STREAMFLOW MAP OF THE EASTERN BLACK SEA REGION, TURKEY

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Abstract

The purpose of this study is to generate a streamflow map for the coastal part of the Eastern Black Sea Region which is located in the north east of Turkey. The topographic structure of the region is an obstacle in terms of the number of observation gauges. In order to determine spatial variation of flow and to estimate flow on any ungauged points in the region, interpolation between gauged and ungauged points is applicable. For this purpose, any hydrological models which depend on a large number of meteorological dataset can be used. Instead, in this study, ordinary and universal kriging as geostatistical interpolation methods are used to interpolate mean annual flow depth over the study area, thus, flow values on ungauged points can be easily estimated. Kriging methods are compared to simple regression based on the relationship between flow data and basin area. Calibration results of observed and estimated flow depths for ordinary and universal kriging methods are satisfactory, the determination coefficients are found to be 0.84 and 0.87, respectively. Besides, the validation

results show that the performance of kriging methods is superior compared to the regression model.

Keywords: Streamflow map, ordinary kriging, universal kriging, simple regression, the Eastern Black Sea Region

1. INTRODUCTION

Spatially distributed hydrological models provide more cost-effective means of determining water potential assessment within a basin; however the accuracy of model results depends strongly on the accuracy of model inputs, particularly precipitation observations. In mountainous regions, most of the precipitation observations usually have 30% or higher error whereas streamflow errors vary from 5% to 10%–15% [1]. In addition, the number of observation gauges is limited in developing countries. Besides, in cases where spatial streamflow estimation for longer periods such as monthly, seasonal or annual-scale is required, simpler relationships may prove sufficient approximation [2]. In order to avoid the complexity of hydrological models which depends on accurate and large number of meteorological dataset, available flow observation data can be used for determining spatial variation of streamflow.

Spatial variability of flow has been represented by various techniques. For instance, flow depth has been defined as a regionalized phenomenon that used a centroid based method by performing ordinary kriging to predict long-term streamflows corresponding to different exceedance probabilities over space and time [2]. The method locating gauged flow values at the centroids of the basins was previously used for runoff mapping [3, 4, 5]. This approach was also used for flood regionalization [6]. The main idea in this study was that spatial proximity is a significantly better estimator of regional flood frequencies than are basin attributes.

The total area in mapping can sometimes be divided into fundamental units, i.e. sub-dividing a larger basin into sub drainage basins or into a regular grid network. The drainage basins can be defined by points in space and during the mapping processes average of the runoff from all the sub drainage basins that fall within a grid cell are used. A disadvantage of this method is that some cells don't include observation points. To overcome this problem, a deterministic interpolation was applied and used as the Triangulated Irregular Network (TIN) technique (i.e. linear interpolation within the TIN facets represented by the gauging station which has been considered as nodes) [7].

Other studies are based on disaggregation and covariance approaches [8, 9]. These approaches were developed for mapping annual runoff along the river network using water balance constraints in the estimations [10]. It was subsequently extended, generalized and applied to mean annual runoff coupled with empirical relations and was presented by an application to assess water resources in France [11]. Effects of local features such as karst and river regulations were then added into this approach to produce the maps of mean runoff for France [12].

Top-kriging (topological kriging) was presented in ungauged catchments [13] as a method to estimate streamflow-related variables. The concept was built [10] and extended in a number of ways. Although the method was tested for the 100-year flood case for two Austrian regions, it can be used to spatially interpolate for a range of streamflow-related variables such as mean annual flow, low flow and flood characteristics, and it provides more robust estimates than regional regression models [14]. Top-kriging has been recently used to estimate flood quantiles and flow duration curves for ungauged sites and has been compared to canonical kriging and regression equations [15, 16]. Block kriging was coupled with water balance and data uncertainty analyses to estimate mean annual runoff for a large basin in China [17].

In this study, it is aimed to determine spatial variation of flow for the coastal part of the Eastern Black Sea Region, Turkey since such a study is not available for the region. Considering that the region has a significant hydropower potential [18], importance of knowing flow at ungauged points. The coastal part of the Eastern Black Sea Region is mountainous such that most of the precipitation observation stations were located in the valley floors and they could not represent orographic precipitation characteristics of the region [19]. Because of this, use of any hydrological model based on precipitation data is not convenient to determine flow variability for the study area. In order to produce a streamflow map, a previous study [2] which was based on kriging application for different exceedance probabilities of streamflow estimation is followed. The difference of this study from the previous one is the use of mean annual flow observation data instead of flow data corresponding to different exceedance probabilities. Besides, this study includes a universal kriging application to produce streamflow map for the coastal part of the Eastern Black Sea Region.

2. STUDY AREA and DATA

The study area is the coastal part of the Eastern Black Sea Region which is situated in the north east of Turkey, between the coordinates $40^o 31'$ - $41^o 24'$ North and $38^o 08'$ - $41^o 26'$ East. This coastal part can be defined as the region between the Eastern Black Sea Mountain chain and the Black Sea (Fig. 1). The Eastern Black Sea Mountain chain is parallel to the coast as the north boundary of the study area, and it rises to more than 3000 m above msl (mean sea level). The Black Sea Region has a rocky steep coast [20].

Humid and mild climate dominates in the coastal area of the Eastern Black Sea Region. Yearly average temperature in the coastline is about 14-15 ^oC, however it decreases with increasing elevation. Snowfall can be seen in winter. The mean precipitation of the coastal part of the study area is more than 1000 mm, and in many points it exceeds 2000 mm.

Mean annual flow observations from 40 flow gauges are used in this study. Locations of the gauges are shown in Fig. 1. Area and elevations of the flow gauges are given in Table 1. “No” column of Table 1 corresponds to numbers on the map in Fig. 1.

The flow observation record length varies from 10 to 49 between years 1944 and 2006 with some gaps in the data. In order to complete a gap in any gauge record, regression equations were generated using continuous data from the neighboring gauges. The observed flows are not influenced by any upstream water structure or dam. Data homogeneity was first checked out with the double mass curve method. Mann-Kendall trend test was also performed. It was found that 22 gauges out of 40 were homogeneous and no trend was found. For the remaining 18 gauges, the non-homogeneity and/or the available trends were insignificant [20]. The most significant difference between the observed and the adjusted flow was found 17.5% in Kanlipelit (No 12). Other gauges among these 18 flow gauges showed less significant differences such that mean annual flow records were used without any adjustment.

Elevation of both rain and flow gauges, flow direction and accumulation which are the requirements of stream network, drainage basin area of the flow gauges are delineated in Geographical Information System (GIS) environment. Digital elevation model (DEM) is produced from Shuttle Radar Topographical Mission (SRTM) with about 90 m resolution. Universal Transverse Mercator (UTM) coordinate system is used in the study.

3. METHOD

Kriging is a spatial interpolation technique which incorporates spatial correlation models formulated by covariance or variogram functions. Kriging provides optimal linear estimations at ungauged points by assuming that the spatial variation of the property is a realisation of a random function that has been observed at data points only [21].

The first step in the kriging process is to obtain a model of spatial autocorrelation, variogram. The empirical (experimental) variogram $\gamma^*(h)$ is defined as:

$$\gamma^*(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[z(x_i+h)-z(x_i)\right]^2 \qquad (1)$$

where h is the distance (also called the lag) of two observation points $z(x_i)$ and $z(x_i+h)$, measures of $z(x)$ on locations x_i and x_i+h. $N(h)$ is the total number of observation points linked by h.

The variogram $\gamma^*(h)$ is a graph which relates the differences of the regionalized variable z to the distance h between the data points. Experimental variogram is obtained using the observation points and needs to be approximated by a theoretical function $\gamma(h)$ which allows one to predict the variogram analytically for any distance, h. The theoretical models most commonly used are Gaussian, Spherical, Exponential etc. characterized by the parameters range, sill and nugget.

Once the theoretical variogram has been fitted to the experimental one, it is possible to apply the prediction by kriging. In kriging, the estimated value $z(x_o)$ at location x_o is a linear combination of observed values $z(x_i)$, $i = 1,\ldots, N$ located in the neighbourhood of x_o:

$$z(x_0)=\sum_{i=1}^{N}\lambda_i z(x_i) \qquad (2)$$

where the unknowns of the equation are the weights λ_i. These weights are found by solving a system of linear equations which is known as "ordinary kriging system":

$$\begin{cases}\sum_{j=1}^{N}\lambda_j\gamma(x_i-x_j)-\mu=\gamma(x_0-x_i)\\ \sum_{j=1}^{N}\lambda_j=1\end{cases} \qquad (3)$$

In Eq. (3), $(x_i\text{-}x_j)$ represents the Euclidian distance between x_i and x_j, γ is the theoretical variogram and μ is the Lagrangian multiplier. Ordinary kriging assumes that the random field has a constant but unknown mean. However, in practice, environmental fields often show non-constant mean values. To remedy nonstationarity problem, universal kriging was developed. Universal kriging can model tendency by some form of trend surface and then compute the semivariogram using residual values from that surface. Universal kriging system in which trend is often a function of coordinates is shown as:

$$\begin{cases} \sum_{j=1}^{N} \lambda_j \gamma\left(x_i - x_j\right) + \sum_{l=1}^{k} \mu_l f_l\left(x_i\right) = \gamma\left(x_0 - x_i\right) \\ \sum_{j=1}^{N} \lambda_j f_l\left(x_i\right) = f_l\left(x_0\right) \end{cases} \tag{4}$$

where f_l is the l-th basic function of spatial coordinates that describes drift. k is the number of functions used in drift modeling. μ_l is the Lagrangian multiplier associated with the l-th unbiased condition.

Detailed information about kriging method can be found in [22, 23, 24].

4. RESULTS AND DISCUSSION

Flow depth can be calculated by dividing total flow volume (Q_i) for a given period at a site i to basin area above the i-th site (A_i). Flow depth (Q_i/A_i) as a regionalized variable, is uniformly distributed throughout the basin indicating a homogeneous basin where the increase in flow volume is proportional to enlargement of the basin area. If the stationarity hypothesis is valid, ordinary kriging is applicable. This hypothesis can be proved by investigating the relationship between flow and basin area for nested basins, i.e. the basin of one gauge is part of a larger basin contributing to another gauge [2]. However, the study area includes a mixture of nested and non-nested basins; therefore nested basins are separated and investigated using their flow data and areas. As seen from Fig. 2, flow increases with the basin area for nested basins in the region. For the coastal part of the Eastern Black Sea Region, the rainy and humid climate is responsible of abundance water resources in the basins where both flow and flow depth increase in the downstream direction. Based on the approximate linear relationship between flow and basin area for the nested basins and climate characteristics of the region, flow depth is assumed to be homogenously distributed all over the region and therefore ordinary kriging can be applied.

On the other hand, being different from other meteorological variables such as precipitation, flow depth is related to basin area and represents an area instead of a point. Therefore, the representative value of the flow depth is allocated on the centroid of the basin [2] instead of the actual observation location which is the outlet of the basin. Centroids of each basin in the study area are shown in Fig. 1.

As geostatistics works generally best when data have a normal distribution, flow data has been checked against normality. The data were found to be normally distributed at α significance level of 0.05. In developing the empirical variogram, only the isotropy case is considered. Because of the limited data, only the omnidirectional variogram is computed, which means in all directions the spatial variability is assumed to be identical [25]. Theoretical model fitting is carried out using one of the most applied methods, cross-validation approximation. The empirical isotropic variogram and fitted model are shown in Fig. 3. A Gaussian model is fitted and cross-validated with observed data. The validity of Gaussian model is verified using determination coefficient (R^2), Root Mean Square Error (*RMSE*) and mean standardized residual error (*MSRE*) calculated as:

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(Q_{est_i} - Q_{obs_i} \right)^2 \right]^{1/2} \qquad (5)$$

$$MSRE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(Q_{est_i} - Q_{obs_i} \right) / \sigma_i \right] \qquad (6)$$

where Q_{est} and Q_{obs} represent estimated and observed flows and N is the number of data, σ is the standard deviation of estimation error. The best fit of a theoretical model to an empirical variogram is achieved when *MSRE* equals to approximately zero. On the other hand, *RMSE* is better for the estimation efficiency of the extremes [26, 27].

Cross validation result of observed and estimated flow depth values for ordinary kriging method are given in Table 2 and Fig. 4 (a). As seen from Table 2, *RMSE* value is 185.76 mm for flow depth data of which minimum, mean and maximum values are 382.0, 996.3 and 2284.9 mm, respectively.

A previous study [28] has indicated that spatial distribution of precipitation on the coastal part of the Eastern Black Sea Region is not homogenous. Precipitation increases slightly with longitude which means northeastern part of the region receives greater precipitation than does the western part. Due to precipitation amount, flow values of the southern part are greater, namely a trend is observed in the flow depth data such that the average varies over the study area. As previously defined, universal kriging can incorporate the effect of the trend. The universal kriging algorithm can produce a trend model by fitting a polynomial function to the flow depth data. The locations of flow observation points are plotted on the *x*-*y* plane and depicted in Fig. 5 from which a quadratic trend on the east-west direction and a linear trend on the north-south direction are observed. These trends represented by a mathematical formula are removed from the observations and added back before estimations are made. Cross validation results of observed and estimated flow depth values for universal kriging are given in Table 2 and Fig. 4 (b), after removing trends from the data. As seen from Table 2 and Fig. 4, the difference in calibration between ordinary and universal models is minor, however universal method seems better based on the R^2 (0.87) and MSRE (-0.009) values.

The kriged maps of flow depth are shown in Fig. 6. Streamflow maps are similar. Increase in the flow depth from west to east side of the study area is clear in both maps.

To test the validity of the flow depth map, 6 among 40 flow gauges are randomly chosen. The validation results of randomly chosen gauges are summarized in Table 3 where *RE* shows the relative error in percent, calculated as:

$$RE = \frac{Q_{est} - Q_{obs}}{Q_{obs}} \times 100 \qquad (7)$$

The equivalent flow depths are multiplied by their corresponding areas and flow estimations (Q_{est}) at any validation points are yielded. In the validation stage, kriging methods are compared to simple regression equation which is shown in Fig. 7. R^2 of area based regression equation is 0.70 which is lower than that of kriging methods. Although R^2 value can be statistically accepted, this result confirms that drainage area alone is not adequate to explain regional differences in annual streamflow [29]. In addition, R^2 seemed to be partially controlled by the position of greater values (points on upper right position in Figure 7) which indicates an unstable situation [30].

In the validation stage, minimum and maximum relative errors are -39.8 and 14.2 in ordinary, -42.0 and 14.7 in universal whereas these are -50.2 and 59.7 using regression equation. Relative errors are high in low flow estimations, as a comparison criterion it seems to be meaningless and the absolute error (*AE*) which is the difference between estimation and observation can therefore be accepted. For the gauge Cucenkopru (No 9) which has the highest *RE*, *AEs* are found to be -2.26 and -2.39 m^3/s in ordinary and universal models, respectively. The validation results appear satisfactory in terms of kriging methods.

5. CONCLUSIONS

In this study, to determine spatial variation of flow, streamflow maps were produced for the coastal part of the Eastern Black Sea Region, Turkey. The mean annual flow depth was considered as a regionalized variable, thus ordinary and universal kriging methods could be applied.

Mean annual flow depth is obtained using mean annual flow observation which represents the difference annual evaporation and precipitation and provides a measure of the overall water resource for a region. It gives a valuable information for the basin under consideration and useful for comparing water amount of one basin with those of another. It is used for surface water hydrology and hydrologic design and is characterizing flow regime in a stream.

In this study, two kriging methods are used. Ordinary Kriging is commonly used in practice and has various applications in streamflow estimation studies. On the other hand, universal kriging assumes a trend is available over the area. Universal kriging is also performed due to spatial variability of the precipitation in the study area.

Kriging methods were compared to simple regression based on the relationship between flow data and basin area. From this study, following conclusions can be drawn:

- Kriging application of mean annual flow depth gives satisfactory results meaning that it is applicable on flow data at annual time scale.
- The performance of kriging models was superior compared to the regression model based on the flow data and basin area relationship. Considering calibration results, universal kriging was better than ordinary kriging but the difference was not statistically significant.
- The flow depth map can be a useful tool for flow estimation on ungauged locations in the Eastern Black Sea Region. Promising results of calibration and validation encourage one to suggest this method for other hydrologic applications in different regions in Turkey.

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Figure Captions

Figure 1. Study area and flow gauges with basin boundaries

Figure 2. Relationship between flow and basin area for nested basins

Figure 3. Experimental variogram of the flow depth with Gaussian model fitted

Figure 4. Cross validation of observed and estimated flow depth for (a) ordinary and (b) universal kriging

Figure 5. Trend analysis of flow depth data

Figure 6. Streamflow maps produced using (a) ordinary and (b) universal kriging for the study area

Figure 7. Simple regression relationship between flow data and basin area

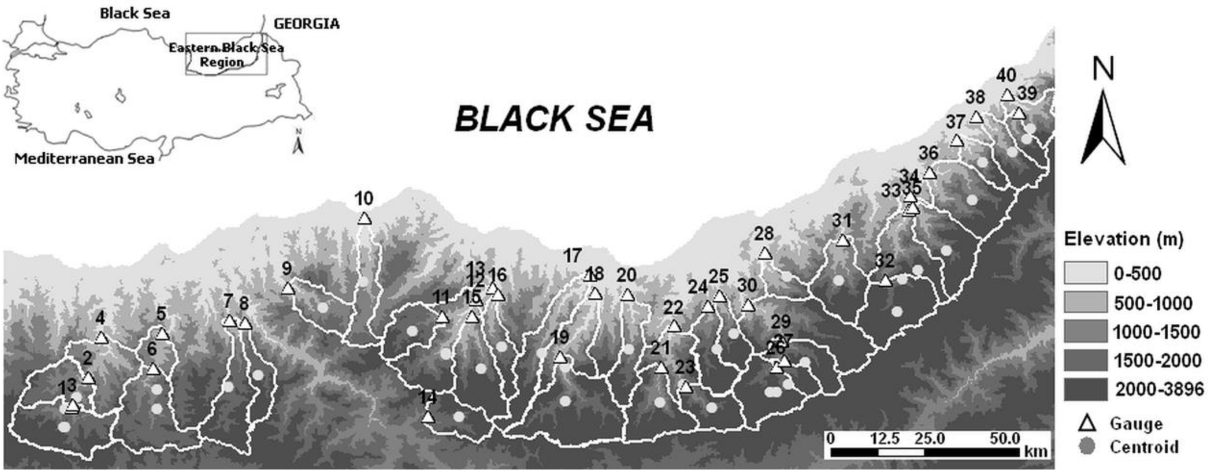
Table Captions

Table 1. Area and elevation of the flow gauges

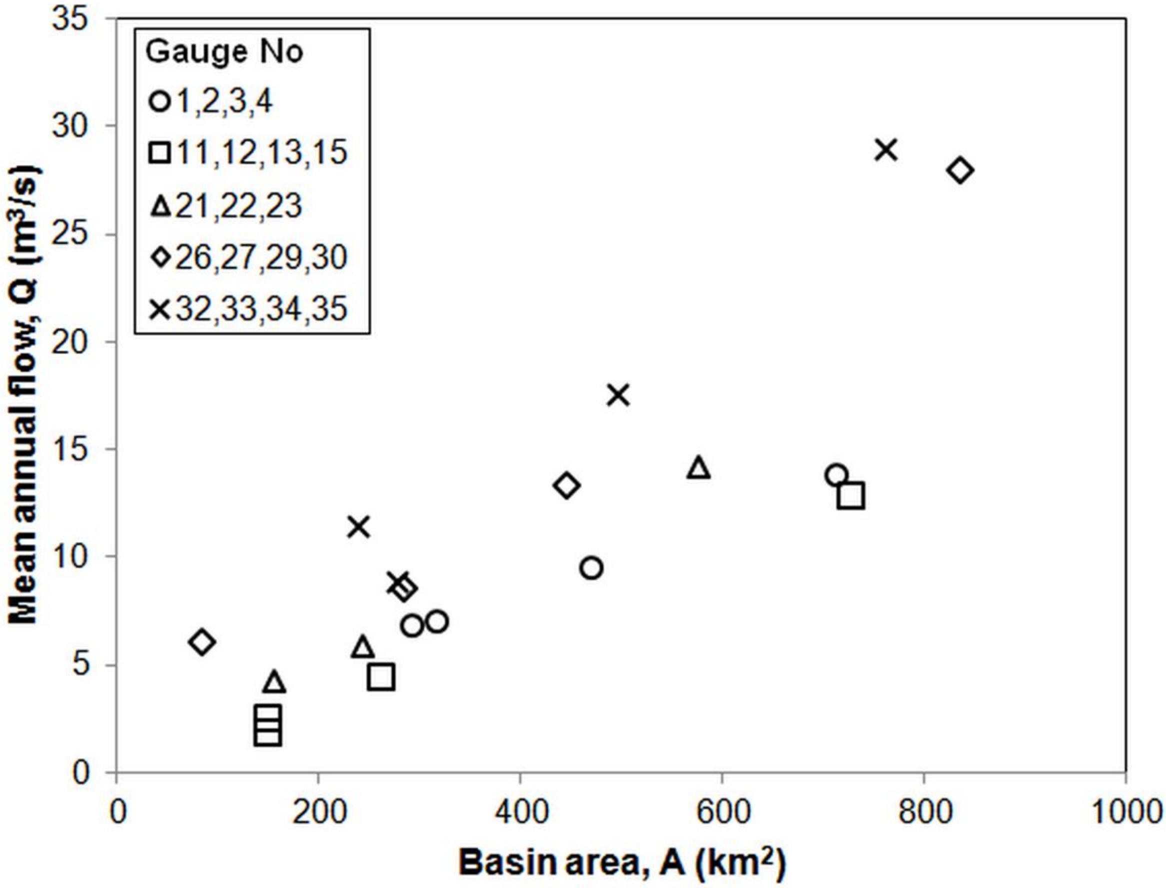
Table 2. Cross validation of flow depth

Table 3. Validation results based on the streamflow maps and regression

Figure 1


Black Sea
GEORGIA
Eastern Black Sea Region
Mediterranean Sea
BLACK SEA
N
Elevation (m)
0-500
500-1000
1000-1500
1500-2000
2000-3896
Gauge
Centroid
0 12.5 25.0 50.0 km

353 **Figure 2**



354

Figure 3

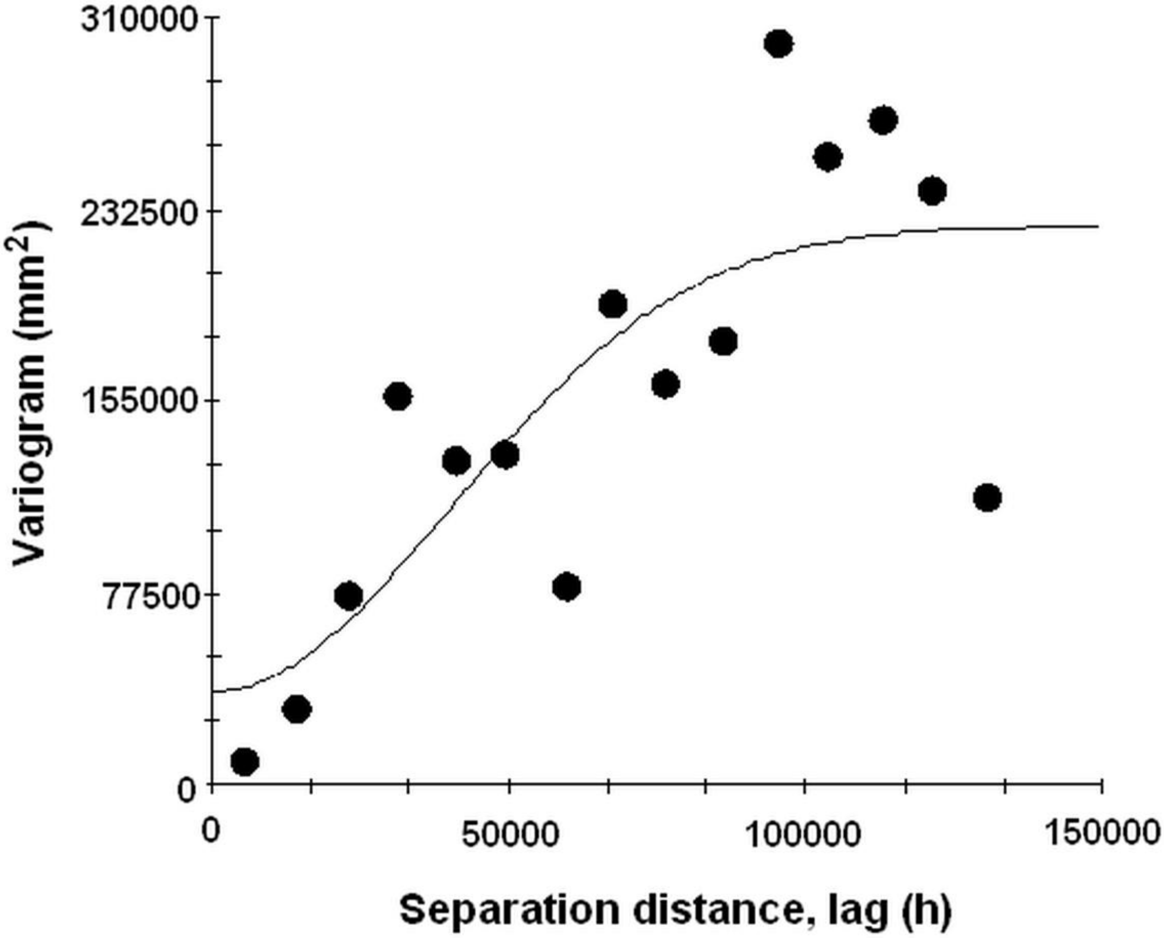
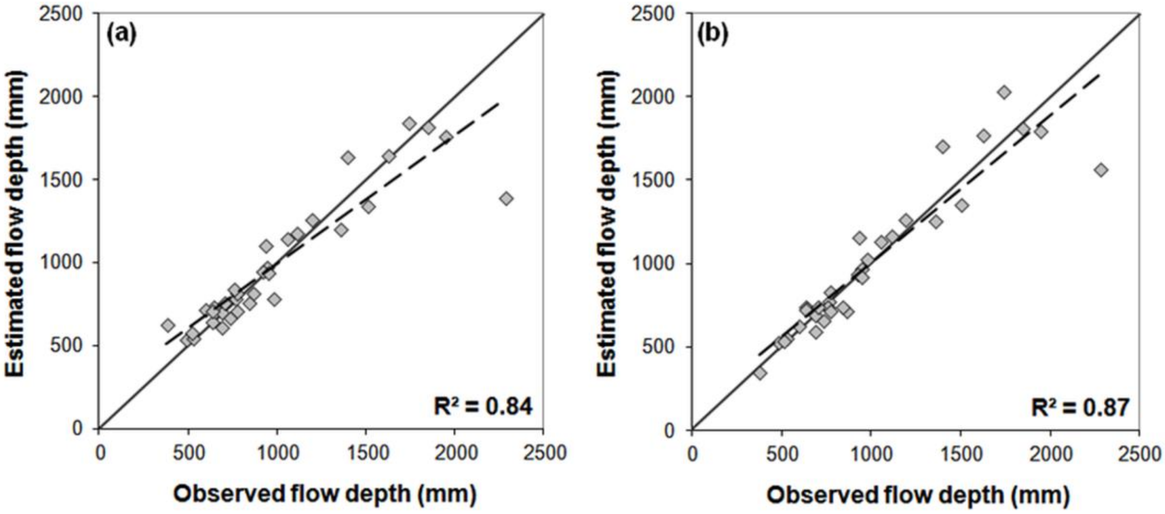

310000
232500
155000
77500
0
0
50000
100000
150000
Variogram (mm²)
Separation distance, lag (h)

Figure 4



(a)
Estimated flow depth (mm)
Observed flow depth (mm)
R² = 0.84
(b)
Estimated flow depth (mm)
Observed flow depth (mm)
R² = 0.87

Figure 5

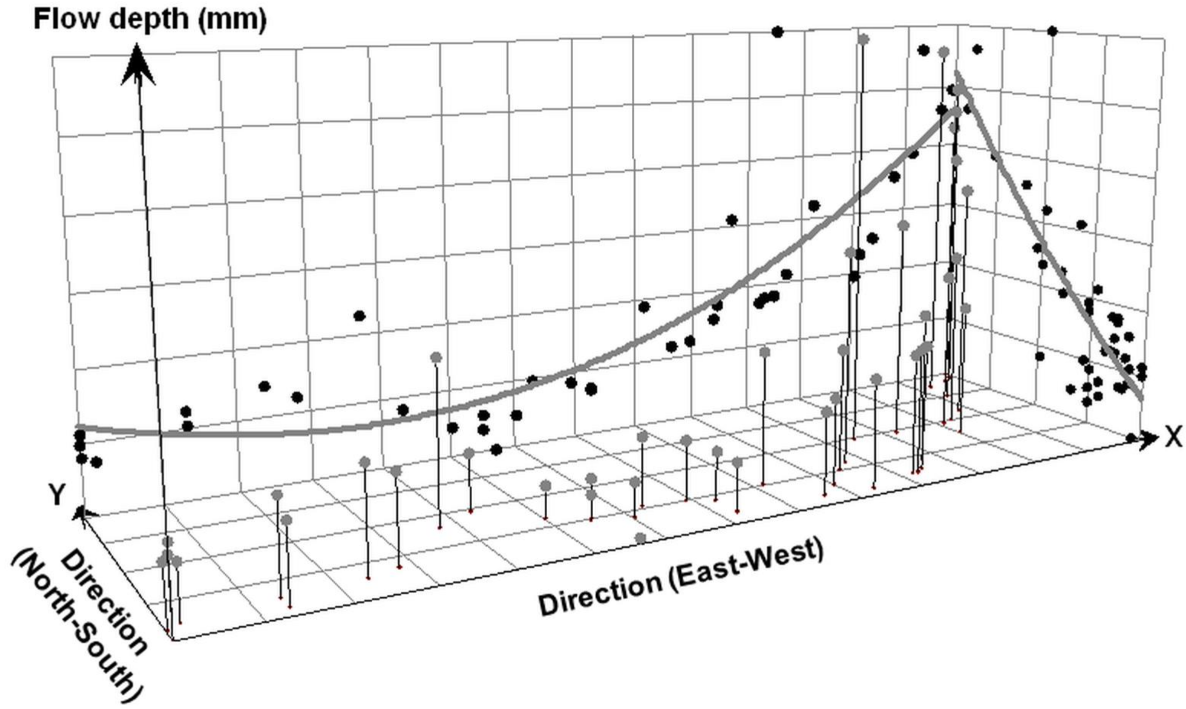
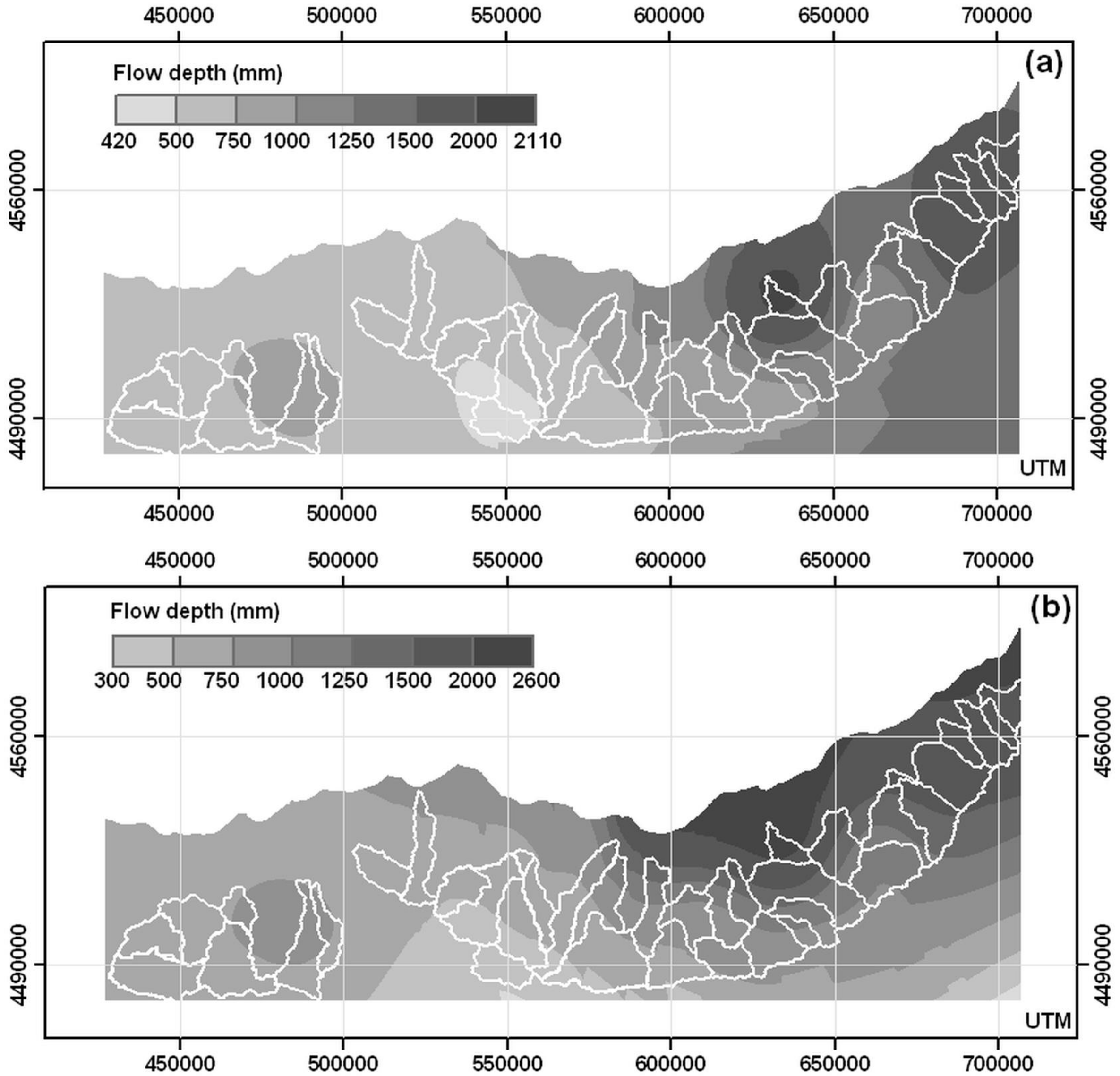
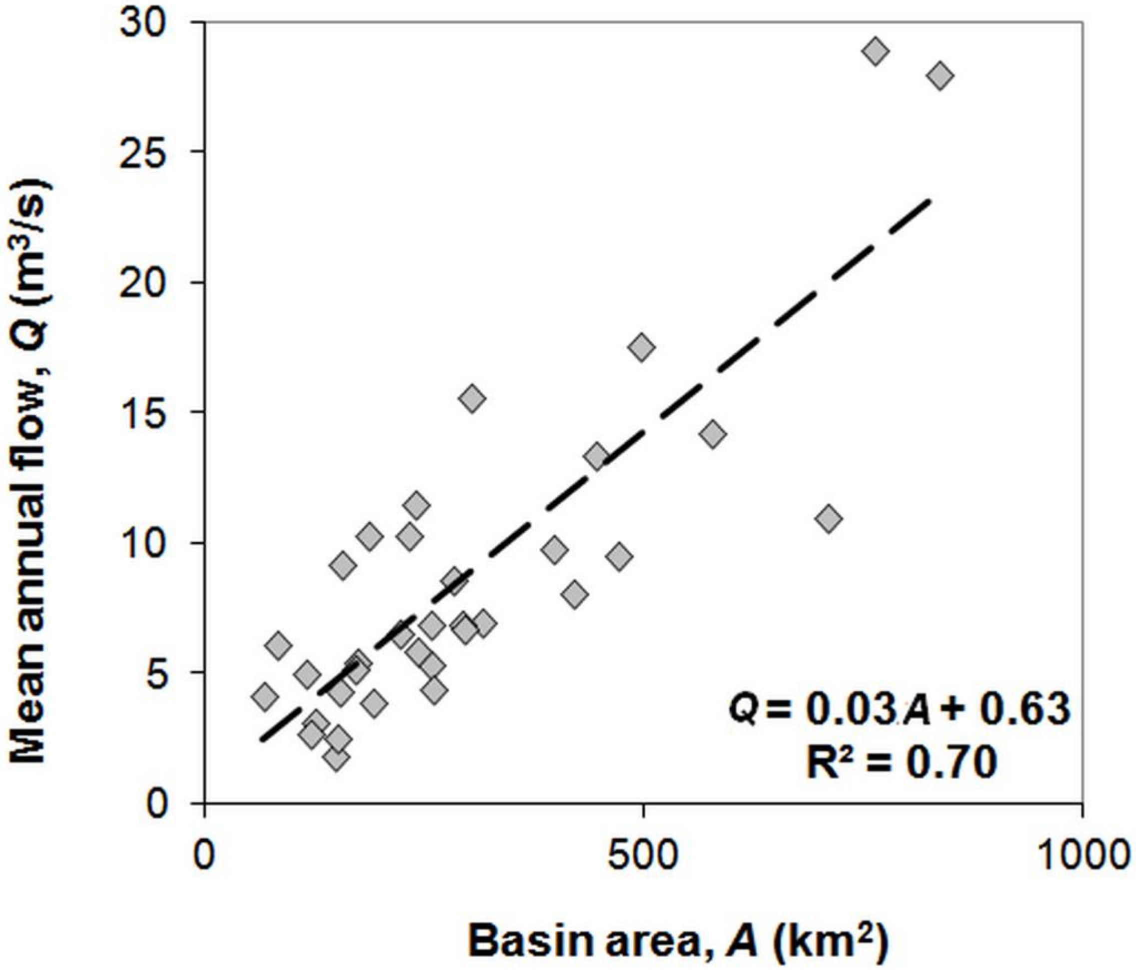


Figure 6



(a)
Flow depth (mm)
420 500 750 1000 1250 1500 2000 2110
450000 500000 550000 600000 650000 700000
4560000
4490000
UTM
(b)
Flow depth (mm)
300 500 750 1000 1250 1500 2000 2600
450000 500000 550000 600000 650000 700000
4560000
4490000
UTM

Figure 7



Mean annual flow, Q (m^3/s)
30
25
20
15
10
5
0
0
500
1000
Basin area, A (km^2)
$Q = 0.03A + 0.63$
$R^2 = 0.70$

Table 1

No	Gauge name	Area (km^2)	Elevation (m)	Record period	No	Gauge name	Area (km^2)	Elevation (m)	Record period
1	Ikisu	317.2	1037	1986-1999	21	Alcakkopru	243	700	1979-2005
2	Alancik	470.2	700	1986-2004	22	Ulucami	576.8	260	1979-2005
3	Ikisu	292.7	990	1965-1974	23	Serah	154.7	1170	1966-2001
4	Dereli	713	248	1962-2004	24	Yenikoy	171.6	470	1982-2004
5	Tuglacik	397.9	400	1986-2006	25	Cevizlik	115.9	400	1982-2002
6	Sinirkoy	296.9	650	1983-2005	26	Toskoy	223.1	1296	1965-2002
7	Hasanseyh	256.8	370	1984-2006	27	Toskoy	284.3	1210	1986-2001
8	Suttasi	124.9	188	1970-2004	28	Komurculer	83.3	250	1984-2002
9	CucenKopru	162.7	240	1980-2006	29	Derekoy	445.2	942	1966-2002
10	Bahadirli	191.4	17	1962-2002	30	Simsirli	834.9	308	1988-2004
11	Ormanustu	150	770	1985-1999	31	Kaptanpasa	231.2	480	1984-2006
12	Kanlipelit	708	257	1951-1989	32	Cat	277.6	1250	1982-1999
13	Ogutlu	728.4	160	1984-2004	33	Konaklar	496.7	300	1980-2005
14	Ikisu	149.6	1450	1984-1999	34	Topluca	762.3	233	1964-2002
15	Ortakoy	261	380	1980-2002	35	Mikronkopru	239.2	370	1980-2004
16	Ciftdere	121.5	250	1980-2006	36	Kemerkopru	302.2	230	1984-1997
17	Findikli	258.6	90	1979-2004	37	Arili	92.15	150	1982-2005
18	Agnas	635.7	78	1944-2002	38	Koprubasi	156	60	1966-2003
19	Aytas	421.2	510	1979-2005	39	Kucukkoy	66.37	310	1985-2006
20	Ortakoy	173.6	150	1979-2006	40	Baskoy	186.2	75	1978-2006

Table 2

	Ordinary	Universal
R^2	0.84	0.87
RMSE (mm)	185.76	164.48
MSRE	-0.059	-0.009

Table 3

No	Gauge name	Q_{obs} (m^3/s)	Q_{est} (m^3/s)					
			Ordinary		Universal		Regression	
4	Dereli	13.80	15.04	(8.95)	15.15	(9.8)	20.09	(45.7)
9	Cucenkopru	5.68	3.42	(-39.8)	3.29	(-42.0)	5.07	(-10.6)
13	Ogutlu	12.85	11.80	(-8.14)	11.73	(-8.7)	20.52	(59.7)
18	Agnas	12.20	13.93	(14.2)	13.99	(14.7)	17.98	(47.4)
32	Cat	8.79	9.98	(13.5)	8.96	(1.91)	8.21	(-6.65)
37	Arili	6.32	5.06	(-20.0)	5.27	(-16.6)	3.15	(-50.2)

**Parentheses represent relative errors (RE%)*

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