured cross-sections along a channel or river with minimal cost and the least amount of time.

REFERENCES

1. Desbarats, A. J., Logan, C. E., Hinton, M. J., & Sharpe, D. R. (2002). On the kriging of water table elevations using collateral information from a digital elevation model. *J. Hydrol., 255*, 25-38.
2. Haberlandt, U., Klocking, B., Krysanova, V., & Becker, A. (2001). Regionalisation of the base flow index from dynamically simulated flow components, a case study in the Elbe river basin. *J. Hydrol., 248*, 35-53.
3. Wang, Y., Ma, T., & Luo, Z. (2001). Geostatistical and geochemical analysis of surface water leakage into groundwater on a regional scale: a case study in the Luilin karst system, northern China. *J. Hydrol., 246*, 223-234.
4. DHI, MIKE 11 reference an users manuals, Danish Hydraulic Institute (2000).
5. Isaaks, E. H., & Srivastava, R. M. (1989). Applied geostatistics. Oxford Univ. Press, New York.
6. Hassani Pak, A. A. (1998). *Geostatistics*. Tehran Univ. Pubs., No. 2389, I.R. of Iran, (in Persian).
7. Shahrokhnia, M. A. (1998). Flood management analysis of Karoon river at southern Ahwaz plain. M.Sc. thesis, Shiraz Univ., Shiraz, I.R. of Iran, (in Persian).
8. Javan, M. & Shahrokhnia, M. A. (2002). Flood management analysis of Karun river in southwestern Iran. *1st North American DHI Software Conference.* Orlando, Florida, 10-12 June.
9. Shahrokhnia, M. A. & Javan, M. (2002). Velocity and conveyance changes during floods in Karun river, Iran. *1st North American DHI Software Conference.* Orlando, Florida, 10-12 June.
10. Yates, S. R. & Yates, M. V. (1990). Geostatistics for waste management: A user's manual for the geopack geostatistical software system. EPA report 600/8-90/004.