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DEVELOPMENT OF A REGIONAL MODEL FOR HYDROPOWER POTENTIAL IN WESTERN GREECE

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ABSTRACT

A regional model was developed in the present study for the determination of the flow duration curve at ungaged catchments, in western and northwestern Greece, which is a hydrologically homogenous region. A flow duration curve indicates the water availability at a site and is important for the estimation of the hydropower potential. A flow duration curve was generated for each of seven available stations at different rivers and then the parameters of the flow duration curves were correlated with geomorphological and climatic characteristics of the drainage basins for the derivation of the equations of the regional model. The model was verified using three hold out stations, in which the error ranged from 0.3 to 1.1%.

KEYWORDS: Epirus; Western Sterea; hydropower potential; regional model; water availability.

1. INTRODUCTION

The bold relief, characteristic of the Greek peninsula, contributes to a great diversification of climatic types in very short distances, as well as to a division into a plethora of small water basins and many water districts (fourteen). Two water districts constitute the study area of the present research; the water districts of Western Sterea and Epirus. The north-south direction of the Pindos mountain range, parallel to the coastline, plays an important role in precipitation and runoff regimes in Greece. Extending vertical to the prevailing western air masses, the mountain range causes the ascending and condensation of air masses, dividing the country into western high and eastern low precipitation areas. The climate varies from dry at the eastern Greece to humid at the north and western regions of Greece. The mean annual areal precipitation is characterized by high variability, ranging from 1150 mm in the northwestern part of the country to 350 in the central-eastern part. The availability of water resources is proportional to the general precipitation pattern.

A considerable attempt is being made during the last years for the precise determination of the water quantities consumed in each water district. The total annual demand for water under the present conditions, in all water districts of the country is estimated at 8184.3 hm^3. The 84% of these quantities are allocated for irrigation purposes, 12% for domestic use, 3% for industrial and energy purposes and 1% for livestock farming (NTUA, 2008). Regarding the two water districts of the study, the percentage of Western Sterea is about 5% of the total, while the respective value for Epirus is 2.5%. The water quantity allocated for the energy sector is used only for cooling purposes of the thermal electrical energy stations.

The monitoring of the hydrometeorological conditions constitutes basic infrastructure, necessary for the rational management of water resources (Baltas, 2004; Sofios *et al.,* 2007; Baltas and Mimikou 2006), as well as for the exploitation of the hydropower potential, which is in demand due to the requirement for energy production from alternative, emission free sources. Hydropower generation is sensitive to the amount of streamflow, thus requiring the operation of a dense network of hydrometric stations, which is often not feasible to be done. The aim of the present study is to develop a simple technique for estimating water availability at ungaged catchments in western and northwestern Greece. This was done by the regionalization of monthly flow duration characteristics at the water districts of Western Sterea and Epirus (Mimikou and Rao 1983, Mimikou 1982, 1984). Geomorphological, hydrological and climatic characteristics of the drainage basins were used as input information to the regional model and conclusions were drawn concerning the accuracy of the technique.

2. STUDY AREA

The study area consists of the water districts of Western Sterea and Epirus, which present common boundaries, similar size, geomorphological, climatic and hydrological conditions. They are at the western and northwestern part of the country and are characterized by a surplus of water resources, which is of major importance for the economy, at local and national level.

The water district of Epirus is 10.026 km^2 in area with the highest precipitation volume of the entire country. It is characterized by a surplus of water balance and low development rate. The major rivers of the water district are River Arachthos (146 km), River Kalamas (136 km) and River Aoos. Temperature-precipitation diagrams at the meteorological stations of Arta and Ioannina, both cities are located in Epirus water district, were derived. These diagrams depict the mean monthly values of precipitation and air temperature for the time period 1965-1995. The Arta meteorological presents high precipitation volume with mean annual value of 1063 mm and mean annual air temperature of 17^{o}C. Walter (1955) and Bagnouls & Gaussen (1957) and Alexander *et al*. (2006) proposed the combined representation of temperature and precipitation values through the year to display climatic patterns. Walter (1955) produced the well known standardised format for graphically representing the Bagnouls and Gaussen climatic diagrams. The points of inflection of the two curves (Figure 1) show the time points when rainfall depth is two times the air temperature. The area enclosed from the two curves indicates the duration and the intensity of the dry period. The high temperatures during the summer months denote losses due to water evaporation and evapotranspiration.

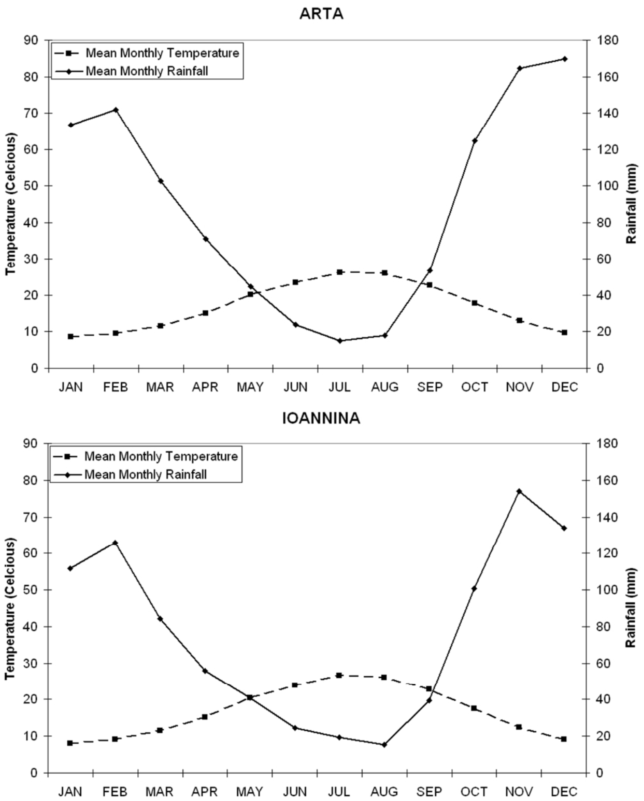

Figure 1. Temperature – precipitation diagrams

The water district of Western Sterea is 10.199 km^2 in area. The rivers Acheloos, Evinos and Mornos and the lake Trichonida constitute the major surface water resources of the district, in addition to the underground water resources, which generally stay unutilized. The water resources are mainly used for irrigation and for the production of energy. At present, a part (equal to 8.6%) of the district's water potential, from the river basins of Evinos and Mornos, is used for the water supply of the capital city of Athens. A small part is also transferred to Thessaly via the Plastiras lake. Four hydroelectric plants have been constructed in Acheloos river basin for the production of electrical energy. Regarding the coastal areas (e.g. Gulf of Ambrakikos, Arta), the water resources have been degraded due to the extensive agriculture.

3. METHODOLOGY

3.1 Data analysis and check

The data used in this study were hydrological, climatic and geomorphological. The hydrological data (monthly flows) derived from the analysis of the measurements of the hydrometric stations in Western and Northwestern Greece. These were provided through the use of a Data Base system of raw and processed hydrometeorological and hydrological data that was developed as part of the Data Base of Hydrological and Meteorological Information (D.B.H.M.I). The selection of stations in each river basin was based on the record length and the data reliability. The stations at each river, the basin area and the mean hyper annual runoff and the runoff coefficient for each station are presented in Table 1.

A quality check was performed on the mean hyperannual runoff of the hydrometric stations and on the runoff coefficients of the respective river basins. It is expected that for each river, the mean annual runoff should increase with the increase in the basin area. This is valid for all stations. Concerning the runoff coefficient, a decrease is expected with the increase in the basin area. Despite the fact that this is not the case at the river of Kalamas, the stations were included in the calibration of the model, except from the station of Gormos that is characterized by lower runoff coefficient and smaller basin area in comparison to the other stations. Overall, ten stations were selected for the study. Seven of them were used for the regional model calibration and three for the model verification. The stations and the boundaries of their drainage basins are depicted in Figure 2. In this figure, the stations from north to south in the water district of Epirus are named in Table 1.

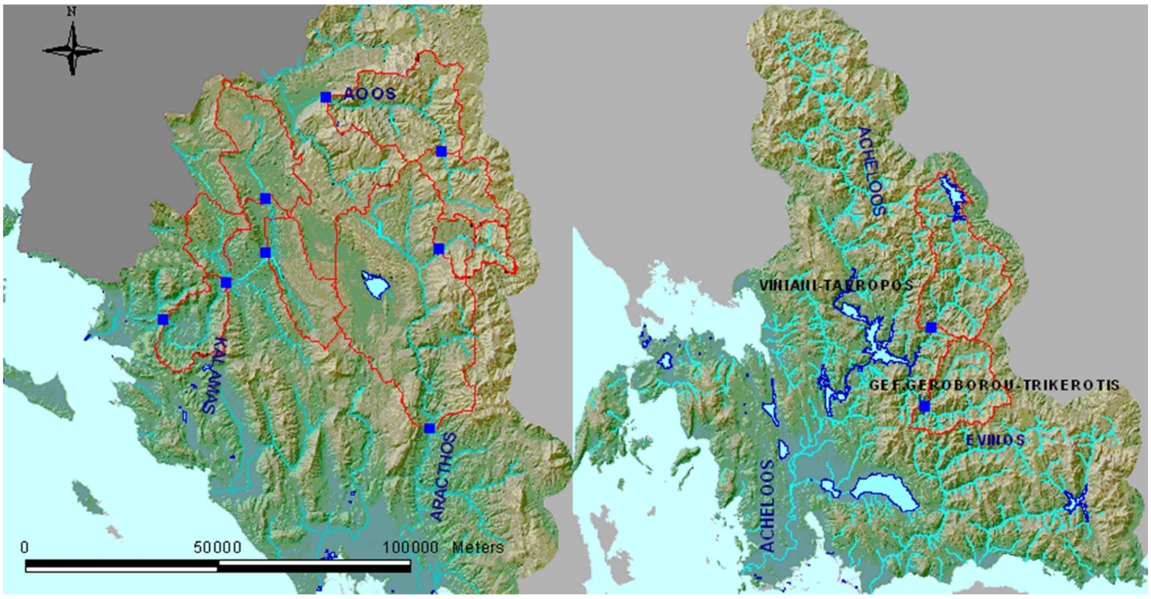

Figure 2. Stations and their drainage basins in the water districts of Epirus (left) and Western Sterea (right)

3.2 Climatic, topographic and geomorphological characteristics

The climatic data concern the mean annual areal precipitation P (mm) of the selected stations whereas the geomorphological data involve the drainage area A (km^2), the length L (km) of the main river course upstream the flow gauge station and the hypsometric fall H (m), which is equal to the difference between the altitude of the station and the average altitude of the drainage basin. These characteristics were estimated using Geographic Information Systems (GIS) (ESRI 2004).

Regarding the water district of Epirus, the mean annual rainfall ranges from 1000-1200 mm at the coastal areas to 2000 mm at the mountainous areas respectively. The mean annual rainfall volume is estimated at 15.878 hm^3 (Ministry of Development, 1997). The volume of surface runoff is about 5.523 hm^3. The river basins with area greater than 1000 km^2 are those of Aoos, Arachthos and Kalamas, covering about 58% of the total extent of the district. Aoos is a transboundary river that flows towards the Albanian territory. The Aoos river basin is 2.083 km^2 in area and the length of the river is 96 km within the Greek boundaries. A percentage equal to 22% of the total extent of the district corresponds to watersheds with area less than 40 km^2.

Concerning the water district of Western Sterea, the mean annual rainfall depth ranges between 800-1000 mm at the coastal and flat areas, 1400 mm at the mountainous areas, while it exceeds 1800 mm at high-elevation areas. The mean annual rainfall volume is estimated at 8.680 hm^3, based on the mean annual rainfall depth and the extent of the water district (Ministry of Development, 1997). The surface runoff is about 5.296 hm^3. The river basins with area greater than 1000 km^2 are those of Acheloos (5.635 km^2) and Evinos, which cover 65% of the total extent of the district. A percentage equal to 23% corresponds to the watersheds that are less than 40 km^2. The topographic, geomorphological and climatic characteristics of the selected stations and their basins are shown in Table 1.

Table 1. Characteristics of the selected hydrometric stations and their drainage basins

Station	X	Y	Altitude (m)	Mean Annual Prec. P(mm)	Basin Area A (km^2)	River Length L (km)	Hypso metric fall H (m)	Mean Hyper annual Runoff ($m^3 s^{-1}$)	Runoff Coeff.
Gefyra Konitsis (Aoos)	214293	4429406	404.4	1152.2	671.5	76.2	956.8	21.91	0.893
Vovoussa (Aoos)	247671	4424382	971.8	1251.5	202.8	35.3	524.3	7.24	0.899
Gefyra Aretis (Kalamas)	208465	4414176	377.5	1271	365.5	41.5	308.4	8.39	0.569
Gefyra Soulopoulo (Kalamas)	208869	4401871	160.4	1276.1	686.8	60.8	474.3	19.32	0.695
Metsovitikos - Megalo Peristeri (Arachthos)	247718	4402458	595.4	1246.5	170.9	24.2	659.0	4.6	0.68
Raveni (Kalamas)	200168	4394787	81.9	1291.7	1295.3	79	506.4	47.34	0.766
Kioteki (Kalamas)	186086	4386730	20.3	1285.7	1516.3	115.7	533.0	37.38	0.705
Pistiana (Arachthos)	246135	4362211	164.1	1483	1113.7	85.2	858.7	31.47	0.601
Viniani-Tavropos (Acheloos)	300495	4316759	340	1258.5	717.8	64.7	729.2	15.34	0.536
Gefyra Geroborou-Trikeriotis (Acheloos)	298405	4294542	410.3	1241.5	437.2	33.5	744.0	10.35	0.601

3.3 Flow duration curves

The flow duration curve is the plot of discharge Q versus the percent of time (D) during the period of the record in which the particular discharge is equaled or exceeded. The flow duration curves reflect the availability of discharge at a site and are very important for the determination of the hydrodynamic potential at a given site along the river course (Cigizoglu and Bayazit, 2000; Yu and Yang, 1996; 2000). The potential depends on the hydraulic head and the available runoff of the river at that location. The discharge value of a given flow duration curve shows the available runoff for hydrodynamic exploitation at the respective percent of the time. The average runoff $\overline{Q}$ can be calculated via the flow duration curve.

The total hydrodynamic potential of a country is equal to the sum of all the hydrodynamic potentials that can be used for hydropower production (Mimikou, 1994). The divisions of the hydrodynamic potential are the following:

The Theoretical hydrodynamic potential is the total average energy that theoretically can be produced annually and is calculated by the equation:

$$E_{TH} = 8760\ I_{TH}\ \text{(kWh)} \tag{1}$$

where

$I_{TH}=9.81\sum(\overline{Q}\ \overline{H})$ (kW)

$\overline{Q}$ is the average hyperannual surface runoff (without losses) from a drainage area A and $\overline{H}$ is the total average drop between the study site and the sea surface (or other reference).

The theoretical hydrodynamic potential is usually given in units of kilowatt-hours per square kilometer (kWh km^{-2}), so it is divided by the respective drainage area.

The Technically exploitable hydrodynamic potential is the total theoretical hydrodynamic potential, subtracting the losses of the hydrodynamic exploitation (REF). It represents the total of the average useful energy that could (theoretically) be produced per year and for the rivers in Greece it is given from the equation (Mimikou, 1994):

$$E_T = 20 \div 30\%\ E_{TH} \tag{2}$$

The Economically exploitable hydrodynamic is the technically exploitable hydrodynamic, provided that the utilisation cost does not make prohibitive the cost of electrical power production (compared to the production of the same energy from another source) (Mimikou, 1994). The economically exploitable hydrodynamic is expressed by a ratio percentage of the technically exploitable potential:

$$E_0 \approx 20 \div 80\%\ E_T \tag{3}$$

3.3.1 Calibration of the flow duration curve

In this study, monthly values of runoff were used for the derivation of the flow duration curves. The mathematical models in literature for the calibration of the flow duration curves are the following (Mimikou and Kaemaki, 1985):

$$Q=a\exp(-bD) \tag{4}$$

$$Q=a\,D^{-b} \tag{5}$$

$$Q=a-b\ln D \tag{6}$$

$$Q=a-bD+cD^2 \tag{7}$$

$$Q=a-bD+cD^2-dD^3 \tag{8}$$

Model selection was based on the resulting correlation coefficients. The calibration of the flow duration curves consists of two steps; first, the monthly flow data were classified in descending order and the values of the parameter D (percentage of time that the respective runoff was exceeded) were calculated for each monthly value of discharge using the equation $D = m / (n+1)$, where m is the classification number of each monthly discharge and n is the total number of months with flow data. Next, the discharges corresponding to 4%, 8%, 12% …100% of the percent of time D were extracted by linear interpolation to generate 25 pairs of (discharge Q, parameter D) values for each station. Afterwards, the flow duration curve, plot of Q versus D was produced for each of the seven stations and the models of equations 4-8 were fitted to the plot. The performance of each model for the Raveni station is shown in Figure 3. The model with the greater correlation coefficient was selected to be the best model to parameterize the flow duration characteristics at each station. It was found that the model of equation (8) is the best suited for all stations.

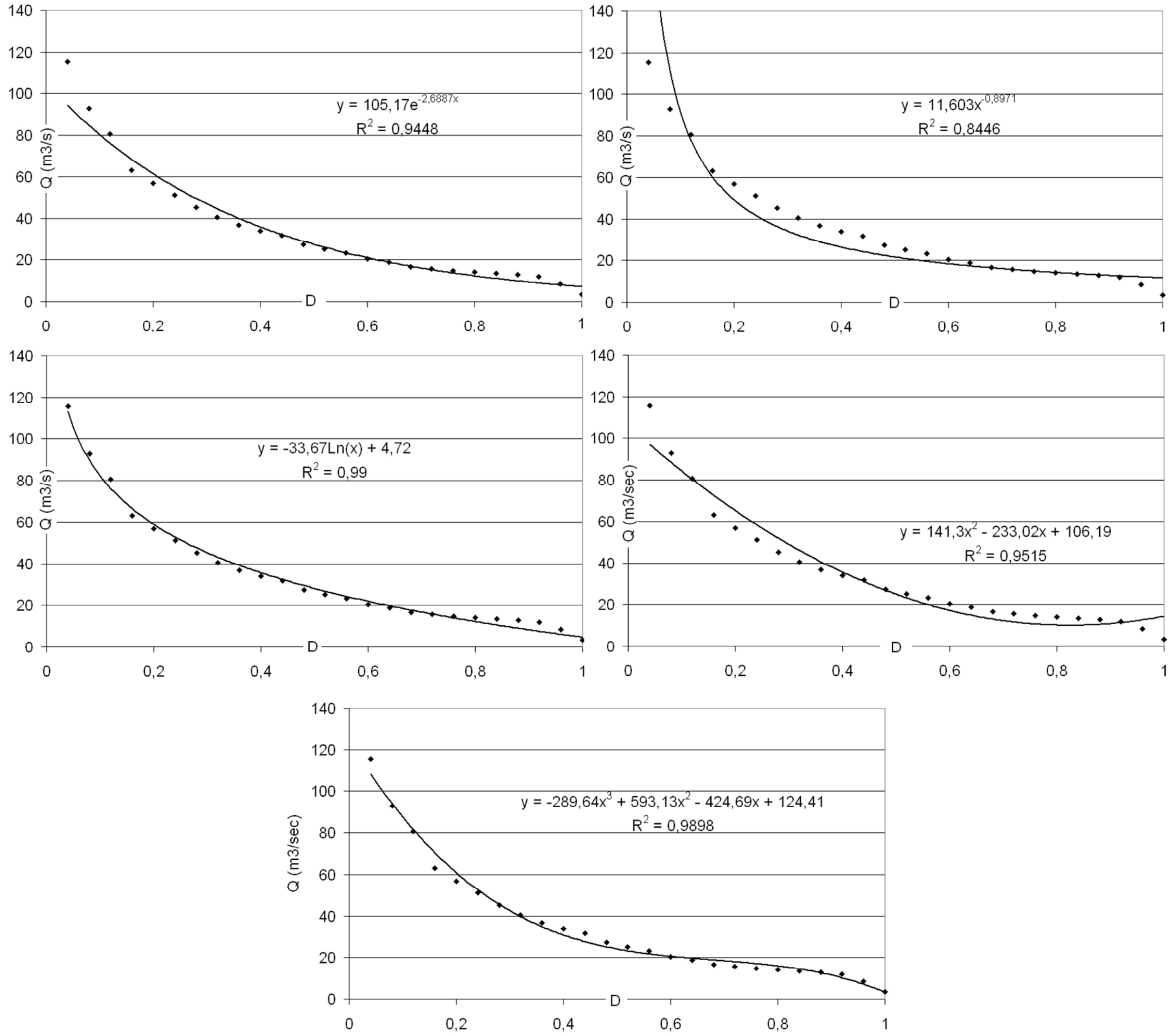

Figure 3. Performance of each model for the Raveni station

4. RESULTS

4.1 The regional model

The purpose of this study is to develop a regional model in order to describe the geographical variation of the four parameters a, b, c, d of the selected model, in a hydrologically homogenous area. The parameters of the model of equation (8) for all stations and the correlation coefficient are shown in Table 2.

Table 2. Parameters of the selected model and the respective correlation coefficient

Stations	a	b	c	d	Correlation Coeff.
Vovoussa	23.479	66.020	71.000	28.467	0.997
Gefyra Aretis	21.982	54.196	57.724	22.942	0.999
Metsovitikos-Megalo Peristeri	12.099	28.938	33.219	15.855	0.990
Kioteki	159.300	572.660	814.870	394.040	0.988
Pistiana	89.375	255.040	299.870	129.210	0.998
Raveni	124.410	424.690	593.130	289.640	0.990
Gefyra Geroborou-Trikeriotis	34.291	102.900	123.640	54.772	0.995

The regional model resulted from the multiple regression analysis of each one of the parameters a,b,c,d with the morphoclimatic characteristics P, A, H and L of the drainage basins, which are shown in Table 1. The function LINEST in MS Excel was used for the multiple regression analysis. The regression equations that were tested are the following:

$$V=bo+b_1P+b_2A+b_3L+b_4H \tag{9}$$

$$V=boP^{b1}(A/L)^{b2}H^{b3} \tag{10}$$

$$V=boP^{b1}A^{b2}(H/L)^{b3} \tag{11}$$

$$V=boP^{b1}A^{b2}H^{b3}L^{b4} \tag{12}$$

where V is the dependent variable, which represents the parameters a, b, c, d and $b_{o,}$ $b_{1,}b_{2\ ,}b_{3,}$ b_4 are constants. Equation (12) outperforms all the tested models as it presented the highest correlation coefficient for all parameters, in all stations. The equations of the regional model and the respective coefficients are the following:

$$a= 16.949\ P^{-1.090}\ A^{1.254}\ H^{0.160}\ L^{-0.048} \qquad r= 0.994 \tag{13}$$

$$b= 27.556\ P^{-1.108}\ A^{1.771}\ H^{0.065}\ L^{-0.556} \qquad r= 0.981 \tag{14}$$

$$c= 0.297\ P^{-0.392}\ A^{2.229}\ H^{-0.114}\ L^{-1.113} \qquad r= 0.949 \tag{15}$$

$$d= 0.000134\ P^{0.696}\ A^{2.598}\ H^{-0.279}\ L^{-1.671} \qquad r= 0.902 \tag{16}$$

The regional model, as described from the above equations, may be used at any other catchment in the hydrologically homogenous area of western and northwestern Greece, for the determination of the parameters a,b,c,d of the monthly flow duration curves.

4.2 Model Verification

Three hydrometric stations from different rivers that were excluded from the calibration procedure were used for the verification of the developed regional model. These stations were: Soulopoulo on Kalamas River, Gefyra Konitsis on Aoos River and Viniani–Tavropos station on Acheloos River. The geomorphological and the climatic characteristics of the drainage basins of these three stations were known, thus the parameters a, b, c, d were calculated by using the equations (13) to (16) of the regional model. Afterwards, equation (8) of the selected model was used for the calculation of discharge Q versus the parameter D in order to plot the monthly flow duration curve.

The flow duration curves at the above three stations were compared with the curves derived from the observed data. The fitting of the curves is very good for each of the three stations. The root mean square error ε indicates the accuracy of the developed regional model and was calculated from the equation:

$$\varepsilon\ (\%) = N^{-1}\left[\sum_{i=1}^{N}\left(\frac{Q_i - Q'_i}{Q_i}\right)^2\right]^{1/2} \tag{17}$$

where: Q_i is the observed discharge, Q_i**'** is the modeled discharge, N is the number of data.
The root mean square error for each station was: Soulopoulo: ε= 1.4%, Viniani- Tavropos: ε=0.70% and Gefyra Konitsis: ε=0.3%.

5. CONCLUSIONS - SUGGESTIONS

The flow duration curves indicate the water availability at a river site and they are important for the estimation of the hydropower potential in preliminary hydroelectric energy studies. The best model of monthly flow duration curve was proved to be the following: $Q=a-bD+cD^2-dD^3$, where D is the percent of time during the period of the record in which the discharge Q is equaled or exceeded. The geomorphological characteristics of the drainage basin area, the hypsometric fall and the length of the main river course from the divide of the basin to a certain site, as well as the climatic characteristic of the mean annual areal precipitation were necessary for explaining the geographic variation of the flow duration parameters a, b, c, d.

The developed regional model can be successfully used for the estimation of the flow duration curves at ungaged sites, but within the hydrologically homogenous region of western and northwestern Greece. Comparing the results of this study to a previous one for the same region (Mimikou and Kaemaki, 1985), the accuracy of the developed regional model was proved to be better, due to the greater time period of monthly flow data records of the used hydrometric stations.

The incorporation of additional characteristics, such as terrain slope, vegetation cover and geological formations of the hydrological basin into the regional model is suggested to be tested in other studies concerning the present water districts. In addition, a regional model could be developed in other water districts of the country in order to test the performance of this technique.

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