NATIONAL TECHNICAL UNIVERSITY

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OF POST-GRADUATE STUDIES
"WATER RESOURCES SCIENCE & TECHNOLOGY"

MASTER THESIS

DEVELOPMENT OF A REGIONAL MODEL FOR THE DETERMINATION OF ENVIRONMENTAL FLOWS BASED ON HYDROMETRIC DATA

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WATER
RESOURCES
SCIENCE &
TECHNOLOGY

SUPERVISOR: Professor EVANGELOS BALTAS

Athens, February 2021

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SERGIOS LAGOGIANNIS

Committee

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Athens, February 2021

ABSTRACT

This research study was based on recent (2018-2019) raw hydrometric data, comprising of concurrent measurements of stage and discharge in Greek rivers. The gauging sites had a good spatial distribution over mainland Greece, located in six River Basin Districts, covering the most part of southern, central and north-northeastern parts of the country. The availability of hydrometric data has enabled the preliminary hydrologic analysis of a big number of basins over Greece and subsequently made possible to a) examine the performance of different rating curves and b) develop a regional model to determine environmental flow, based on geomorphological and climatic characteristics.

At first, a brief theoretical background on the significant hydrologic concepts and tools included in this study is given. Then a quality control process was implemented, since all the hydrologic tools incorporated were directly dependent on the quality of the hydrometric data. The quality control, resulted in the selection of valid gauging sites, exclusion of erroneous measurements and increased performance of the tools incorporated. Three rating curves were examined over the selected sites. Their performance was evaluated and the optimal relationship was established, for each position examined. The possibility of detecting a prevailing rating curve for Greek rivers was also examined.

Next, four low-flow indices (Q_{90}, Q_{95}, 10% MAF, 30% MAF) were acquired for each site, from the most widely used hydrologic methods for environmental flow assessment. Subsequently, they were compared to discharge values set by Greek regulations, to determine the most appropriate index for approximating environmental flow.

Finally, a regional model for determination of environmental flow was developed, through stepwise multiple linear regression and its performance was discussed and evaluated. The model, estimates the Q_{90} index (regarded here as indicative of environmental flow) based on four independent geomorphological and climatic descriptors of each catchment: catchment area (A), mean annual precipitation (P), curve number (CN) and slope (S). The suggested model could be a significant tool to assess e-flows, at sites where timeseries of discharge are not available, which is more than often the case in Greek rivers.

ΠΕΡΙΛΗΨΗ

Η παρούσα έρευνα έχει βασιστεί σε πρόσφατα (2018-2019) πρωτογενή υδρομετρικά δεδομένα, από ταυτόχρονες μετρήσεις στάθμης και παροχής που διενεργήθηκαν σε ποτάμια στην Ελλάδα. Οι σταθμοί μέτρησης έχουν υψηλή χωρική κατανομή στην ηπειρωτική Ελλάδα, κατανέμονται εντός έξι διαφορετικών Υδατικών Διαμερισμάτων και καταλαμβάνουν το μεγαλύτερο μέρος των νότιων, κεντρικών και βορειο-βορειοανατολικών τμημάτων της χώρας. Η διαθεσιμότητα υδρομετρικών δεδομένων, επέτρεψε την προκαταρκτική υδρολογική ανάλυση μεγάλου αριθμού Λεκανών Απορροής Ποταμών (ΛΑΠ) και στη συνέχεια κατέστησε δυνατή α) την εξέταση της προσαρμογής διαφορετικών καμπυλών στάθμης-παροχής και β) την ανάπτυξη ενός μοντέλου για τον προσδιορισμό της οικολογικής παροχής ποταμών, με βάση τα γεωμορφολογικά και κλιματικά χαρακτηριστικά των ΛΑΠ.

Αρχικά, δίνεται ένα σύντομο θεωρητικό υπόβαθρο για τις πλέον σημαντικές υδρολογικές έννοιες και εργαλεία, που εμπεριέχονται σε αυτήν τη μελέτη. Στη συνέχεια εφαρμόζεται μια διαδικασία ποιοτικού ελέγχου που κρίθηκε απαραίτητη, δεδομένου ότι όλα τα υδρολογικά εργαλεία που χρησιμοποιήθηκαν εξαρτώνται άμεσα από την ποιότητα των υδρομετρικών δεδομένων. Ο ποιοτικός έλεγχος, είχε ως αποτέλεσμα την επιλογή των έγκυρων σταθμών μέτρησης και παράλληλα συνέβαλλε στον αποκλεισμό λανθασμένων μετρήσεων και την αύξηση της απόδοσης των εργαλείων που αξιοποιήθηκαν. Στη συνέχεια εξετάστηκαν τρεις σχέσεις για την κατάρτιση της καμπύλης στάθμης-παροχής στις επιλεγμένες θέσεις. Η απόδοση τους αξιολογήθηκε και προσδιορίστηκε η βέλτιστη σχέση, για κάθε θέση που εξετάστηκε. Επίσης διερευνήθηκε η πιθανότητα ύπαρξης μιας επικρατούσας καμπύλης στάθμης-παροχής, για όλα ποτάμια της Ελλάδας.

Στη συνέχεια, για κάθε θέση, εκτιμήθηκαν οι τιμές παροχής για τέσσερεις δείκτες χαμηλής ροής (Q_{90}, Q_{95}, 10% MAF, 30% MAF). Οι τέσσερεις δείκτες χαμηλής ροής θεωρούνται γενικά ενδεικτικοί της οικολογικής παροχής και προκύπτουν από τις δύο ευρύτερα χρησιμοποιούμενες υδρολογικές μεθόδους. Οι τιμές αυτές, συγκρίθηκαν με τις τιμές οικολογικής παροχής που ορίζουν οι ελληνικοί κανονισμοί και επιλέχθηκε ο πλέον αντιπροσωπευτικός δείκτης.

Τέλος, αναπτύχθηκε ένα μοντέλο για τον προσδιορισμό της οικολογικής παροχής, μέσω πολλαπλής γραμμικής παλινδρόμησης και η απόδοσή του συζητήθηκε και αξιολογήθηκε. Το μοντέλο, εκτιμά τον δείκτη Q_{90}, που θεωρείται εδώ ως αντιπροσωπευτικός της οικολογικής παροχής, βάσει τεσσάρων ανεξάρτητων γεωμορφολογικών και κλιματικών χαρακτηριστικών κάθε ΛΑΠ: έκταση λεκάνης (A), μέση ετήσια βροχόπτωση (P), αριθμός καμπύλης απορροής (CN) και μέση κλίση (S). Το προτεινόμενο μοντέλο θα μπορούσε να είναι ένα σημαντικό εργαλείο για την εκτίμηση της οικολογικής παροχής, σε τοποθεσίες όπου δεν υπάρχουν διαθέσιμες χρονοσειρές παροχής, περιορισμός που συναντάται αρκετά συχνά σε ποτάμια στην Ελλάδα.

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TABLE OF CONTENTS

ABBREVIATIONS

e-flow	Environmental flow
EFA	Environmental flow assessment
Q_{90}	Discharge value equaled or exceeded 90% of time (in a FDC)
Q_{95}	Discharge value equaled or exceeded 95% of time (in a FDC)
10% MAF	10% of Mean Annual Flow
30% MAF	30% of Mean Annual Flow
7Q10	7-day average minimum for 10-year return period
RDB	River Basin District
A	Catchment area
L	Length of main stem
H	Average catchment elevation
P	Average annual precipitation
S	Slope
CN	Curve number
FDC	Flow duration curve
R^2	Coefficient of determination
RMSE	Root mean square error
MAPE	Mean absolute percentage error
MLR	Multiple Linear Regression
GIS	Geographical Information System
NMWP	National Monitoring Water Network
USGS	United States Geological Survey
USDA	United States Department of Agriculture

EXTENDED ABSTRACT

Introduction

As increasing human water demands compete with varying water allocation needs and ecosystem reservation, water resources management is confronted with serious challenges (Arthington et al., 2018). In recent decades there has been a considerable shift of interest in management of water resources, towards the provision of environmental flows as a mean of protecting, preserving and restoring riverine ecosystems. Raised concern on environmental issues related to water allocation issues, combined with a deeper understanding of the water cycle has led to a growing demand for hydrometric data. However, the ability to plan and effectively manage water resources is often limited from the absence of consistent and high-quality hydrometric data (Walker, 2000; Singh et al., 2014) (Petts, 2009; Poff, 2018).

Even more, scarcity of relevant and valid data is worldwide a frequent shortcoming due to costs of installation, operation, and management of the gauge (Atieh et al., 2017) that significantly impairs planning, decision making and environmental protection (Irving et al., 2018). The problem of lack of sufficient hydrological data is particularly severe in Greece, where the network of hydrometric stations, which were installed and operated by the Public Power Corporation in previous decades, have recently halted their operation. This has changed, however, with the implementation of the European Framework Directive 2000/60. Greece has created the National Monitoring Water Network (NMWN) to systematically and consistently gauge and monitor quantitative and qualitative status of surface water and groundwater.

The monitoring program operated by NMWN has made available, for the first time in recent years, consistent streamflow data from gauging stations located in the most significant Greek rivers, distributed over six River Basin Districts (RBD), covering the most part of mainland Greece. The data spans over a period of almost two years, from April of 2018 until December of 2019, consisting of 21 concurrent measurements of stage and discharge, per gauging site. The availability of this datasets, made it possible to apply a series of hydrological tools and conduct a primary hydrologic analysis for a big part of Greece, focusing on stage-discharge relationship and assessment of environmental flows.

Theoretical Background

Q-H Curves

The stage-discharge relationship, also referred to as rating curve, is the empirical or sometimes (also) theoretical relationship between stage (H) and discharge (Q) in a river section (Braca & Grafiche Futura, 2008). The development of a rating curve involves three main steps: a) the collection of field data, i.e. stage (H) and discharge (Q), b) the quality control of the data and c) the selection of the appropriate method to establish a mathematical model that associates the stage and discharge parameters (Othman et al., 2019). Quality control refers to the process of scrutinizing the raw hydrometric datasets to identify any potential erroneous measurements and determine the valid stage and discharge pairs. The process of curve fitting involves a generalized function, the coefficients of which will be optimized for the best fit between the measured equation and the gauging data (Chandrasekaran & Muttil, 2005).

Environmental Flow

The concept of environmental flow (e-flow) was developed to yield the quality and quantity of flow that must be maintained in a river, in order not to affect its specific desired ecological features and to achieve the desired ecological objectives. These features may relate to the physicochemical or biological characteristics of the river as well as the relationships between them. A large number of methodologies for environmental flow assessment (EFA) have been developed worldwide and can be grouped in four basic categories: a) hydrologic, b) hydraulic, c) habitat simulation and d) holistic. No method is overall superior to the others, however hydrologic methodologies are the simplest and non-resource intent methodologies as well as the more widely used for EFA (Tharme, 2003). Flow Duration Curves (FDC) and Mean Annual Flow (MAF) are the most widely used of the hydrologic methodologies where, low-flow indices are set as exceedance percentiles of FDCs or percentages of MAF.

Flow Duration Curves

A FDC is a cumulative frequency curve over the whole range of discharges recorded over a specific time period (Searcy, 1959). It illustrates the percent of time a certain discharge was equaled or exceeded over a certain time period and is considered as a signature of the flow regime of a basin. It is used in defining ecological flows and in low-flows estimation (Farmer et al., 2015; Verma et al., 2017). As a general rule, the shape and general characteristics of a FDC are directly related to the period-of-records data on which it is constructed. In addition, the shape of a FDC is impacted greatly by two determining factors: climate and catchment characteristics (Castellarin et al., 2013).

Regional Model

The determination of e-flows requires continuous long-term streamflow information but only few sites are under constant and consistent gauging. In the absence of streamflow observations, decisions made in ungauged sites are based on data spatially transferred from other, gauged, sites. The process of transferring parameters of models calibrated in gauged catchments (donor) to neighboring ungauged catchments (receiver) of interest is generally referred to as regionalization (Merz & Blöschl, 2004). The regression model approach is perhaps the most widely used technique in low-flow estimation at ungauged sites (Smakhtin, 2001; Kokkonen et al., 2003, Ouarda et al., 2008) as they are easy to use and usually do not need much effort to provide their inputs (Eslamian et al., 2010). Regression models are mathematical methods that examine potential relationship of a flow signature (e.g. low-flow index) with independent geomorphological or climatic characteristics of a catchment. Once the relationship is established, the flow index can be estimated in the ungauged basin by defining the values of the physical and climatic attributes selected

Study Area & Data Used

This research study was based on the analysis of primary (raw) data, spanning over a two-year period from April of 2018 until December of 2019, of gauging sites covering the most part of mainland Greece. For each month a unique value was recorded over stage and discharge, totaling 21 measurements per site. In the absence of more measurements, these unique values were treated as indicative mean values for each month in this research. Audit of the datasets excluded all gauging sites with regulated flow regimes, sites with frequent cross-section alterations, sites with insufficient number of measurements and sites in transboundary rivers that do not originate from Greece.

Finally, 16 sites were selected (Figure 1), with a high number of good quality measurements and significant geomorphological variation. The selected sites were distributed over a wide range of mainland Greece, occupying six different River Basin Districts (RBD).

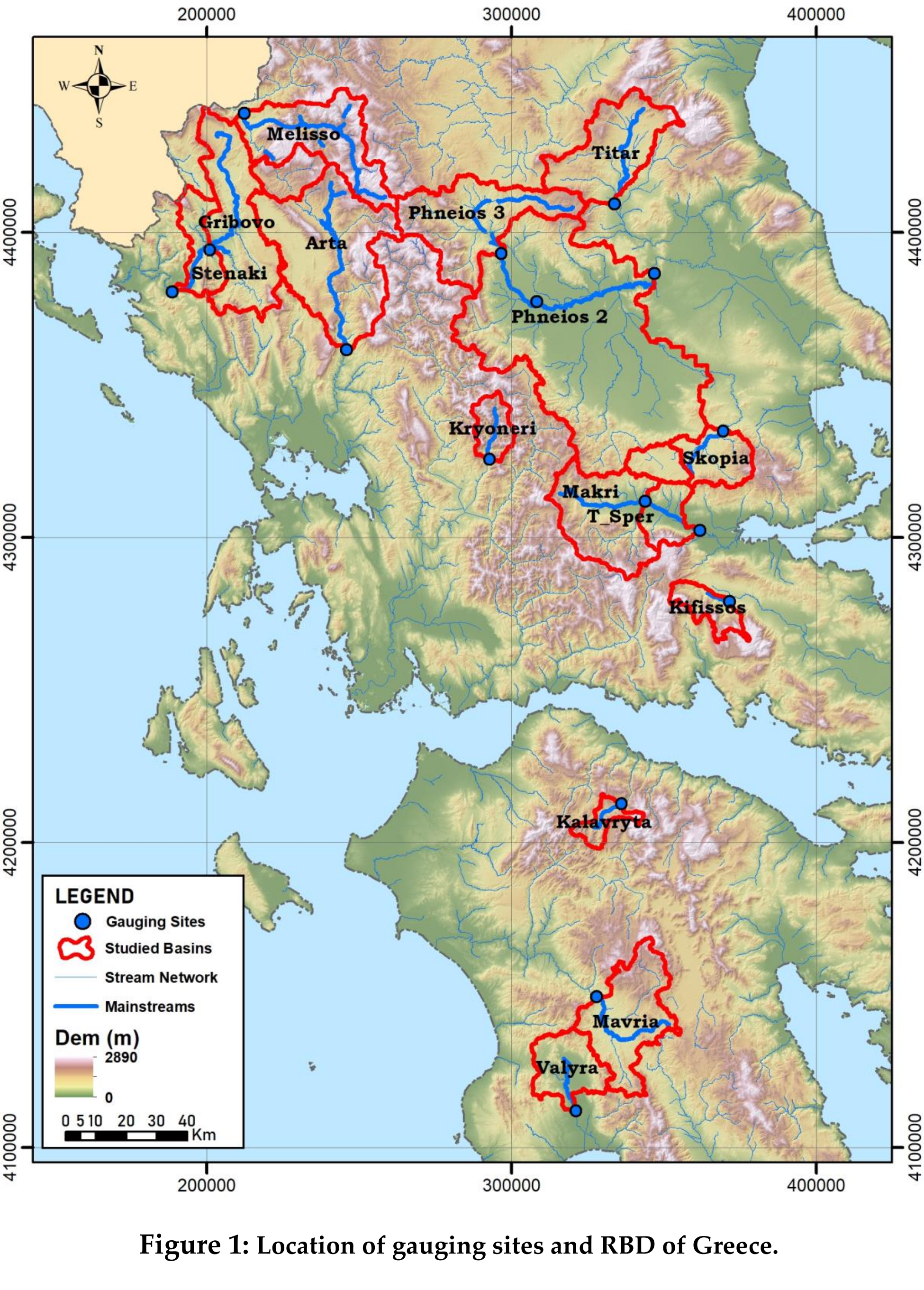


Figure 1: Location of gauging sites and RBD of Greece.

Four of them Arta, Stenaki, Gribovo and Melisso are located in the RBD of Epirus, in the north-western part of Greece. Three of them Kalavrita, Mavria and Valyra are located, in the southern part of Greece, the first in Northern Peloponnese RBD and the latter two in the Western Peloponnese RBD. Another cluster of 5 sites Pineios2, Pineios3, Titar, Skopia and Trikala is located in the RBD of Thessaly. The remaining four sites fall within the prefecture of Sterea Ellada; Makri, T_Sper and Kifissos in the Eastern Sterea Ellada RBD and Kryoneri in Western Sterea Ellada RBD. All gauging sites included in the Thessaly and Sterea Ellada RDBs, occupy locations in central Greece.

Six geomorphological and climatic characteristics of the examined sites were selected as independent variables: catchment area (*A*), length of main stem (*L*), mean annual precipitation (*P*), mean basin elevation (*H*), curve number (CN) and slope (*S*). The values of the developed geomorphological and climatic characteristics for the selected sites are presented in Table 1.

Table 1: Catchment descriptors examined in the regression analysis as independent variables

Gauging Site	Catchment Area (km²)	Length of main stem (km)	Mean Annual Precipitation (mm)	Mean Basin Elevation (m)	Curve Number	Slope (degree)
Arta	1602.0	86.7	736.25	914.5	63	21.3
Gribovo	1049.5	78.8	828.87	603.4	67	18.2
Kalavrita	143.6	25.0	598.17	1054.7	62	22.0
Kifissos	220.4	27.8	474.59	997.3	70	21.6
Kryoneri	219.9	27.2	511.08	1190.0	60	35.0
Makri	864.2	45.5	483.40	795.2	61	20.6
Mavria	848.7	49.0	652.90	768.0	60	15.4
Melisso	915.0	86.5	702.49	1291.2	68	24.9
Pineios2	5027.8	146.40	479.67	433.01	73	12.6
Pineios3	1059.5	56.70	551.37	822.80	72	20.1
Skopia	368.0	36.6	418.33	664.6	75	12.7
Stenaki	1380.3	104.1	831.15	581.4	65	19.6
T_Sper	1146.8	74.3	479.77	716.4	63	19.2
Titar	839.3	51.0	482.42	725.0	63	15.3
Valyra	445.0	29.6	667.46	375.2	68	14.8

Catchment area (A), Length of main stem (L), Mean annual precipitation (mm), mean basin elevation (m), curve number (CN) and slope (S).

The *A*, *L*, *H* and *S* where acquired from geoprocessing of a Digital Elevation Map (DEM) of Greece in Geographic Information Systems (GIS). The DEM used had a 5 m x 5 m grid, geometric accuracy RMSE of z ≤ 2.0 m and an absolute accuracy about 3.9 m for a 95% confidence level provided by the National Cadastre & Mapping Agency S.A.

To estimate CN values for each basin, datasets of hydrologic soil type and land cover/land use were needed. The process used to acquire CN values for every grid cell, is presented in

Figure 2. At first, every possible combination of land use/land cover and hydrological soil type in each grid cell was identified, based on the USDA soil texture triangle. Next a unique 3-digit number was ascribed to each grid cell. To define soil type the European Soil Dataset from program *LUCAS_2015* was incorporated while for the Corine Land Cover 2018 (*CLC_2018*) dataset was utilized for land use/land cover information. Subsequently, a lookup table was created to match-up the 3-digit number to a CN value. The look-up table was created from combined information of international standards (National Engineering Handbook of USDA) (NRCS, 2009) and the Flood Risk Managements Plans from Special Secretariat for Water which specifies CN values for Greece.

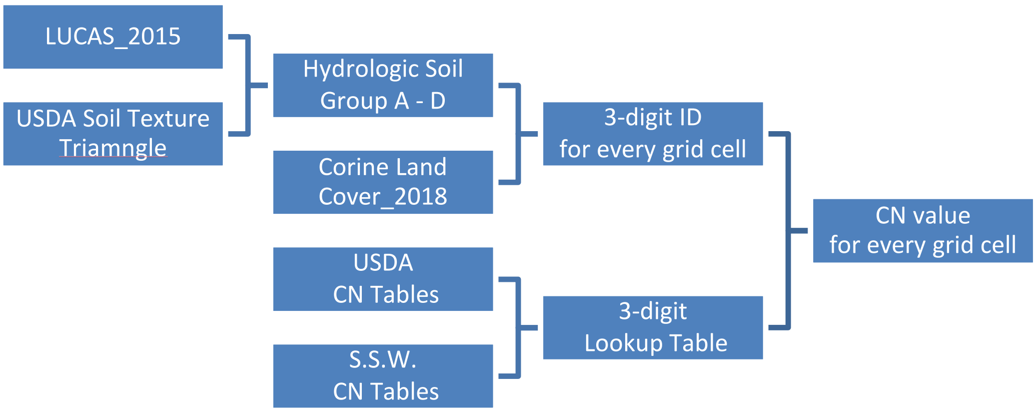


Figure 2: Flow diagram of the process used to acquire curve number (CN) values.

To acquire *P* values over the examined basins, the latest version issued (22.0e) of E-OBS dataset was used. E-OBS is a daily gridded observational dataset for precipitation, with a high spatial resolution of a 0.25 ° x 0.25 ° grid, from the European Climate Assessment & Dataset project (ECA&D). The dataset used, comprised of consecutive daily precipitation values in mm for 30 hydrologic years, namely from 01 October of 1989 up to 01 October of 2019. Since the precipitation values were given in point measures/features, surface interpolation technique of Thiessen polygons was utilized and then the daily precipitation for each basin was given as the sum of product of coverage percentage times the measured precipitation.

Methodological Framework

Q-H Curves

To begin with the curve fitting process, a quality control scheme was implemented in order to audit the raw data for possible uncertainties and errors. This procedure was used to determine if any measurements were to be deleted before the curve fitting or not. Scrutiny of measurements requires expertise knowledge, thorough examination of each single Q-H pair and sound hydrological reasoning for every exclusion done. Omitting measurement pairs is a risky process and should be used sparingly. On the other hand, over-refinement of the rating model has to be avoided

Three fundamental criteria were implemented in this procedure. The first one concerned measurements that deviated more than 8% from the provisional rating curve. The second criterion concerned measurements of discharge that varied greatly over the same or similar stage. The third criterion was the examination of the trendline between the discharge and the stage, based on the concept of hydrological consistency. An additional rule was applied for the minimum amount of measurements accepted per site, to develop a rating curve. It is also important to state that zero discharge values were not included in the set of measurement that would be used for curve fitting. A combined examination of raw data, field notes and scatter plots, for each site, was used to locate dubious Q-H pairs.

Next, in order to determine which stage-discharge relationship has superior performance in the examined gauging sites, three relationships proposed were examined (Mimikou & Baltas, 2018):

1. Power law function,

$$Q = k(H - a)^b \tag{1}$$

2. Second degree polynomial (2nd degree polynomial),

$$Q = A_0 + A_1 H + A_2 H^2 \tag{2}$$

3. Second degree polynomial of the natural logarithm (ln-polynomial),

$$ln(Q) = A_0 + A_1 lnH + A_2 (lnH)^2 \tag{3}$$

where, Q is the discharge, H is the stage height, a is the stage height at which discharge is zero, A_0, A_1, A_2 are coefficients of the model and k and b are site specific constants.

The curve fitting was performed with the Curve Fitting Toolbox of MATLAB®. The application performs regression analysis on a library of linear and non-linear models, as well as, on manually configured equations. The power law and the 2nd degree polynomial were available as presets of the application, while the ln-polynomial was inserted manually. The curve fitting process was done with 95% confidence bounds.

The coefficient of determination (R^2) and the Root Mean Square Error (RMSE) were used to evaluate and compare the efficiency of the rating curves. The R^2 is a statistical measure, representing the proportion of variance of the dependent value that is predicted from the independent value. The R^2 is widely used and is calculated as described below:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(y_{est,i} - y_{obs,i}\right)^2}{\sum_{i=1}^{N}\left(y_{obs,i} - \hat{y}_{obs}\right)^2} \quad (4)$$

where, $\sum_{i=1}^{N}(y_{est,i} - y_{obs,i})^2$, is the sum of squares of the residuals, describing the total deviation of the response values from the fit to the response values and $\sum_{i=1}^{N}(y_{i} - \hat{y})^2$, is the sum of squares total describing the dispersion of the observed variables around their mean. The RMSE is the square root of the variance of the residuals and is an assessment of the model's predictive ability. It is a measure of how scattered from the regression line the residuals are. RMSE is calculated as described below:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{N}\left(y_{est,i} - y_{obs,i}\right)^2} \quad (5)$$

Derivation of Environmental Flow Indices

The approach of this study on assessing e-flows is based on hydrological methods and therefore the FDC and MAF methods, the two most widely used hydrological methods, were selected and examined. In total, four low-flow indices were developed, two from using the FDC (Q_{90} and Q_{95}) and two from the MAF (10% and 30% MAF) methods. Subsequently, the four low-flow indices were compared through a selection process scheme, to the values proposed by Greek regulations. The low-flow index that produced the better approximations of the values determined by the Greek regulations, was selected as a representative e-flow index and was used into the regression model.

Unlike rating curves, no measurements were excluded in the process of developing the low-flow indices. It was decided that all measurements of discharge, even when there are potential errors in the measurement, can be used as indicative values as a compromise for the limited amount of measurements. This conjecture, implies that all Q measurements available could still provide information on a) the order of magnitude of a discharge measurement and b) on the frequency of occurrence. Finally, zero discharge values were also included in the process.

The Greek regulations, define three different methods for calculating discharge, from which the biggest value should be regarded as the recommended e-flow:

- 30% of the average supply of the summer months June - July - August
- 50% of the average supply for the month of September
- 30 l/s at least, in each case

The biggest discharge values were considered here as target values, by which the fitness of the four low-flow indices (Q_{90}, Q_{95}, 10% MAF, 30% MAF) were to be judged. Subsequently, the four low-flow indices were developed.

The process of creating the FDCs requires that monthly discharges are gathered and sorted in a decreasing order of magnitude and value rank m is assigned to each discharge, starting with 1 for the largest value. Then exceedance probability is then calculated for each value by the equation:

$$P = \frac{m}{n+1} \times 100 \tag{6}$$

where n is the total number of measurements. The FDCs for each site were constructed and the discharge values corresponding to 90% and 95% exceedance probability were acquired, denoted as Q_{90} and Q_{95} respectively. Finally for the MAF method, the average discharge is calculated for each of the two years of records and the mean of the two, is assumed as the mean annual flow. From this value, the designated percentages of 10% and 30% are acquired.

Regression analysis

The Multiple Linear Regression (MLR) is based on the assumptions that a certain linear relationship between the dependent (low-flow index) and independent variables (A, L, P, H, CN, S) exists and that the independent variables are not highly correlated with each other. The model was developed using stepwise regression and backward elimination approach with manual intervention, to eliminate statistically insignificant variables. The basic form of a linear multivariate model is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \tag{7}$$

where: y, is the response variable, β_0, is the intercept, β_i, is the slope coefficient for the i explanatory variable and x_i, is the explanatory variable.

All six independent variables were initially included in the regression's analysis. Additionally, combinations of descriptors were also examined, like the catchment area divided by the length of main stem (*A*/*L*) and the specific discharge (*Q*/*A*). The dataset was divided with a 75-25% rule for calibration and validation purposes. A selection process was applied, to ensure that both datasets would include gauging sites covering all range of values of the independent variables. Also clustering of gauging sites based on common features, for example catchment area or specific discharge was examined.

The prediction accuracy of the forecasting model was measured by the Mean Absolute Percentage Error (MAPE), the Standard Error (SE), R^2 and RMSE. MAPE is defined by the formula:

$$M = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{A_i - F_i}{A_i}\right| \quad (8)$$

where A_i is the actual value and F_i the predicted value.

The SE indicates how precise the model's predictions are, using the units of the dependent variable and smaller values of SE signify a better fit of the model. The SE is defined as:

$$SE = \frac{\sigma}{\sqrt{n}} \quad (9)$$

, where σ is the standard deviation and n is the sample population.

Results and Discussion

Q-H Curves

The performance for each of the three rating curves per site, is given in Figure 3. The measurements from gauging sites Trikala and Titar, were deemed as flawed altogether and were not included in the curve fitting process. Out of the remaining 14 gauging sites examined, none of the three rating curve was found to absolutely over-perform over the others. Specifically, the 2^{nd} degree polynomial has proved to have a better fit in 6 out of 14 sites (42.8%). The rest 8 sites are equally distributed between the other two rating curves, resulting in over-performance of power law and ln-polynomial in 4 sites (28.5%) each.

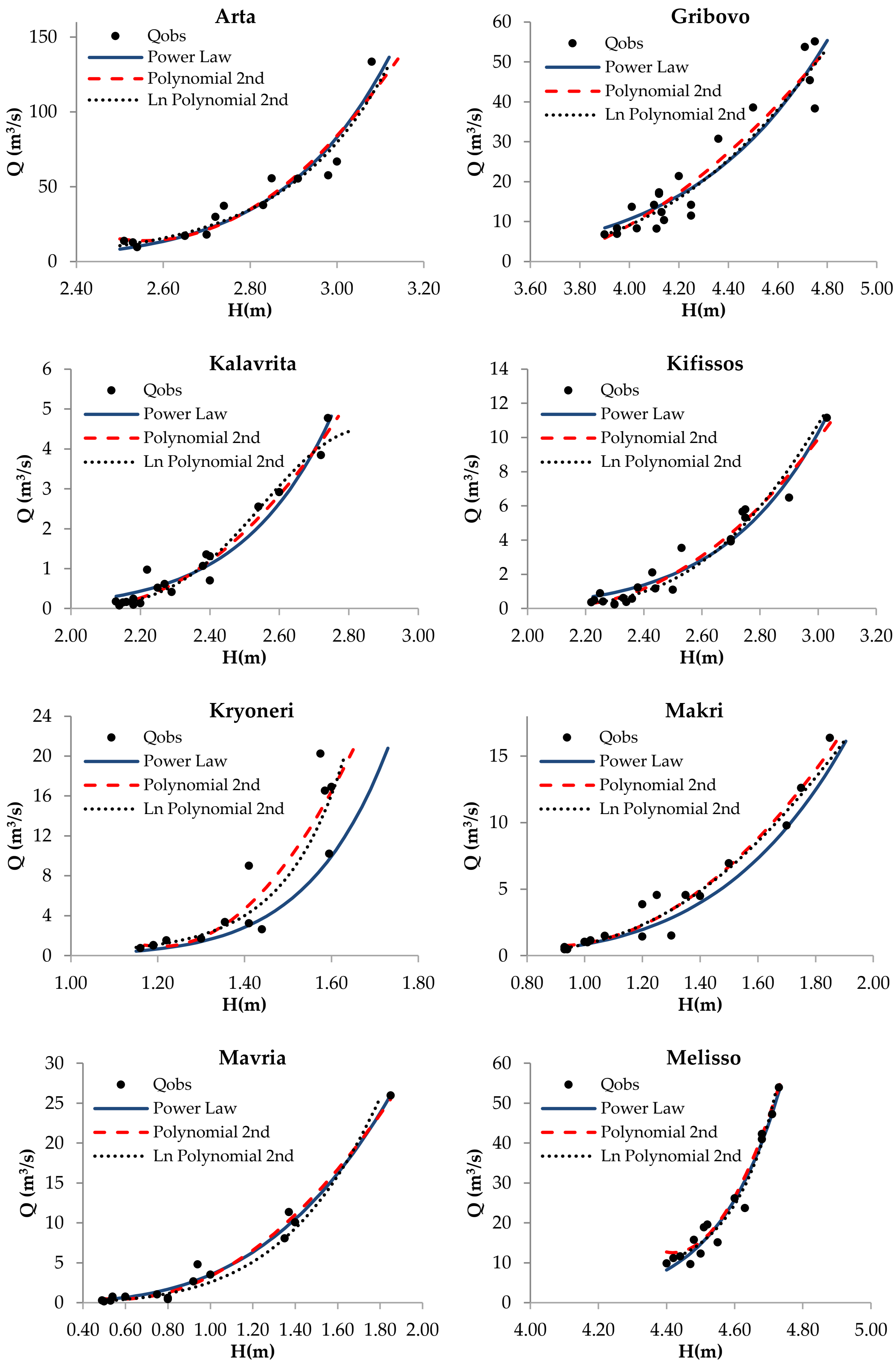


Figure 3: Performance of the three examined rating curves for all 14 gauging sites (continued).

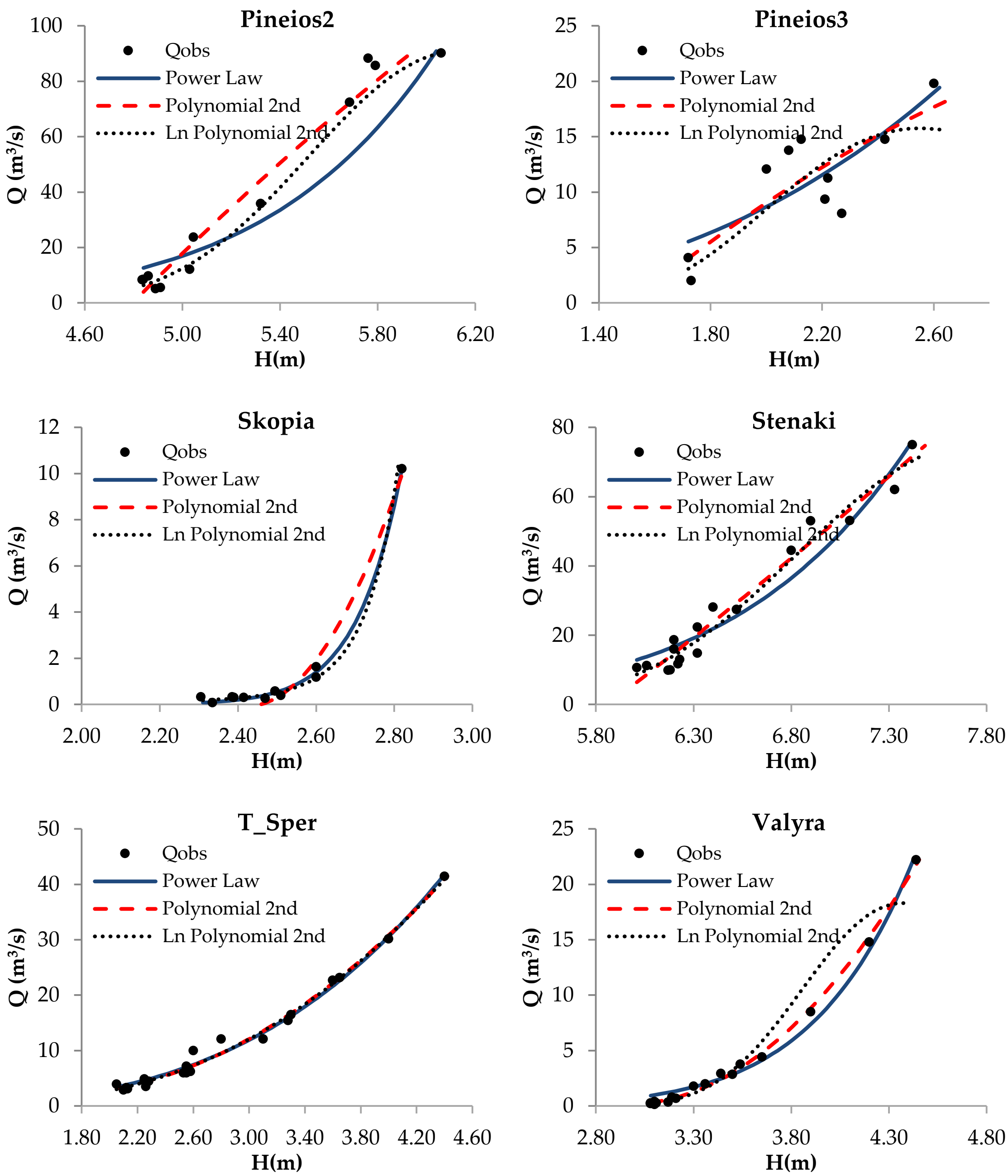


Figure 3: Performance of the three examined rating curves for all 14 gauging sites.

In most of the sites, all three rating curves had high performances and also values of R^2 and RMSE similar to each other (Table 2). As a result of the similar performances, for one, and the diverse methods of calculation of R^2 and RMSE, for the other, the proposed best fitting rating curve per site, was not always the same for both measures of fit. The 5 sites where inconsistency between the measures-of-fit was observed were Kryoneri, Melisso, Pineios2, Pineios3 and T_Sper.

Table 2: The scores of R^2 and RMSE of the three rating curves, for each site.

Gauging site	R^2			**RMSE**		
	Power law	**Poly 2nd**	**Ln-Poly**	**Power law**	**Poly 2nd**	**Ln-Poly**
Arta	0.910	0.893	**0.932**	9.449	10.297	**9.411**
Gribovo	0.891	**0.901**	0.870	5.155	**4.907**	5.009
Kalavrita	0.955	**0.967**	0.884	0.282	**0.244**	0.261
Kifissos	0.943	**0.957**	0.877	0.672	**0.582**	0.656
Kryoneri	0.824	0.827	**0.903**	4.638	**2.803**	2.905
Makri	**0.966**	0.962	0.927	**0.825**	0.870	0.899
Mavria	**0.983**	0.982	0.897	**0.862**	0.896	1.507
Melisso	0.961	**0.962**	0.924	2.834	3.086	**2.674**
Pineios2	0.899	**0.968**	0.935	13.126	6.144	**5.711**
Pineios3	0.648	0.677	**0.757**	2.996	**2.867**	3.224
Skopia	**0.996**	0.982	0.888	**0.158**	0.371	0.453
Stenaki	0.934	**0.965**	0.927	5.233	**3.777**	3.790
T_Sper	**0.988**	0.988	0.967	1.037	1.023	**1.018**
Valyra	0.987	**0.997**	0.966	0.645	**0.291**	1.366

Eventually each of these sites was independently examined, to determine the best fitting rating curve. The optimal rating curve for each of the 14 gauging sites defined by this research study, is presented in Table 3.

Table 3: The optimal fitting rating curve for each site.

Gauging Site	Rating Curve	
Arta	$lnQ = 0.1525 - 4.829lnH + 7.895(lnH)^2$	R^2 + RMSE
Gribovo	$Q = 261.94 - 161.96H + 24.689H^2$	R^2 + RMSE
Kalavrita	$Q = 37.84 - 36.99H + 9.05H^2$	R^2 + RMSE
Kifissos	$Q = 56.751 - 53.371H + 12.586H^2$	R^2 + RMSE
Kryoneri	$lnQ = -1.012 + 4.773lnH + 7.008(lnH)^2$	R^2
Makri	$Q = 1.058H^{4.408}$	R^2 + RMSE
Mavria	$Q = 3.497H^{3.262}$	R^2 + RMSE
Melisso	$lnQ = 291 - 403lnH + 140.5(lnH)^2$	RMSE
Pineios2	$lnQ = -150 + 170.2lnH - 46.87(lnH)^2$	RMSE
Pineios3	$Q = -40.25 + 32.5H - 3.93H^2$	RMSE
Skopia	$Q = 9.75 * 10^{-11}H^{24.48}$	R^2 + RMSE
Stenaki	$Q = -205.3 + 26.288H + 1.4864H^2$	R^2 + RMSE
T_Sper	$Q = 0.3238H^{3.28}$	R^2
Valyra	$Q = 88.538 - 59.474H + 10.009H^2$	R^2 + RMSE

The spatial distribution of the best fitting rating curve over the 14 examined sites, is given in Figure 4.

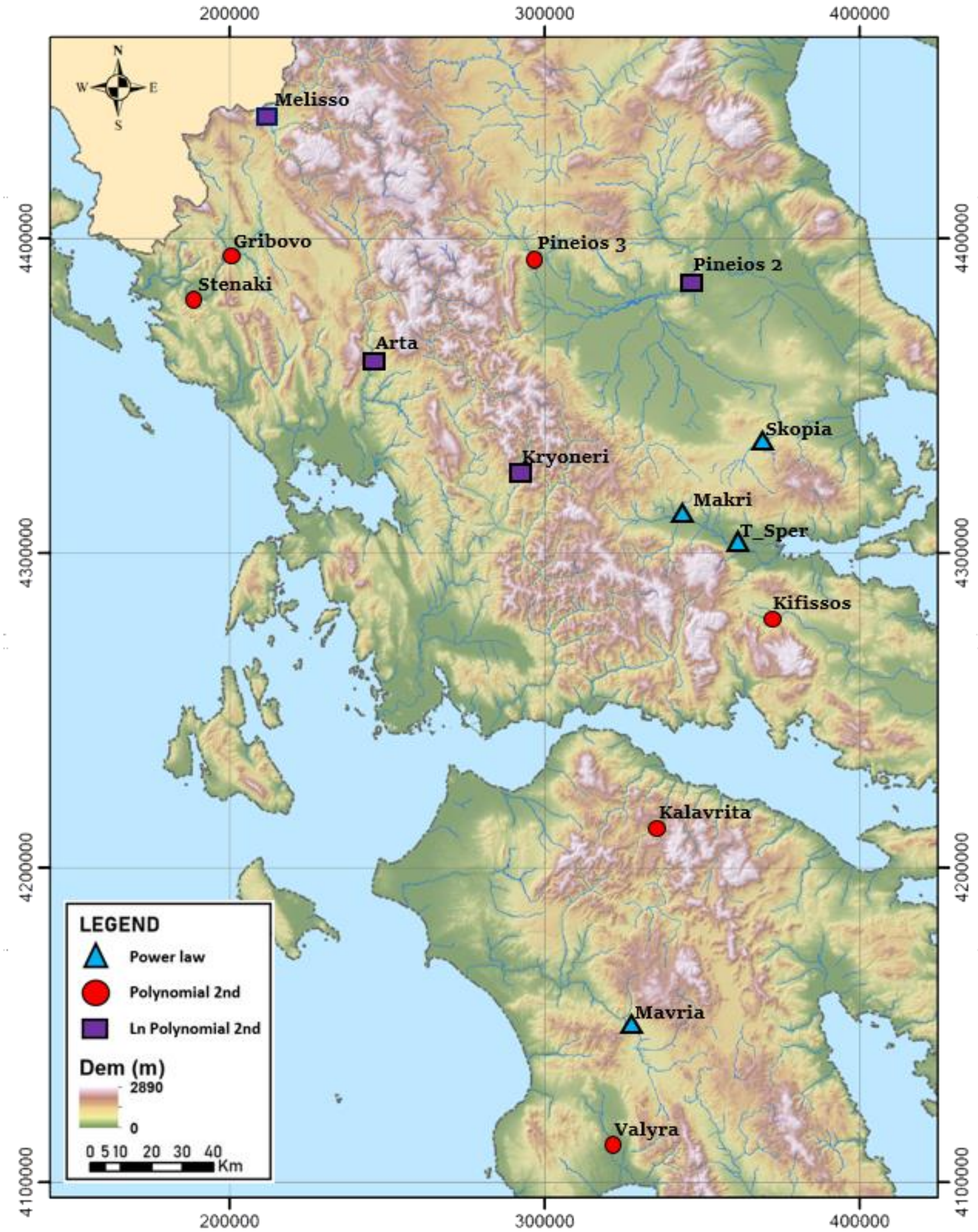


Figure 4: Spatial distribution of better performing rating curves, over the 14 sites.

Concerning the distribution of the rating curves, the 2nd degree polynomial has proved to have a better fit in 6 out of 14 sites (42.8%). The rest 8 sites are equally distributed between the other two rating curves, resulting in over-performance of power law and ln-polynomial in 4 sites (28.5%) each (Figure 5).

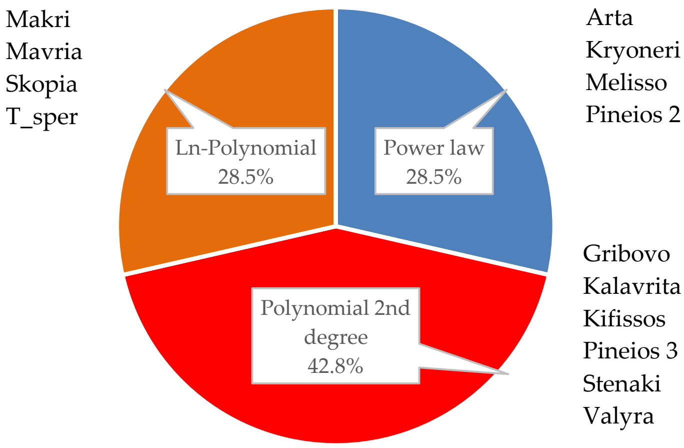


Figure 5: Distribution of best fitting rating curve, per site.

Quality control of the raw hydrometric data proved to be an essential step of the whole process, since only 25% of the total sites remained unaffected by it (Table 4). For the rest 75% of sites, the screening process either a) was necessary in order to obtain a rating curve or b) significantly improved the goodness of fit of a rating curve, although it was not necessary.

Table 4: Effect of the quality control process on the number of measurements.

Station name	Initial number of measurements	Final number of measurements	Excluded measurements
Arta	21	14	7
Gribovo	21	20	1
Kalavrita	21	19	2
Kifissos	21	21	0
Trikala	17	Rejected	-
Kryoneri	21	13	8
Makri	21	18	3
Mavria	15	15	0
Melisso	20	15	5
Pineios2	17	12	5
Pineios3	13	10	3
Skopia	15	11	4
Stenaki	17	17	0
T_Sper	21	21	0
Titar	18	Rejected	-
Valyra	21	19	2

In total out of 16 gauging sites examined, there was no exclusion of measurements in 4 of them (25% of total), minor intervention ranging from 1 to 3 pairs discarded in 5 of them (31.25% of total) and significant intervention by excluding from 4 up to 8 measurements in 5 of them (31.25% of total). In addition there were two sites, Trikala and Titar, (12.5% of total) that were deemed as flawed altogether and were not included in the curve fitting process.

Estimation of e-flows

At first, discharges according to the three methodologies proposed for e-flow by the Greek regulations, were estimated. Subsequently, the four low-flow indices from hydrological methods were estimated. Two of them were acquired as percentiles of the FDC (Q_{90} and Q_{95}) while the other two as percentages of MAF (10% and 30% MAF).

The suitability and applicability of the four low-flow indices developed (Q_{90}, Q_{95}, 10% MAF, 30% MAF) as EFA, was estimated based on how efficiently they could approximate the discharge values derived from the current Greek legislation, which were set here as target values (Table 5). The method with the best performance would be the one that manages to estimate discharge values closer to the target values, as often as possible.

Table 5: Discharge values estimated for the four low-flow indices and target values for all sites.

Gauging Site	Target values (m^3/s)	Q_{90} (m^3/s)	Q_{95} (m^3/s)	10% MAF (m^3/s)	30% MAF (m^3/s)
Arta	7.22	6.52	5.33	3.32	9.96
Gribovo	4.77	7.13	6.78	2.19	6.57
Kalavrita	0.16	0.10	0.07	0.12	0.37
Kifissos	0.18	0.28	0.23	0.25	0.76
Kryoneri	0.78	1.03	0.78	0.70	2.09
Makri	0.35	0.48	0.47	0.35	1.04
Mavria	0.20	0.22	0.00	0.41	1.23
Melisso	4.69	7.76	7.60	2.29	6.87
Pineios2	3.41	0.00	0.00	3.77	11.31
Pineios3	0.57	0.00	0.00	0.58	1.74
Skopia	0.10	0.06	0.00	0.13	0.39
Stenaki	5.90	9.96	0.00	2.41	7.23
T_Sper	1.60	3.14	2.90	1.09	3.26
Titar	0.13	0.00	0.00	0.05	0.15
Valyra	0.22	0.22	0.15	0.32	0.97

A comparative analysis, of the discharge value of the four low-flow indices (Q_{90}, Q_{95}, 10% MAF, 30% MAF) to the target values, was conducted (Table 6). Q_{90} proved to be the preferred index, as it had a consistent and acceptable estimation error in all examined sites, with 32% error in sites of overestimations and 39% error in sites of underestimation. The Q_{90}, was equaling or slightly exceeding the target values in the majority of the sites and only underestimated discharge in three sites. However a limitation of the Q_{90} index was the fact that it produced zero discharge values for 3 out of the 15 sites.

Table 6: Percentage error for each of the four methods examined, compared to the discharge target values, set by Greek regulations.

	Q_{90}	Q_{95}	10% MAF	30% MAF
Overestimation Error	32%	30%	24%	53%
Underestimation Error	-39%	-80%	-92%	0
Sites where target value was equaled or exceeded	9	7	7	15
Sites where target value was underestimated	3	2	8	0
Sites with estimated zero values	3	6	0	0

The four low-flow indices were plotted on the FDC of each site, to recapitulate the above results (Figure 6). Their relevant position on the curve indicate their fitness (or unfitness) as EFA methods.

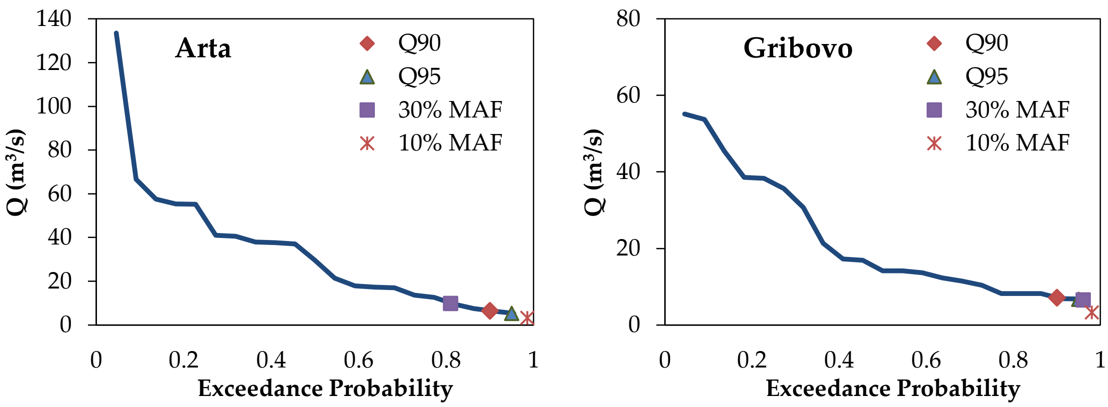
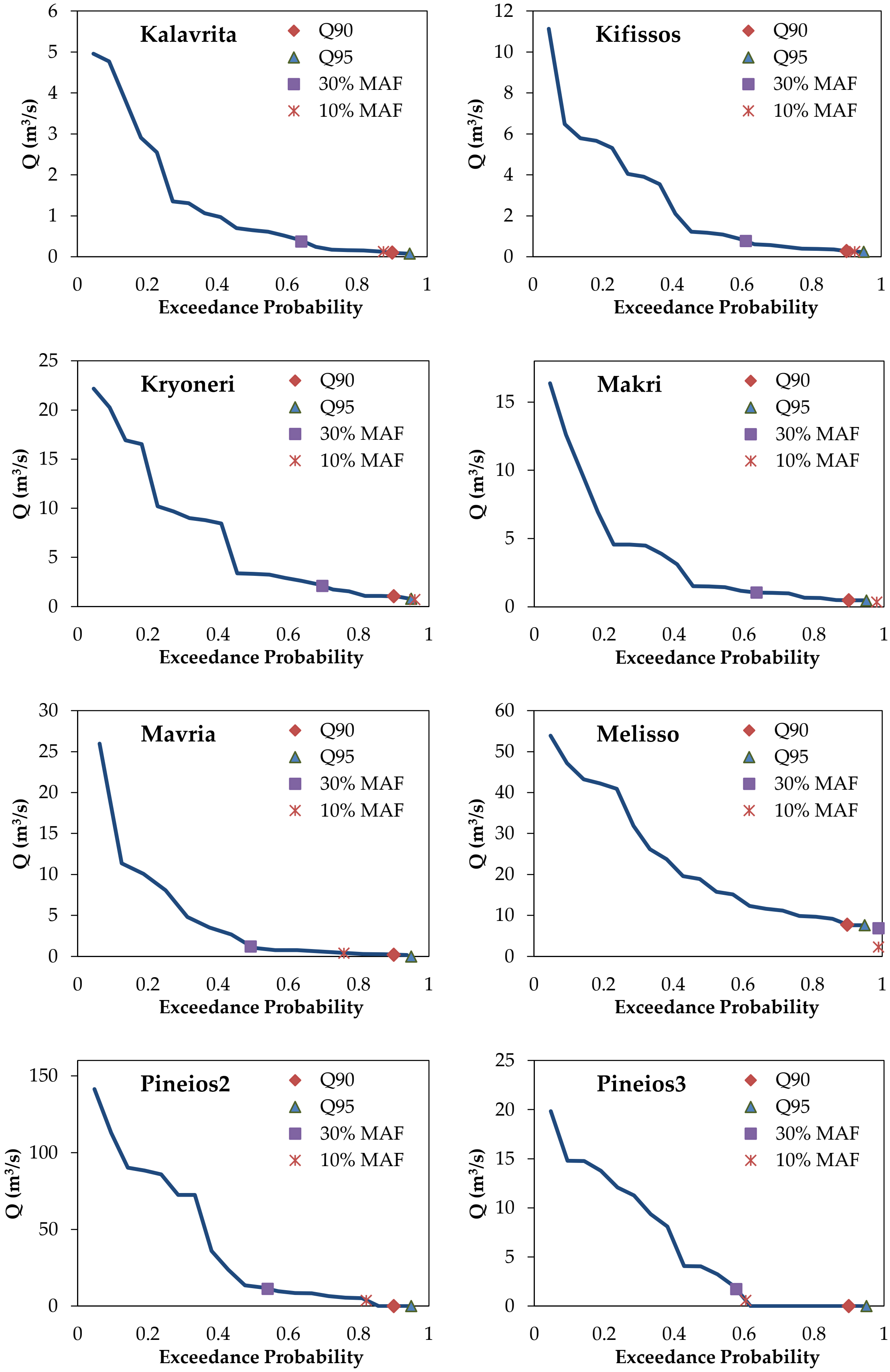


Figure 6: Flow duration curves and the distribution of the four examined low-flow indices (continued)


Kalavrita
Kifissos
Kryoneri
Makri
Mavria
Melisso
Pineios2
Pineios3
Q90
Q95
30% MAF
10% MAF
Q (m³/s)
Exceedance Probability

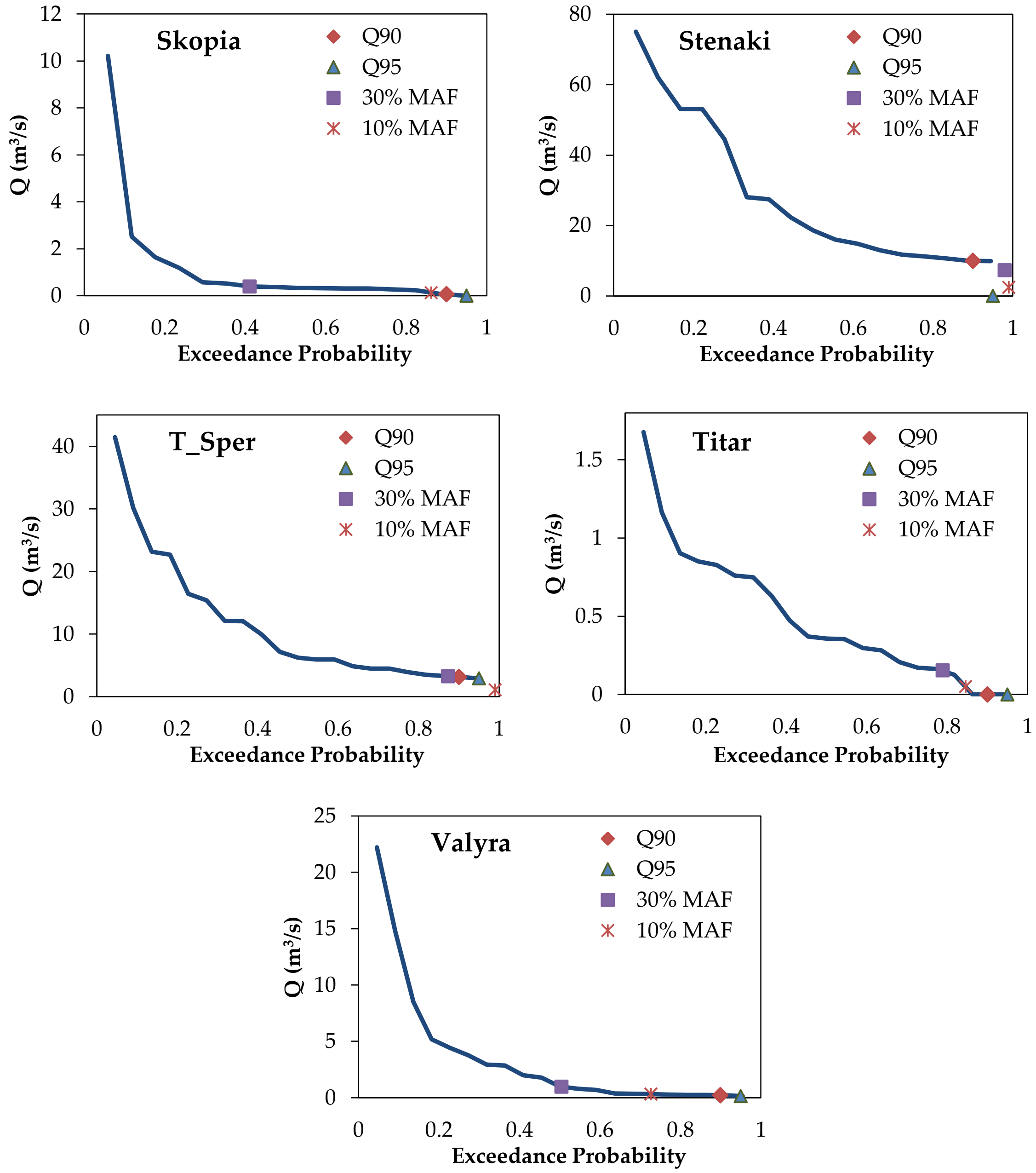


Figure 6: Flow duration curves and the distribution of the four examined low-flow indices.

Regression Analysis

The regression model was developed with the Q_{90} index as the dependent variable, since it proved to be the better performing low-flow index for e-flow approximation. Various climatic and geomorphological characteristics of the examined sites were acquired for each gauging site (Table 1), and different combinations of them were examined as independent variables, in the stepwise regression process.

The stepwise regression process and backward elimination approach, proved four descriptors to be statistically decisive: A, P, CN and S. Following numerous trials, the optimal model for the prediction of e-flows in ungauged basins was:

$$Q_{90} = -41.984 + 0.0059 * A + 0.0117 * P + 0.3836 * CN + 0.4280 * S \quad (10)$$

The scores on the performance measures of the regression model were 0.967 and 0.937 for the R^2 and SE, respectively. Adding more variables, would not necessarily result in a higher performance but could rather lead to an unstable and overfitting model. Furthermore, incorporating more independent variables would produce a more complex model, which is ill-advised; the simpler a model can be the better it is.

The MAPE for the validation group was 36.3%, which was moderately high but, nonetheless, an acceptable percentage of error (Table 7). Given the small number of sites, i.e. 12 sites, on which the regression analysis was performed, and the uncertainty in the initial measurements, the MAPE value was considered as acceptable.

Table 7: Performance of the regression model on the validation dataset.

Gauging Site	Observed Q_{90} (m^3/s)	Estimated Q_{90} (m^3/s)	Percentage Error
Kryoneri	1.03	3.33	69.10%
Melisso	7.76	8.46	8.26%
Arta	6.52	9.53	31.59%

Possible justification on the heterogeneity in error values of the individual validation sites was sought after in the variation of their physical attributes. This finding could suggest that the regression model has a good performance in sites where the hydrological responses are more typical of bigger catchments and mild reliefs.

Conclusions

This research study was based on recent (2018-2019) raw hydrometric data made available by the NMWN, which provided the opportunity to apply a set of different hydrologic tools, over significant rivers, in six RBD of Greece. The use of actual measurements instead of synthetic timeseries, was highly valued and is expected to result in increased validity of the results. The study focused, on the examination of a) the dominant rating curve, over Greek rivers and b) the development of a regional model for determination of environmental flows in ungauged basins.

Three rating curves (power law, 2nd degree polynomial, ln-polynomial) were examined, to define the better performing one, over the selected gauging sites. This question was also addressed with the intention to estimate, if a certain rating curve exists, that describes better the stage and discharge relationship for Greek rivers.

The study focused on the development of a regional model, for the determination of e-flows based on recent (2018-2019) raw hydrometric data. Raw data employed, concerned 16 gauging sites, with a wide spatial distribution over mainland Greece. Given that all hydrologic tools used in this research study, are primarily affected by the quality (and quantity) of the input data, a quality control process was implemented to audit the raw data. The quality control resulted in exclusion of erroneous measurement in most of the gauging sites.

To define the environmental flow, four low-flow indices were acquired for each site, with the implementation of FDC and MAF hydrologic methods. Selection of the most representative low-flow index was judged on the better approximation of the target e-flow values, set by Greek regulations. Subsequently, geomorphological and climatic characteristics of each basin were obtained and a link to the selected low-flow index (Q_{90}) was established, through a multiple linear regression. The developed model could be used to predict environmental flows in ungauged basins, on the concept of transfer of hydrologic information.

The main conclusions derived from this research study are:

Rating Curves

- The 2nd degree polynomial was the better fitting rating curve in most cases, but only within a small majority on the 14 examined sites (42.8% of total). The rest eight sites were evenly distributed over the other two rating curves examined.
- None of the rating curves examined proved to be dominant over the others. It is therefore unlikely that a single rating curve could describe the stage and discharge relationship for Greek rivers.

- Although outperformed in many cases, the power law rating curve performed well overall and had similar performance to the 2nd degree polynomial. Therefore the power law rating curve could be used equally often as the 2nd degree polynomial in Greek rivers.
- The ln-polynomial proved to perform better in sites with few measurements and/or sites of high uncertainty. As a rule, the ln-polynomial had good performance in sites where the other two had moderate performances and vice-versa, proposing a complementary relationship between them.
- Furthermore, the quality control of raw data proved to be an essential step of the rating curve process, as it affected 75% of the sites. It excluded erroneous measurements and significantly improved the performance of the rating curves.

Regression Model

- The regression model developed had high performance, with R^2 of 0.967 and standard error of 0.937 m^3/s. The validity of the model, was given by the 36.32% overall MAPE of the validation dataset.
- Catchment area (A), mean annual precipitation (P), curve number (CN) and slope (S) proved to be the statistically significant characteristics for the model.
- Further examination on the physical attributes of the gauging sites, suggested that the model had better performance in sites with bigger catchments and mild reliefs. The performance of the model derived solely for such sites improved significantly, and MAPE was reduced to 19.92%.
- The error of the model, in estimation of the environmental flow for the validation gauging sites, was in all cases an overestimation error. This finding adds to the robustness of the model, as higher estimations would produce more environmentally safe discharge values.
- The Q_{90} proved to be a good indicator for environmental flow assessment, as it had the better approximation of the discharge values set by the Greek regulations, out of the four examined low-flow indices.
- The use of Q_{90} as indicator of the e-flow sets certain limitation to the applicability of the model, since sites with Q_{90} zero value render the model invalid. However, this is

most likely expected in sites with small catchment areas and flashy regimes, strengthening the suggestion that the proposed model is more appropriate for large (<800 km2) catchment areas.

1. INTRODUCTION

As increasing human water demands compete with varying water allocation needs and ecosystem reservation, water resources management is confronted with serious challenges (Arthington et al., 2018). Growing human population, degradation of ecosystems and uncertainty from climate change effects are noted as major impacts on the hydrologic cycle (Ward et al., 2019; Curtis, 2020). The availability of records of river flow is vital to developing our understanding of the hydrological cycle (Dixon et al., 2013). They are fundamental in understanding past and present hydroclimatic variability and they are also necessary on developing prediction models, in the calibration and validation process. But, even though, hydrological variables are the most essential piece of information, when analyzing or modeling stream ecosystems, relevant data are often limited, in their spatiotemporal scale and resolution (Irving et al., 2018).

As a consequence, the ability to plan and effectively manage water resources is often limited from the absence of consistent and high-quality hydrometric data (Walker, 2000; Singh et al., 2014). Valid hydrometric data are used in the investigation of scientific hypotheses, predictions for ungauged basins, flood risk assessment, assessment of available water resources and provision of environmental flows (e-flows) (Merz & Blöschl, 2004; Farmer et al., 2015; Detzel & Fernandes, 2016). River flow data, which occupy a central position in the practice of hydrometry, often constitute the primary (raw) data of any hydrological tool.

In recent decades there has been a considerable shift of interest in management of water resources, towards the provision of e-flows as a mean of protecting, preserving and restoring riverine ecosystems (Petts, 2009; Poff, 2018). This trend has also significantly affected the water science and engineering community and led to the application of numerous hydrologic tools, in order to address the issue. Hydrological methods have proved to be, the most commonly used techniques for assessment of e-flows (Tharme, 2003; Pyrce, 2004). They are based on analyzing streamflow timeseries, to suggest different low-flow indices, which are assumed as representative for the sufficient flow to ensure ecosystem integrity. However, more than often, planning and implementation of environmental preventative measures are needed in rivers where no gauging stations are installed (Atieh et al., 2017). The need for hydrological prediction in ungauged basins has resulted in the transfer of hydrological information obtained in other regions (Castellarin et al., 2004; Sanborn & Bledsoe, 2006). Even more, scarcity of relevant and valid data is worldwide a frequent shortcoming due to costs of installation, operation, and management of the gauge (Atieh et al., 2017) that significantly impair planning, decision making and environmental protection (Irving et al., 2018). Raised concern on environmental issues, related to water allocation issues combined with a deeper understanding of the water cycle has led to a growing demand for hydrometric data.

The problem of lack of sufficient hydrological data is particularly severe in Greece. As a matter of fact, apart from the network of hydrometric stations, which were installed and operated by the Public Power Corporation in previous decades but decreased significantly in numbers, or even have recently halted their operation, there has been no other planned and consistent gauging effort. This has changed, however, with the implementation of the European Framework Directive 2000/60, establishing a framework for Community action in the field of water policy. Incorporating the 200/60 Directive, Greece has created the National Monitoring Water Network (NMWN) to systematically and consistently gauge and monitor quantitative and qualitative status of surface water and groundwater.

The monitoring program operated by NMWN has made available, for the first time in recent years, consistent streamflow data from gauging stations located in the most significant Greek rivers, covering the most part of mainland Greece. The used data spans over a period of almost two years, from April of 2018 until December of 2019, consisting of 21 concurrent measurements of stage and discharge, for gauging sites distributed over six River Basin Districts (RBD) of the country. The availability of this datasets, made it possible to apply a series of hydrological tools and conduct a primary hydrologic analysis for a big part of Greece, focusing on stage-discharge relationship and on e-flow of rivers.

1.1 Scope

Making use of recent (2018-2019) streamflow data, this research study sets the goal to conduct a preliminary hydrologic analysis over a considerable amount of basins in Greece and a) investigate on the dominant rating curve over the available sites and possibly suggest a prevailing rating curve suitable for Greek rivers and b) develop a regression model that would predict e-flow based on geomorphological and climatic characteristic of the basin. This model could then be used in order to predict e-flow in ungauged basins, relying on the concept of transfer of hydrological information.

In the first part, three rating curves proposed for Greek rivers are examined: the power law, the 2nd degree polynomial and the logarithmic 2nd degree polynomial. Their performance over different sites is examined and conclusions on the suitability of each rating curve are drawn.

In the second part, a regression model is developed, which predicts e-flow for basins, based on their geomorphological and climatic characteristics. The e-flow in this model is approximated by a low-flow index. For this purpose, four low-flow indices, two derived as percentiles from flow duration curves (Q_{90}, Q_{95}) and two derived as a percentage of the mean annual flow (10% and 30% MAF), are estimated. Subsequently they are compared to the e-flows suggested by the Greek regulations, to decide the most representative index.

Then a range of geomorphologic and climatic characteristics are calculated, such as: catchment area (A), length of main stem (L), mean annual precipitation (P), curve number (CN), mean basin elevation (H) and slope (S). These basin descriptors are used as independent variables in the multiple linear regression (MLR) model and various combinations of them are examined. A 75-25% rule for calibration and validation is applied over the gauging sites, to assess the efficiency of the model. To conclude, following numerous trials, the optimal model for the prediction of e-flows in ungauged basins is developed.

1.2 Structure of the research study

This research study is divided into 6 chapters, as follows:

In Chapter 1, a brief introduction is made and the scope of the research study is stated.

In Chapter 2, provide a theoretical background and a brief literature review of the main hydrological concepts and tools that are utilized in this study, i.e. rating curves, e-flows, flow duration curves and regression analysis.

In Chapter 3, the study area and the data used are analyzed. In the first part, handling of raw hydrometric data is addressed. Next, the gauging sites and their locations are presented.

Finally, processing of relevant datasets to acquire climatic and geomorphological characteristics for the basins is given.

In Chapter 4, the methodological framework for developing the rating curves and the regression analysis are described. Tools used to evaluate their performance are also documented in this part. Moreover, the hydrological methods implemented for the assessment of low-flow indices are described.

In Chapter 5, the results of this research are presented. Firstly, the performance of the rating curves for each site is discussed. Then a comparison is made among the low-flow indices to select the one that will be used in the regression analysis. Finally, the optimal regression models is developed and remarks on its accuracy and applicability are made.

In Chapter 6, a summary of the research study is done and conclusions are drawn. Furthermore, suggestions for future work are made, to further examine the validity of the results of this study as well as to extent this work.

2. LITERATURE REVIEW

2.1 Stage-Discharge Relationship

The stage-discharge relationship, also referred to as rating curve, is the empirical or sometimes (also) theoretical relationship between stage (H) and discharge (Q) in a river section (Braca & Grafiche Futura, 2008). Since continuous measuring of the discharge has a significant cost, is time consuming and impractical during floods (Mimikou & Baltas, 2018), rating curves are employed as a tool to acquire discharge values from stage measurements, which can be obtained with comparative ease and economy. Stage-discharge relationships have been used for well over a century for monitoring river streamflows (Chandrasekaran & Muttil, 2005; Braca & Grafiche Futura, 2008).

A rating curve is established by making a series of concurrent measurements of stage and discharge, over a certain period of time. Discharges are calculated from velocity measurements and then paired with stage observations. Ideally, the measurements should be distributed over a range of stages, wide as possible, and they should also be sufficient to determine the shape of the curve (Wilcock, 2016). The number of observations should be proportional to the frequency of flow at different stages (Herschy, 1993). This is to say that, measurements should be denser in the sub-ranges of discharge that have higher probability of occurrence.

There is no consensus on the number of measurements that can be considered as sufficient to develop a rating curve. This number can be rather site-specific, since fewer measurements could be enough to capture the discharge ranges of a river with a uniform flow-regime but insufficient for a highly variable one. According to the World Meteorological Organization (2010) and the manual on stream gauging it has published "a minimum should include at least 12 to 15 measurements, all made during the period of analysis". This is consistent with ISO regulation 1100-2 (ISO, 1998) proposing that at least a sample of 12-15 measurement over the period of analysis, should be incorporated. Standards issued by other authorities set the threshold of at least 5 measurements (Wilcock, 2016).

If the dispersion of points in the scatter plot is negligible and a smooth single curve can be drawn through the plotted points then a single-valued relationship rating curve is required.

Nevertheless, in reality the discharge is also a function of other factors, predominantly of the water-surface slope and of changes in cross-section geometry (Schmidt & Yen, 2001). In non-steady state the rating curve has a loop shape, called hysteresis, such that at the same stage more discharge passes through the river during rising stages than in the falling ones.

Quality control of raw data

It becomes evident that gauging data are the single most important part of curve rating development. It is a fact that the frequency, timing and accuracy of measurements will form the shaping of the curve and define the applicability and any temporary rating deviations (Hamilton et al., 2016). Having measurements distributed over the full range of stage, timed so that they capture all changes in the hydraulic properties of the control reach and also uniform with small uncertainty rating curve development and maintenance would be an easy task. In reality thought many limitations exists and ideal gauging as described above are next to impossible. There are many operational constrains affecting frequency, timing and quality of gauging. Measurement constrains are remote sites, adverse weather, winter, high energy streams (mountains), low energy streams (prairies), occupational safety and the limits of available technology (Hamilton et al., 2016). As a result, too few locations satisfy all assumptions needed for a unique, uniform and stable rating on streams.

However, preliminary examination and quality control of the raw data, by analysts, can compensate for these limitations. Quality control refers to the process of scrutinizing the raw hydrometric datasets to identify any potential erroneous measurements and determine the valid stage and discharge pairs, which were consequently used to develop the rating curves per site. This step should be regarded as a prerequisite of the rating curve process.

Curve fitting

Curve fitting is the process of specifying the model that defines a line of best fit for a set of data points. The result of the fitting process is an estimate of the "true" but unknown coefficients of the model (Hao Wen et al., 2012). There are various methods of developing a rating curve. Manually fitting the curve is a method that has been extensively used in the past and is still in use today. It gives the hydrographer full control of the process, often produces results with limited bias but demand considerable experience and expertise and can be labor-consuming. To evaluate the curve fit, the common practice is to plot the pairs of stage (H) and discharge (Q) measurements with an overlaying rating curve. The two most widely used practices are arithmetic plots and logarithmic plots, while some Q-exponent plots have also been proposed (Fenton, 2001; Hamilton et al., 2016). However, the final curve can be displayed in either type of graph.

The historically preferred method is using arithmetically divided plotting scale. The segment that includes the complete range of height and discharge measured is usually presented. If the range of discharge is large, it may be needed to plot the rating curve in two or more segments each one for low, medium and high water. Special care should be taken though into this process and when the separate segments are joined, they should form a smooth, continuous curve (WMO, 2010). Arithmetic plots offer a significant advantage in allowing to visually interpret precise plotting positions and deviations (Hamilton et al., 2016). These types of graphs are particularly used in the study of the pattern of rating shifts in the lower part of a rating curve.

Many stage-discharge relationships are analyzed through logarithmic plotting scales, by plotting the logarithms of stage against the logarithms of discharge (Herschy, 1993). Logarithmic plots have a significant advantage: under certain conditions (when gauge height is transformed to effective depth of flow on the control section) they plot as a straight line. This transformation allows the analyst to shape correctly the rating curve segment and calibrate the stage-discharge relation with fewer discharge measurements (Hamilton et al., 2016). In contrast a serious disadvantage of the logarithmic plots is that zero and negative numbers are undefined.

However, over the past decades using computers to establish rating curves, has become quite common and usual non-linear regression techniques replaced graphical or analytical techniques previously used (Coz, 2012). Regression fitting of rating equations is used by the Water Survey of Canada (WSC) and in the U.S.A. by the United States Geological Survey (USGS) (Hamilton et al., 2016). Also, probabilistic methods have been used to derive a rating curve. Considerable criticism exists on computer fitted data stemming from the fact that these techniques assume that all input data lie on the same curve as well as that all gauging are of the same quality and therefore of the same weight (Wilcock, 2016). However, effective screening of field data can identify whether a breaking point due to shifting controls exist, and determine that data should be split into different segments before fitted. Additionally, any suspect gauging or outliers should be discarded.

Rating Curve Extension

Another important constrain repeatedly encountered is that discharge measurements are often absent in the area of very low or very high flows (Mimikou & Baltas, 2018). There are various reasons for this limitation. For example, during flood events it is inherently difficult to take measurements, as it is not safe for personnel to reach the site while automatic stage recorders become inundated or can even be destroyed. In cease-to-flow discharges on the other hand it can be impossible to get an accurate measurement, especially when the flow of the stream is within a cobble river-bed. Furthermore, in both cases the infrequent occurrence of these extreme discharges makes it very difficult to get a representative measurement capturing the phenomena.

Nevertheless, it is often necessary to forecast very low or very high discharges for water allocation and flood control reasons. To estimate the discharge during these episodes, the extension of the rating curve is required. Discharge extrapolation of higher values is often employed as an indirect measurement of flood discharge while low-flow extrapolations are needed for water supply management, most commonly domestic use, irrigation and industrial use (Chandrasekaran & Muttil, 2005). Extrapolation of the rating curve is usually based on hydraulic considerations (Lang et al., 2010) and different methods for low-flow and high-flow extrapolation exist. Extrapolated values are always subject to error, but this error is limited if the analyst has a solid knowledge of the principles that govern the shape of rating curve (WMO, 2010). When possible two different methods should be applied and the results should be compared to improve confidence in the extrapolated value. Under no circumstances default computer methods of curve extension should be applied on a developed fitting curve, to get a discharge value beyond the range of stage defined from the field data (Wilcock, 2016).

Maintaining rating curves at established sites

Once a rating curve is established at a gauging site, periodic measurements throughout the operational life of the station should be conducted in order to confirm its validity (Mimikou & Baltas, 2018; Braca, 2020). This is a crucial point because rating curves are subject to changes with time and it is very unlikely that a single curve could apply over a long period of records (Wilcock, 2016). In such cases the dataset should be divided in sub-periods and should be fitted for each of the sub-periods (Clarke, 1999). The main causes that could shift a rating curve are:

- Scouring and sediment transport, resulting in alterations of the river bed geometry.
- Variable backwater effect, from structures downstream.
- Unsteady flow, occurring especially during flood events where intense changes in flow characteristics occur. In unsteady flow the trajectory of flood events appears as a loop; the rising branch is different from the descending branch and none of them coincide with the steady-flow rating curve.
- Vegetation growth, as a seasonal effect that changes the roughness and therefore changing the stage-discharge relationship.

2.2 Environmental Flow

Anthropogenic interventions in riverine ecosystems often result in significant and undesirable changes in its characteristics and affect freshwater biodiversity. In the past few decades, there has been a growing demand worldwide to conserve or even restore ecological health of rivers and preserve lotic biodiversity (Acreman & Dunbar, 2004). The concept of e-flow was developed to yield the quality and quantity of flow that must be maintained in a river, in order not to affect its specific desired ecological features and to achieve the desired ecological objectives. These features may relate to the physicochemical or biological characteristics of the river as well as the relationships between them.

Many interpretations of e-flow exist internationally. The Brisbane Declaration (2007), which was prepared on behalf of 800 delegates from more than 50 countries, provides the definition of e-flow as *"the quantity, timing, and quality of water flows required to sustain fresh water and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems"*. Another description given by Tharme (2003) describes e-flows as an assessment of *"how much of the original flow of a river that should continue to flow down it and onto its floodplains in order to maintain specified, valued features of the ecosystem"*.

Provision of e-flows is a tool often implemented and nowadays made mandatory in European countries under the 2000/60 Framework Directive. In this sense, state policies have committed to guarantee a sufficient level of protection for lotic systems, incorporating environmental and water quality criteria. EFA methods first appeared in early 1940 in the United States, where the main objective was to protect valuable cold-water fisheries (Poff et al., 2017). Rapid progress was made during 1970s, research focused on the minimum supply necessary for the survival of living river creatures, as the health of the river system was associated with maintaining the river supply above a specified critical value. Assessing e-flows is essentially a question of balancing growing human water needs, mainly for food and energy, with the needs of river themselves, predominantly conservation of biodiversity, improvement in ecosystem health and restoration of ecosystem integrity (Petts, 2009).

The need to counter the deterioration conditions in aquatic freshwater ecosystems from infrastructure impacts, water extraction, and altered flow regimes has led to the establishment of the field of Environmental Flows Assessment (EFA) (Arthington et al., 2018). Managing streamflows for ecosystem objectives requires an understanding of the natural flow regime, the current (potentially altered) flow regime and an estimate of how much of a departure from the natural flow regime is acceptable for a set of ecological indicators (Zimmerman et al., 2018).

In recent years, the assessment and management of e-flows have grown to be one of the main issues of concern in the field of water resources management. As more e-flows are implemented and various methods are applied, more knowledge is gained in the scientific community. At the same time, however, this is a field that has not yet been fully understood in its dynamically changing regime and more areas of scientific advancement arise as necessary to improve confidence in e-flows. Incorporating geomorphological cycles, accounting for channel changes and sediment transport variations, and biological dynamics of aquatic organisms into river ecosystem models, are such examples. Another important issue is addressing uncertainty, since projecting future changes in hydrologic regimes through models is not considered a quantitatively precise modeling process. To balance that, risk-based approaches to estimate ambiguity of ecological conditions against a range of possible future hydrologic states are needed (Poff, 2018).

2.2.1 Methodologies for environmental flow assessment

To date, a large number of methodologies for EFA have been developed worldwide to estimate environmental water regimes for rivers, from micro-scale site-specific to regional levels. In an international review by Tharme (2003) an account of more than 207 individual methodologies in 44 countries is given. The choice of the appropriate method to estimate the minimum e-flow heavily depends on both the availability and the appropriateness of the data. The recorded methodologies can be divided into four main categories, namely a) hydrological, b) hydraulic, c) habitat simulation and d) holistic. Two additional categories representing combinations of the above categories can be accounted for. At the same time, more methods continue to improve while others have become obsolete over time. A generalized comparison on their percentage distribution of use, for these methodologies, is given in Figure 2-1, on modified data from Poff et al. (2017).

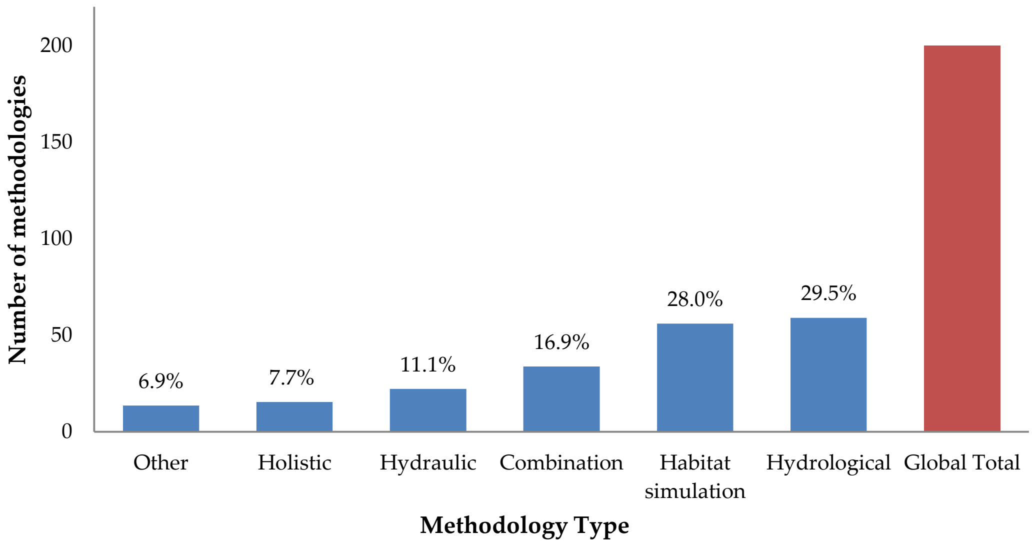


Figure 2-1: Number of methodologies for estimating e-flow and their percentage distribution in use worldwide according to Tharme (2003).

Most e-flow tools are based on the notion of linking hydrological or hydraulic data to the ecological integrity of riverine ecosystems. No method is overall superior than the others and the process of choosing the correct one should be determined by case specific characteristics. For example, hydrological methods are inexpensive and rapid to use, but can be less accurate and are often treated as rough estimates. In contrast, habitat simulation is more flexible and produces site specific results but require hydraulic and ecological in-field data that can be difficult and very expensive to collect. Furthermore, what makes a habitat simulation model suitable for one region can also render it non-relevant for a different hydro-climatic region. The four basic categories of methodologies that remain relevant today are briefly described below.

Hydrological

They are the simplest and non-resource intent methodologies as well as the more widely used for EFA. Usually they recommend a minimum flow that lies within the historic flow range. There are in total 61 different hydrological indices or techniques falling within the hydrological methodologies, accounting for almost 30% of totally used (Figure 2-1). They rely on the process of hydrological data, usually normalized daily or monthly flow records to produce discharge suggestions that should be left in a river. The main concept of these methods proposes that, suggested discharge values ensure the ecological status of the river, avoid degradation below an accepted point and maintain minimal fish habitat. Hydrological methods are often called fixed-percentage or look-up table methods, as they rely on formulae linked to historical flow records to estimate desirable discharges (Poff et al., 2017). Hydrological methods are fast and low cost, as they do not require extensive research and are often given as preliminary flow target values.

The two more extensively used hydrological methods are the Mean Annual Flow (MAF) method (also known as Tennant method) and the Flow Duration Curve (FDC) method. The MAF method is quite simple, as it assumes that maintaining a percentage of the mean annual flow of the river is enough to avoid degradation of the river ecosystem and was developed from an empirical base of many small US streams. The FDCs are used to propose a single figure flow recommendations based on a low-flow index.

Further advancement in hydrological methods has resulted in the widely used Indicators of Hydrologic Alteration (IHA); a software based method, calculating various ecological indices based on statistical analysis of daily flow series and develops inter-annual variation for the before and after flow regulations or abstractions period.

Hydraulic

Hydraulic methods, also known as habitat retention methods, use the changes of various simple geometric hydraulic characteristics, like wetted perimeter or maximum depth, of the river in selected cross-sections, correlating them with the flow. The premise is that by ensuring a threshold value in one of the hydraulic characteristics, a certain level of ecological integrity can be maintained. Such a threshold is a value of the parameter under consideration, below which the quality of the habitat is significantly degraded.

The hydraulic characteristic more often utilized is the wetted perimeter, since it is the most obvious physical dimension that can be changed under altered flow regime (Acreman & Dunbar, 2004). The assumption here is that, river condition can be related to the quantity of wetted perimeter and that protection of this characteristic will accomplish adequate river preservation. In some cases, measurements are made directly in the field; on the contrary in other cases, existing rating curves from gauging stations are used instead. The e-flow is calculated by plotting the variable of concern against discharge and is subsequently defined either as the discharge threshold for which the habitat quality becomes significantly degraded or as the discharge that results in an accepted percentage of reduction in habitat. Hydraulic methodologies have been gradually replaced by the more sophisticated habitat methods.

Habitat simulation

These techniques approach ecological supply through the detailed analysis of the quantity and the suitability of the natural habitat of target species for different values of the discharge. They represent 28% of total methodologies used. They function by linking biological communities with a mesohabitat, also termed as biotope or functional unit in some studies. Then, each mesohabitat can be expressed as a pool, riffle, or run and described by a set of hydraulic and other measurements. The models simulate physical microhabitats by using data on many variables, like velocity, depth, temperature, riverbed material composition from different cross sections and the resulting flow-related changes are modeled in hydraulic programs. Then, information on the preference shown for certain microhabitat, known as suitability index curves, for certain target species is fed into the program. The resulting habitat-discharge curve is used to determine the range of functional relationship between the discharge and physical habitat, within which lies the optimal value of discharge.

Habitat simulation methodologies, were developed in mid '70s in the U.S. and has led to the formal description of computer models to display changing habitat usability with flow, by linking for the first time physical habitat (hydraulic) simulation with habitat evaluation criteria for species and life stages (Petts, 2009). In-stream flow incremental methodology (IFIM) has been the most widely used one (Acreman & Dunbar, 2004). The underlying premise in IFIM is that populations, and hence biodiversity in rivers, are limited by habitat events (Stalnaker et al., 1996). In its core IFIM is based on the physical habitat simulation (PHABSIM) model that consists of two sub-models, the hydraulic model and the habitat model. To set up the hydraulic model, data on topography of the study area for a selected number of sections are given as input in order to calculate the velocity and the depth of flow, for different discharge values. Concerning the habitat model, data on the suitability or preference of the species under study in relation to various parameters (velocity, depth, etc) are given, in order to calculate habitat suitability indices based on the results of the hydraulic model. This raw data used are mainly based on field measurements or the available literature. However these models produce results for specific river reaches or parts and may not be relevant in basin scale.

Holistic

Criticism on the single issue or single specie approach of the aforementioned methodologies, has led to methodologies trying to incorporate all aspects of a river ecosystem, and therefore be "holistic". The fundamental principle in doing so, is trying to maintain the natural variability of flow regime. Holistic approaches make assessment of the whole ecosystem like groundwater and wetlands, involve all different species (from invertebrate to plants) rather than using one target species and all aspects of hydrological regime; floods and low-flows as well (Acreman & Dunbar, 2004). Holistic methodologies may also involve participation of different stakeholders.

The techniques used, are based on field measurements and on the application of a variety of tools and therefore require multidisciplinary expertise and input. The building block methodology (BBM) is at present the most frequently applied holistic methodology. Another top-down approach, the downstream response to imposed flow transformations (DRIFT) process had been developed in recent years, which combines the biological and physical characteristics of the ecosystem combined with socio-economic parameters by simulating various scenarios (Tharme, 2003).

2.2.2 Greek regulations

In Greece the quantitative determination and implementation of e-flows is a very troublesome task, mainly due to data scarcity (Efstratiadis et al., 2014) and lack of standards and of a commonly accepted methodology of estimation. As a consequence, very limited work has been carried out in Greek rivers regarding the development of a specific EFA by taking into account local conditions (Papadaki et al., 2015).

Historically, the concept of ecological flow appeared after the Joint Ministerial Decision (JMD) 69269/5387 which implemented the provisions of the 1650/1986 law on environment. In 1999, the degree of energy utilization was defined as a criterion for qualifying the submitted applications for hydroelectric power generation, in order to make the best use of the existing water potential per location without affecting the ecological supply and the quantities of water required for other uses (e.g. water supply). In that case the e-flow was determined at 30% of the average summer supply.

Finally, a legislative framework for the definition of ecological supply has been established since 2008, as the country complied with the requirements of Directive 2000/60 on the sustainable management of water resources. Law 49828/2008 (Government Gazette 2464 B’/2008), states that until the criteria for estimating the minimum required ecological supply for a river basin are defined, the minimum required in-stream flow should be considered the larger of the following sizes:

- 30% of the average supply of the summer months June - July - August
- 50% of the average supply for the month of September
- 30 l/s at least, in each case

This direction, although originally issued on the licensing of small hydroelectric projects, is applied to various other water management projects as well, since no relevant legislation has been adopted. As a method, it can be included in the hydrological calculation methodologies, given that the hydrological data of monthly flows are used for the calculation. Never the less, the process of estimating e-flows in Greece is far from complete since only general guidelines on what constitutes an ecological flow exist.

2.2.3 Flow Duration Curves

A FDC (Figure 2-2) is a cumulative frequency curve over the whole range of discharges recorded over a specific time period (Searcy, 1959). It illustrates the percent of time a certain discharge was equaled or exceeded over a certain time period. FDC are simple and powerful tools and are often used in hydrologic or other environmental issues (Viola et al., 2011). It has a long application history over water management problems: estimating hydropower potential, irrigation programming, water supply, channel design, and flood damage estimation (Baltas, 2012). It is also used in defining ecological flows and low-flows estimation to name the most frequently encountered (Farmer et al., 2015; Verma et al., 2017). The FDC is a tool widely used to designate low-flow indices, set by specific exceedance percentiles of the cumulative frequency curve of discharges. It is a straightforward hydrological method widely used to assess a discharge threshold, deemed as suitable or sufficient for certain water management and environmental issues.

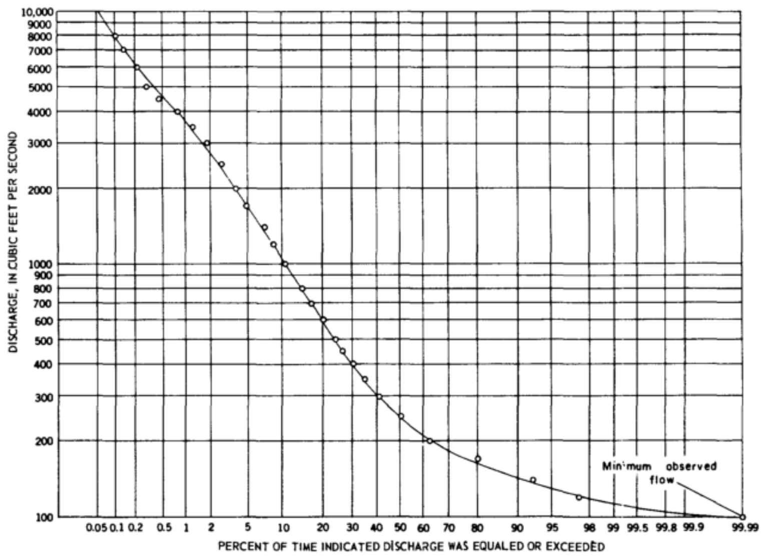


Figure 2-2: Flow Duration Curve (FDC) of Bowie Creek (Searcy, 1959).

FDC is a very informative hydrological tool as it displays the complete record of discharges, from low-flow to the flood events (Smakhtin, 2001). FDC can be developed for different time resolutions, for example daily or monthly. That choice is a matter solely depending on the streamflow data available and the time scale of interest in each case (Verma et al., 2017). The time unit chosen can vary from day, week and month depending on the reason the FDC is constructed. Many applications use daily streamflow since they provide the best way to examine duration characteristics of a river (Vogel & Fennessey, 1995). However in order to draw conclusions over annual minima, monthly time step is commonly incorporated (Botter et al., 2008). An important limitation of the FDC comes from the fact that, it does not show the chronological sequence of flows.

The Q_{90} index (or Q_{95}) is defined as the discharge equaled or exceeded 90% (or 95%) of time. Using indices or exceedance percentiles, is the second most common hydrological method, after the MAF method, for EFA, (Pyrce, 2004). Most of the low-flow indices lie within the 70%-99% range of a FDC. The most common hydrological low-flow indices are Q_{90}, Q_{95} and 7Q10 flows according to both Smakhtin (2001), who reviewed existing methods of low-flow estimation from streamflow time-series and Tharne (2003), who reviewed EFA methods worldwide. Other studies agree, on the most commonly used low-flow indices (Table 2-1). Likewise, 7Q10 is defined as the 7-day average minimum for 10-year return period.

Table 2-1: Most commonly used low-flow indices from review studies (Pyrce, 2004).

Study	Most Common Low-Flow Indices
Smakhtin (2001)	Q_{95}, Q_{90}, 7Q10
Tharme (2003)	Q_{95}, Q_{90}, 7Q10, MAF percentage
Pyrce (2004)	Q_{95}, 7Q10
Instream flows (Reiser et al., 1989) (Karim et al., 1995) (Caissie and El-Jabi, 1995) (Yulianti and Burn, 1998)	MAF percentage, 7Q10, monthly Q_{50}, monthly Q_{90}

Q_{90} and Q_{95} are commonly used to assess e-flow in rivers and to conserve biotic and abiotic river conditions. Q_{95}, the flow which is equaled or exceeded 95% of time, is adopted as the minimum ecological flow in UK, Australia, Taiwan and Bulgaria while other countries like Canada and Brazil typically use the Q_{90} discharge (Tharme, 2003). The most widely used low-flow indices based on review by Pyrce (2004) are 7Q10 and Q_{95}. These low-flow indices are used in many EFA studies across the world (Castellarin et al., 2004; Detzel & Fernandes, 2016; Verma et al., 2017).

2.2.4 Mean Annual Flow

The MAF method, also known as the Montana method (Smakhtin, 2001), is the most widely used hydrological method. The method was developed by Tennant in 1976 who examined the characteristics of 11 cross-sections from different US states. The method uses historical hydrological data to estimate ecological supply and the basic concept is relating percentages of mean annual flow with different ecological conditions of the river. Tennant assessed that for discharges below 10% of mean flow, degradation of riverine ecosystem and aquatic life was expected, while "satisfactory results" were obtained for 30% of mean flow (Jowett, 1997).

Spain and Portugal are examples of countries using Tennant method to set the e-flow for ungauged basins, utilizing the 10% MAF and 2.5-5% MAF respectively (Tharme, 2003). Using different percentages Chile, Canada and New Zealand have recommended the e-flow to be 10, 25 and 30% respectively (Li & Kang, 2014).

2.3 Regional Model

All water management decisions, ranging from water supply issues to irrigation needs and from hydroelectric dam operation to ecological demands, often require continuous long-term streamflow information. However, only few sites are under constant and consistent gauging and more than often no relevant data exists in sites of interest. In the absence of streamflow observations, decisions made in ungauged sites are based on data spatially transferred from other, gauged, sites. The process of transferring parameters of models calibrated in gauged catchments (donor) to neighboring ungauged catchments (receiver) of interest is generally referred to as regionalization (Merz & Blöschl, 2004).

Numerous regionalization methods have been proposed in literature. Among the most widely used, three main groups of regionalization methods can be delineated which are based on: a) regression to catchment attributes, b) spatial proximity and c) catchment similarity. Past and recent studies to determine which of the regionalization approaches is the most appropriate do not seem to reach a consensus (Oudin et al., 2008; Singh et al., 2014). Various reasons could explain that discrepancy; the inconsistent quality of data used, the set of catchment (in terms of quantity and variability) examined, the catchment descriptors chosen, rainfall-runoff models and/or regression methods used, etc.

The list of independent catchment and climatic characteristics related to low-flow indices in regional models can vary greatly, but fall within three main types physical, climate, and human indicators. Most frequently, the independent variables examined are a combination of: catchment area, mean annual precipitation, basin hydraulic conductivity, soil porosity, average basin slope, mean catchment elevation, mean annual potential evapotranspiration, river network density, land use, length of the main stream, catchment shape and watershed perimeter. The specialization of some of the above parameters in subsets is not uncommon. For instance a precipitation seasonality index (e.g. average summer/winter precipitation) is sometimes preferred over mean annual precipitation (Flynn, R.H., 2003; Kuentz et al., 2017).

2.3.1 Regression method

In the first group of methods, the model parameters are estimated from regression to catchment and climatic attributes. Regression models are mathematical methods that examine potential relationship of a flow signature (e.g. low-flow index) with independent geomorphological or climatic characteristics of a catchment. They are inexpensive models, easy to use in other catchments and have low data requirements, as all required inputs of the model are readily available. The regression model approach is perhaps the most widely used technique in low-flow estimation at ungauged sites (Smakhtin, 2001; Kokkonen et al., 2003, Ouarda et al., 2008) as they are easy to use and usually do not need much effort to provide their inputs (Eslamian et al., 2010).

To predict low-flows at ungauged catchments, various low-flow regionalisations have been developed using multiple regression techniques (Pyrce, 2004). Many low-flow indices can be used in various applications and thus, the ecologically relevant streamflow index to be used in a regression model is mainly determined by and limitations of available data. The needed data for ecological prediction ideally must be of high temporal resolution (daily), continuous and consistent with minimum errors. However, hydrological data are "often not available or sufficiently diverse for detailed modeling analyses" (Irving et al., 2018).

Regression equations estimate some dependent flow index based on various independent catchment physiological and climatic characteristics. Once the relationship is established, the flow index can be estimated in the ungauged basin by defining the values of the physical and climatic attributes selected. This approach is based on two premises: first that a well-behaved relationship exists between the observable catchment characteristics and model parameters and second that catchment descriptors selected for the regressions will provide relevant information in terms of the behavior of the ungauged catchment (Oudin et al., 2008). Also a good regression equation should have the least independent variables, although reducing the amount of variables could result in some information loss (Eslamian et al., 2010).

In the US, there have been numerous attempts to assess low-flows, based on 7Q10 index, for ungauged basins using regression equations most of them coming from USGS (Pyrce, 2004). A list of these predictive equations from literature are given in Table 2-2, in which all actual values of parameters are replaced by letters (a, b, c, etc.). The ordinary least square (OLS) technique is the most widely used one (Parajka et al., 2005), in which it is effectively assumed that all observations of the variable being predicted are equally reliable at different sites in a region (Smakhtin, 2001). Among alternative methods the generalized-least-squares (GLS) regression techniques have been used extensively, to account for different record length and the cross correlation between concurrent flows. (Flynn, 2003; Dudley, R. W., 2004).

Table 2-2: Regression models for 7Q10 index, for ungauged catchments in U.S. (Edited from Pyrce, 2004).

Prediction Equation	Source and Location
$7Q10 = a * \exp [b + c(CO) + d(CL) + e(WF) + f(LA) + g(EL)]$	Chang and Boyer (1977) - West Virginia
$7Q10 = a (DA)^{b} (G)^{c}$	Bingham (1986) - Tennessee
$\log 7Q10 = C + a(\log DA) + b(\log PI) + c(GI) + d(\log S)$	Ehlke and Reed (1999) – Pennsylvania
$7Q10 = a (DA)^{b} (SL)^{c} (DR/ST + 0.1)^{d} (10^{d (REG)})$	Ries and Friesz (2000) - Massachusetts
$\log (7Q10 + a) = b + c(2y24) + d(DA) + e(S) + f(SO)$	Rifai et al. (2000) - Texas
$7Q10 = a (DA)^{b} (ABT)^{c} (SGP)^{d}$	Flynn (2003) - New Hampshire
$7Q10 = a (DA)^{b} 10^{c(SG)}$	Dudley (2004) - Maine

ABT: average mean annual basinwide temperature; C: Regression constant; CL: is main channel length; CO: is basin perimeter; DA: is drainage area; DR/ST: is area of stratified drift per unit of total stream length; EL: is mean elevation; G: is streamflow recession index; GI: is geological index; LA: is mean latitude; PI: is annual precipitation index; PW: is average basin mean winter precipitation; REG: is region (0 for eastern, 1 for western); S: is channel slope; SG: is the fraction of the basin underlain by significant sand and gravel aquifers; SGP: is average summer precipitation at the gauging station; SL: is mean basin slope; SO: is the predominant hydrologic soil group; 2y24: is the 2-year, 24-h precipitation; WF: is a watershed form factor.

2.3.2 Spatial proximity method

The second group of methods relies on spatial proximity and is based on the notion that neighboring catchment will have similar hydrologic responses. The premise is that the physical and climatic characteristics are relatively homogeneous within a region and neighboring catchment should behave similarly (Oudin et al., 2008). The spatial distance between two catchments can be estimated with different methods; the type of method used can produce significant differences. For instance, if the nearest neighbor method is applied the complete set of model parameters is taken from one donor while in inverse distance weighting parameters from a number of donor catchments are combined (Parajka et al., 2005). Proximity methods are known to perform well (Merz & Blöschl, 2004; Parajka et al., 2005). However, geographically close catchment are not necessarily similar in climate or most importantly flow regime. Indeed Shu and Burn (2003) suggested that geographically close catchments are not necessarily homogeneous in terms of hydrological response. This issue is quite relevant in Greece, where topography is characterized by intense relief variations and a long coastline. These features not only divide the country into very dissimilar hydroclimatic zones but also result in great diversifications within a few kilometers distance.

2.3.3 Catchment similarity method

The third group of methods is primarily based on the idea that similar catchments will have similar hydrological responses. The measure of similarity is defined by selected static (topography) and/or dynamic (climate) characteristics. Then a set of parameters calibrated for model over a donor catchment, can be transferred into the ungauged catchment of interest. This is a very convenient assumption since physical characteristics, like land cover and topography, are now available for every location of interest, although the quality of the data may vary in different regions. However it has been pointed out that physical and climatic similarity does not ensure similar flow regimes in catchments (Kuentz et al., 2017). In addition selecting a suitable metric of hydrologic similarity is difficult (Singh et al., 2014) and no standard approach is agreed. Merz & Blöschl (2004) suggested that, spatial proximity is a better surrogate of unknown controls on runoff dynamics than catchment attributes.

3. STUDY AREA & DATA USED

3.1 Hydrometric Data

This research study was based on the analysis of primary (raw) data, spanning over a two-year period from April of 2018 until December of 2019, of gauging sites covering the most part of mainland Greece, occupying six RBD. Raw field data consisted of: geographic position information (longitude and latitude) for each gauging site (Table 3-1), a single concurrent measurement of stage and discharge for each month and field notes referring to specific conditions during the time of the measurements, for example floods, zero flow, heavy rain, etc.

Table 3-1: General information on the 16 selected gauging sites (name, geographic positions in WGS '84, river located, initial number of measurements).

Gauging Site	River/Stream Name	Latitude	Longitude	Initial number of measurements
Arta	Aracthos	39.36840	21.05196	21
Gribovo	Kalamas	39.64816	20.51738	21
Kalavrita	Vouraikos	38.05040	22.13388	21
Kifissos	Viotikos Kifissos	38.65240	22.52328	21
Trikala	Lithaios	39.52661	21.76951	17
Kryoneri	Agrafiotis	39.05781	21.60685	21
Makri	Spercheios	38.94465	22.19956	21
Mavria	Alfeios	37.47882	22.05375	15
Melisso	Aoos	40.05465	20.62864	20
Pineios2	Pineios	39.61704	22.21598	17
Pineios3	Pineios	39.66593	21.63115	13
Skopia	Enipeas	39.15602	22.49082	15
Stenaki	Kalamas	39.51922	20.38022	17
T_Sper	Spercheios	38.86162	22.40691	21
Titar	Titarisios	39.81971	22.05920	18
Valyra	Mavrozoumena	37.14156	21.98807	21

For each month a unique value was recorded over stage and discharge, totaling 21 measurements per site. In the absence of more measurements, these unique values were treated as indicative mean values for each month in this research; the uncertainty that could stem from this assumption is seriously taken into account and thoroughly discussed in the last chapter of the research study. The datasets, were made available by the Land Reclamation Institute (LRI), which is one of the involved bodies in the NMWN of Greece. LRI is systematically monitoring the discharge of approximately 50 river stations, covering the most part of mainland Greece.

A first audit of the data, excluded all gauging sites in transboundary rivers that did not originate from Greece, as flow regime in these sites is commonly regulated by other authorities. In majority, these sites were located in the north and northeastern part of Greece. After the exclusion of these sites, the first audit was completed. The remaining 32 gauging sites were located in varying catchment areas, with a considerable spatial distribution that covered parts of northern, central and southern mainland Greece.

Following a thorough second scrutiny process, 16 more sites were discarded on the basis of failing to fulfill fundamental desirable preconditions, such as a natural, unregulated flow regime or a number of valid measurements lower than a threshold value. More specifically, the excluded gauging sites belonged to one or more of the following categories:

- Sites that were heavily affected from dams which lead to alteration of natural flow conditions.
- Sites that were heavily affected from seasonal water extractions, mainly for irrigation purposes.
- Sites with less than 12 non-zero measurements. Inefficient number of measurements, could be either due to inability to measure because of bad weather conditions (eg. heavy rainfall) in the time of measurements or due to too many zero discharge values recorded per site.
- Sites with frequent cross-section alterations due to floods, debris deposition and aggradations.

Finally 16 sites were selected, which satisfied to a good extend the combination of the above criteria. The selected sites had a high number of good quality measurements and possessed significant geographical variation. For the most part there were records of 21 consecutive records of stage and discharge for each site – which was the highest possible record from the raw data provided. However, due to site-specific limitations, some sites selected had fewer measurements. At the lowest, two sites were included with records of as few as 15 measurements. The initial amount of measurements for each site is presented in Table 3-1.

3.2 Study Area

The selected sites were distributed over a wide range of mainland Greece, occupying six different RBD (Figure 3-1). They subbasins defined for each gauging sites varied greatly in their geomorphological characteristics: catchment areas, river length, mean elevation and geology (Figure 3-2).

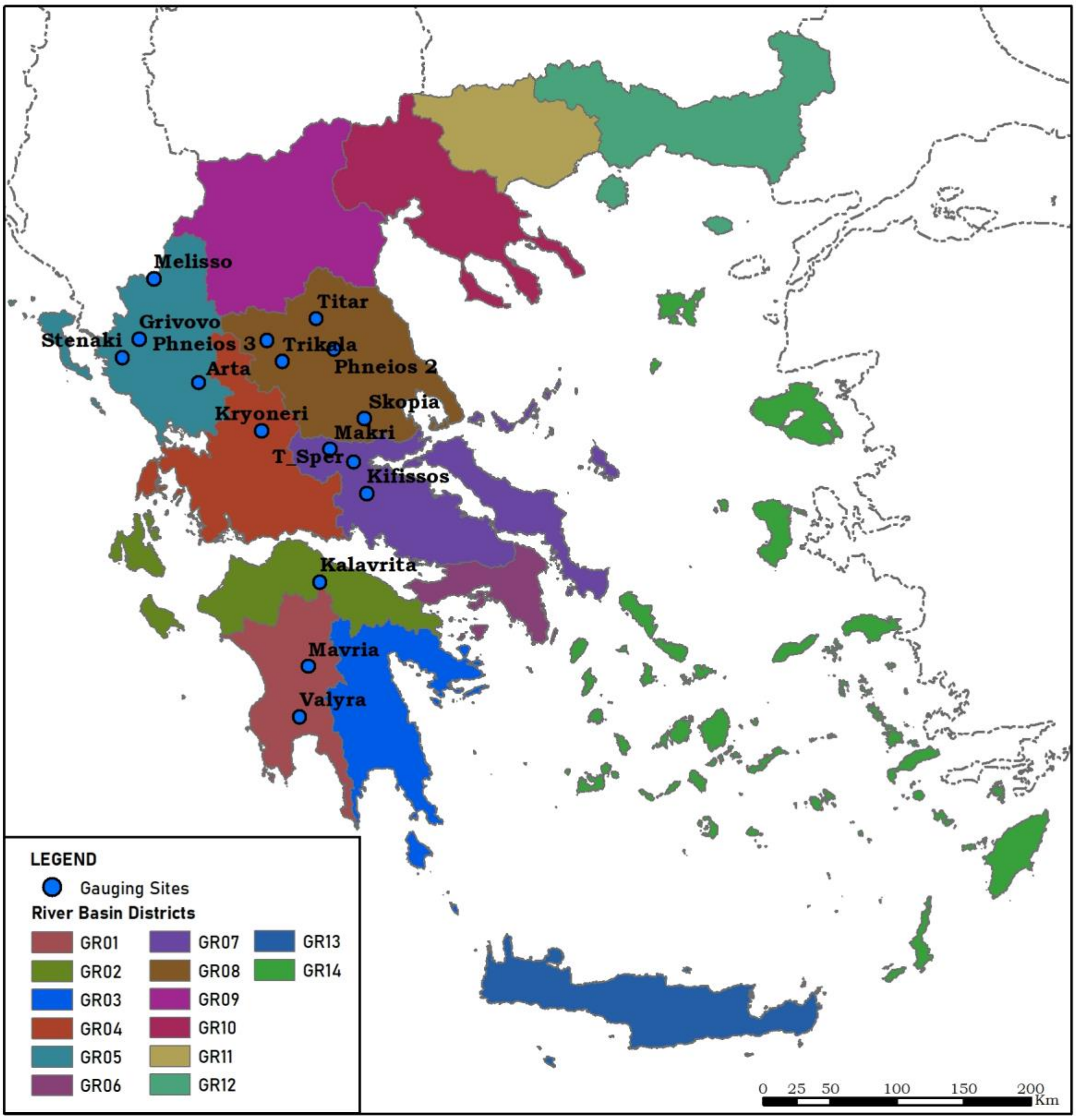


Figure 3-1: Location of gauging sites and RBD of Greece.

Four of them Arta, Stenaki, Gribovo and Melisso are located in the RBD of Epirus, in the north-western part of Greece. Three of them Kalavrita, Mavria and Valyra are located, in the southern part of Greece, the first in Northern Peloponnese RBD and the latter two in the Western Peloponnese RBD. Another cluster of 5 sites Pineios2, Pineios3, Titar, Skopia and

Trikala is located in the RBD of Thessaly. The remaining four sites fall within the prefecture of Sterea Ellada; Makri, T_Sper and Kifissos in the Eastern Sterea Ellada RBD and Kryoneri in Western Sterea Ellada RBD. All gauging sites included in the Thessaly and Sterea Ellada RDBs, occupy locations in central Greece.

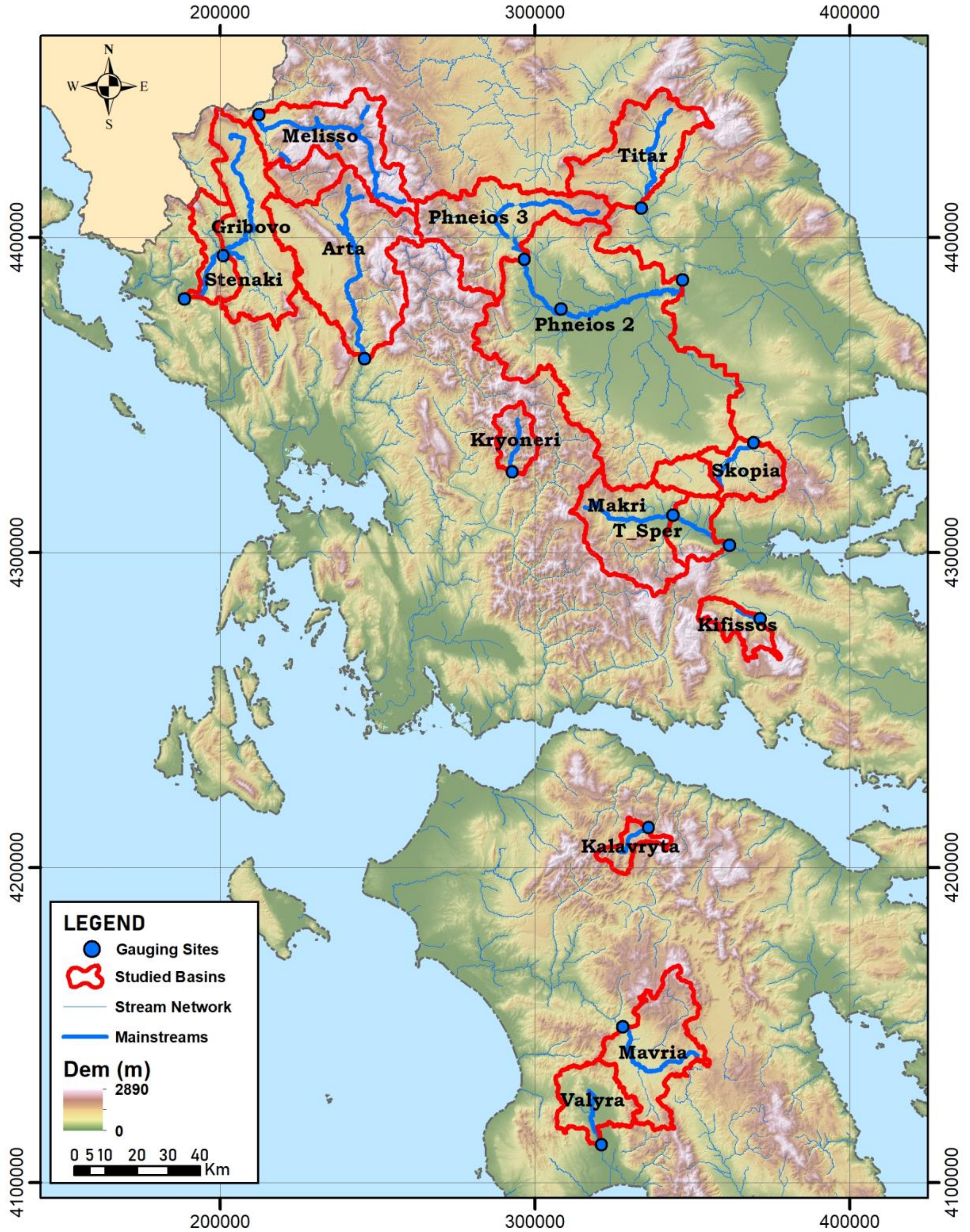


Figure 3-2: Geographical location of gauging sites.

A concise description for each gauging site is given below. The descriptions provide information on the location of the gauging site, e.g. RBD and river, and on gauging conditions, e.g. cross-section condition, ease of measurement, etc. Also, brief geomorphological information on the sub-basin defined upward from each gauging site, are presented.

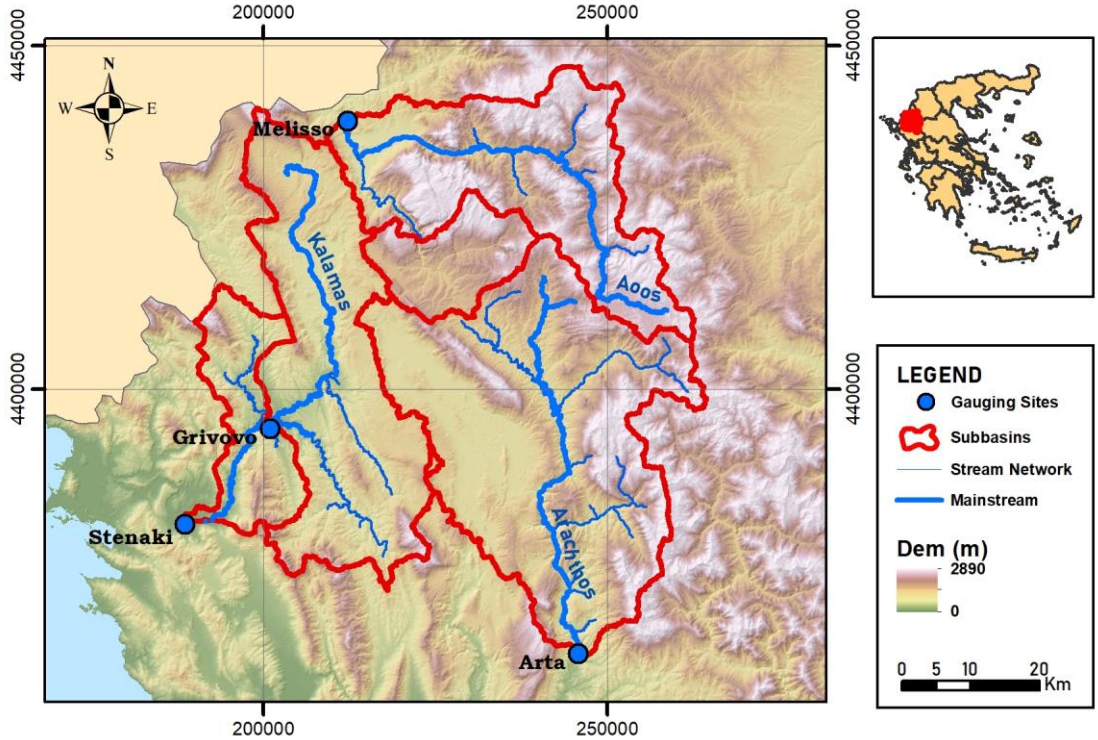


Figure 3-3: Subbasins defined by gauging sites in Epirus RBD (GR05).

Arta

Arta is a gauging site in river Arachthos, located in northwestern Greece, in the RBD of Epirus (Figure 3-3). River Arachthos, moves through impermeable formations of flysch, resulting in large fluctuations of its flow (SSW, 2017a). Arta gauging site is located upstream and remains unaffected by the Pournari dam, which significantly changes the water regime downstream (SSW, 2017a). The flow at the site is described as smooth, usually with high values of discharge and with variable riverbed, mainly in its western part. All measurements were made from a bridge, a stable point with good access.

The sub-basin defined upward from the gauging site covers a total area of 1602.0 km^2 while the length of the river concerning this part is 86.6 km. The basin's mean altitude is as high as 914.5 m and has a mean slope of 21.3°.

Gribovo

Gribovo gauging site is located in river Kalamas, located in northwestern Greece, in the RBD of Epirus (Figure 3-3). River Kalamas springs from Mount Dousko and flows into the Ionian Sea (SSW, 2017a). All measurements were performed with good flow conditions from a bridge. The stream has a constant cross-section and a continuous flow throughout the year. The sub-basin defined upward from the gauging site covers a total area of 1049.5 km^2 while the length of the river concerning this part is 78.8 km. The basin's mean altitude is as high as 603.4 m and has a mean slope of 18.2°.

Stenaki

Stenaki is a gauging site also located in river Kalamas (like Gribovo), but way further down the length of the river and after 4 important tributaries (Tyrias, Smolitsas, Klimatias, Lagkavitsas) have flown into the main stem (Figure 3-3). Stenaki, is located on a bridge northwestern of the village of Kato Koritiani on the provincial road to Agios Arsenios. It is a measuring site with good flow conditions, steady cross-section geometry and ease of access. All measurements were performed from a bridge.

The sub-basin defined upward from the gauging site covers a total area of 1380.3 km^2 while the length of the river concerning this part is 104.1 km. The basin's mean altitude is as high as 581.4 m and has a mean slope of 19.6°.

Melisso

The Melisso gauging site is located within Aoos Basin in the RBD of Epirus (Figure 3-3). The gauging site is close to the river outlet in Albania. The flow in the station is usually steady and the riverbed has stable geometry. In 2019, changes were observed in the bottom of the riverbed which is likely due to erosion effects. In May 2019, during the hydrometric period, a flood event was observed during which it was not possible to conduct measurements at the site due to the big extent of sediment transport. All measurements were performed from a metal bridge.

The sub-basin defined upward from the gauging site covers a total area of 915.0 km^2 while the length of the river concerning this part is 86.5 km. The basin's mean altitude is as high as 1291.2 m and has a mean slope of 24.9°.

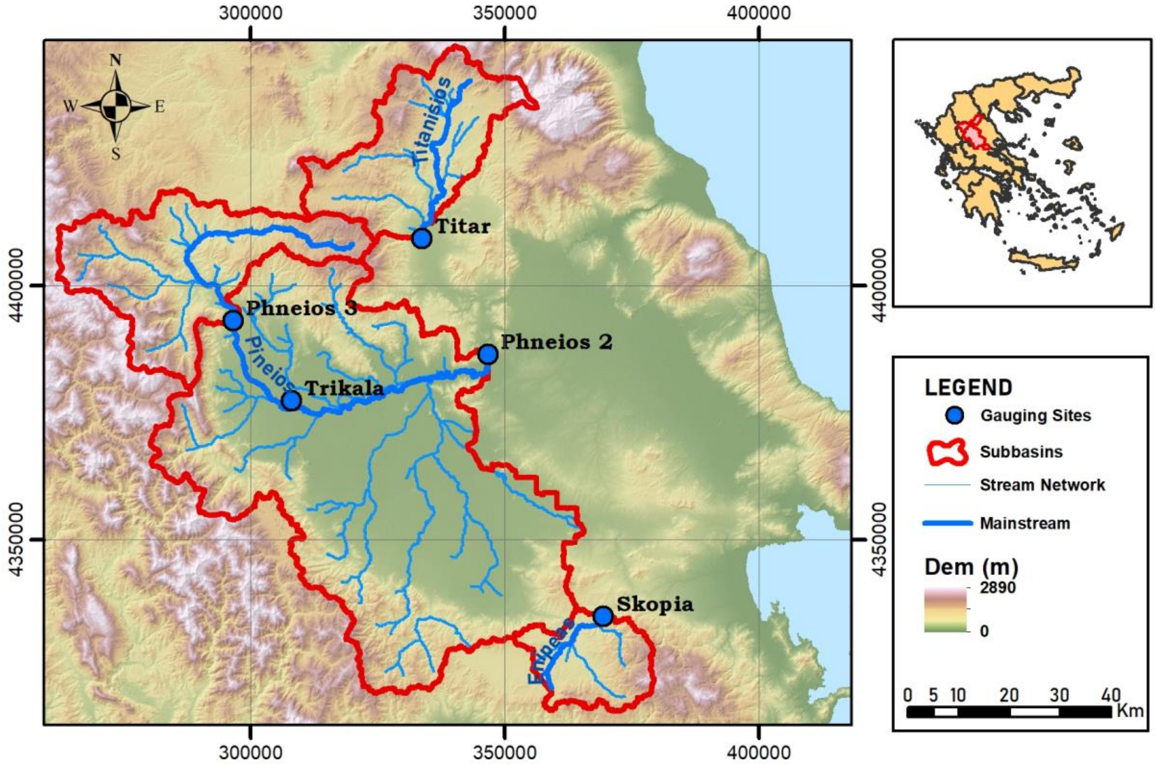


Figure 3-4: Subbasins defined by gauging sites in Thessaly RBD (GR08).

Pineieos2

Pineios2 is a gauging site in river Pineios, in central Greece, in the RBD of Thessaly (Figure 3-4). Pineios springs from the mountain range of Pindus and through the Thessaly plain flows into Aegean Sea. Pineios2 gauging site is located approximately in the center of the Pineios Basin. Thessaly RBD includes the biggest lowland area in Greece, with 51% of the total area covered by crops and is under intense irrigation stress (SSW, 2017b). The gauging is always carried out from a bridge of the national road Larissa - Trikala. The position has good hydraulic conditions, since the banks of the river are defined by vertical concrete blocks and moreover without any obstruction in the cross-section as the bridge has no support pillars.

The sub-basin defined upward from the gauging site covers a total area of 5027.8 km^2 while the length of the river concerning this part is 146.4 km. The basin's mean altitude is as high as 433.0 m and has a mean slope of 12.6°.

Pineios3

Pineios3 is a gauging site in river Pineios, in central Greece, in the RBD of Thessaly (Figure 3-4). It is located in the northwestern part of Pineios basin, to a significant distance from

Pineiso2, another gauging site in the same river. The measurements were made on the new bridge at the northwestern border of Sarakina village. The site has good measurement conditions from the bridge on high flows, wide cross-section, with the possibility of measuring in-stream at low flows. At low discharges a significant part of the flow is not measured, due to the flow of water within the layer of gravel and cobblestones of the riverbed.

The sub-basin defined upward from the gauging site covers a total area of 1059.5 km^2 while the length of the river concerning this part is 56.7 km. The basin's mean altitude is as high as 822.8 m and has a mean slope of 20.1°.

Trikala

Trikala gauging station is sited on Lithaios river, in Thessaly RBD (SSW, 2017b). Lithaios river crosses the city of Trikala, in central Greece (Figure 3-4). The gauging site is located in village Flamouli, just 2 km outside the city of Trikala. It has good measuring conditions and all measurements are done from a bridge.

Titar

Titar is a gauging site in Titarisios river, located in central Greece, in the RDB of Thessaly (Figure 3-4). It is a main tributary of Pineios river and lies in the northern part of Pineios basin (SSW, 2017b). In general, measurements are done in-stream but at higher flows gauging are done from the bridge located at the point.

The sub-basin defined upward from the gauging site covers a total area of 839.3 km^2 while the length of the river concerning this part is 51.0 km. The basin's mean altitude is as high as 725.0 m and has a mean slope of 15.3°.

Skopia

Skopia is a gauging site on river Enipeas located in central Grecece, in the RDB of Thessaly (Figure 3-4). It is a main tributary of Pineios river and is cited in the southernmost part of Pineios basin (SSW, 2017b). The site is remote, with difficulty in access in periods of prolonged rainfall. Gauging were done either from a bridge or in-stream, depending on the flow conditions. In the typical for the site low-flows, the water measurements are carried out directly in-stream.

The sub-basin defined upward from the gauging site covers a total area of 368.0 km^2 while the length of the river concerning this part is 36.6 km. The basin's mean altitude is as high as 664.6 m and has a mean slope of 12.7°.

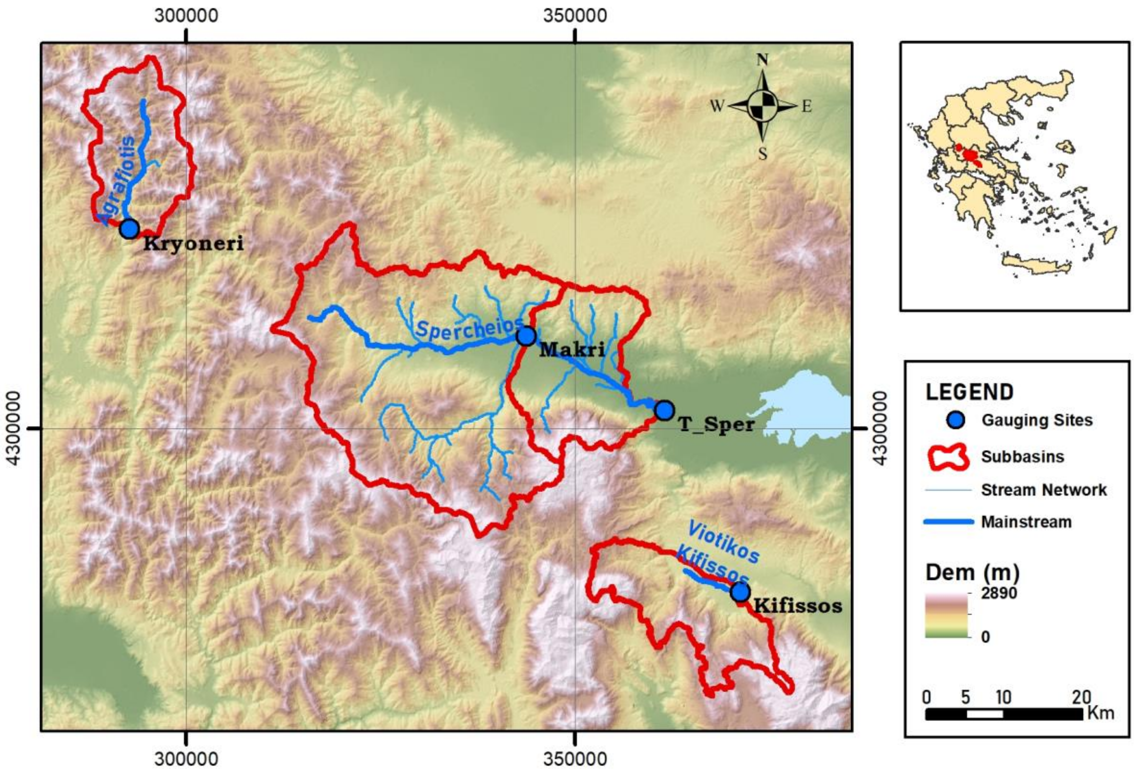


Figure 3-5: Subbasins defined by gauging sites in Central Greece RBD (GR07 & GR04).

Kifissos

Kifissos is a gauging site in Viotikos Kifissos, located in RBD of Eastern Sterea Ellada, in central Greece (Figure 3-5) (SSW, 2013c). Viotikos Kifissos originates from Mount Parnassus. The first three gauging of each year (months January, February and March) where conducted from a bridge while the rest were done directly in-stream.

The sub-basin defined upward from the gauging site covers a total area of 220.4 km^2 while the length of the river concerning this part is 27.8 km. The basin's mean altitude is as high as 997.3 m and has a mean slope of 21.6°.

Kryoneri

Kryoneri is a gauging site on river Agrafiotis located in the RBD of Western Sterea Ellada, in central Greece (Figure 3-5). Agrafiotis is a small reach river, lying within the fairly mountainous Acheloos river basin and is one of the main tributaries of Achellos river (SSW, 2014). Measurements are conducted from a bridge, but during winter months there is difficulty in access. It has steady-state flow conditions and the riverbed type is characterized by large cobbles.

The sub-basin defined upward from the gauging site covers a total area of 219.9 km^2 while the length of the river concerning this part is 27.2 km. The basin's mean altitude is as high as 1190.0 m and has a mean slope of 35.0°.

Makri

Makri gauging site is located in Spercheios river basin, in the RBD of Western Sterea Ellada, in central Greece (Figure 3-5). Measurements were carried out on a bridge in the village of Kastri, with overall good conditions. The measurements conducted during the period January 2019 - May 2019 were performed from the bridge while the rest were done in a directly in-stream.

The sub-basin defined upward from the gauging site covers a total area of 864.2 km^2 while the length of the river concerning this part is 45.5 km. The basin's mean altitude is as high as 795.2 m and has a mean slope of 20.6°.

T_Sper

T_SPER is located in Spercheios river basin, in the RBD of Western Sterea Ellada, in central Greece (Figure 3-5). Flow regime is highly seasonally variable and the channel geometry is dynamically shifting due to excessive sediment transportation (SSW, 2013c). All measurements are made from a bridge with good conditions of gauging.

The sub-basin defined upward from the gauging site covers a total area of 1146.8 km^2 while the length of the river concerning this part is 74.3 km. The basin's mean altitude is as high as 716.4 m and has a mean slope of 19.2°.

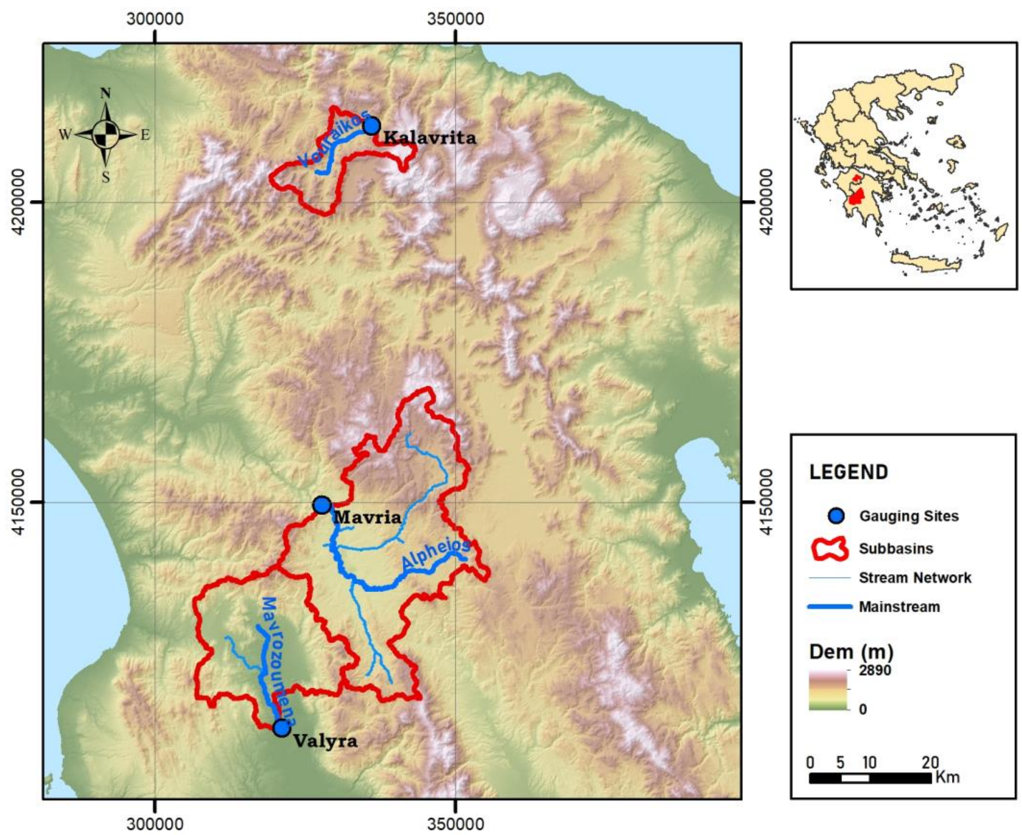


Figure 3-6: Subbasins defined by gauging sites in Peloponnese RBDs (GR01 & GR02).

Kalavrita

Kalavrita is a gauging site in Vouraikos river, located in RBD of Northern Peloponnese and is one of its main rivers (Figure 3-6). Vouraikos is subject to water extractions and hydromorphological alterations due to sand mining (SSW, 2013b). All measurements are done from a bridge, suitable for measurements even in higher flows.

The sub-basin defined upward from the gauging site, covers a total area of 143.6 km^2 while the length of the river concerning this part is 25.0 km. The basin's mean altitude is as high as 1054.7 m and has a mean slope of 22.0°.

Mavria

The Mavria gauging site is located in river Alfeios, extending in western to central Peloponnese (Figure 3-6). Alfeios river originates from the plateau of Arcadia and its basin lies in the RBD of Western Peloponnese (SSW, 2013a). A bridge at this site offers safe measuring conditions, however in low-flow measurements are conducted directly in-stream. With the exception of two, all other measurements were conducted in-stream.

The sub-basin defined upward from the gauging site covers a total area of 848.7 km^2 while the length of the river concerning this part is 49.0 km. The basin's mean altitude is as high as 768.0 m and has a mean slope of 15.4°.

Valyra

Valyra gauging station is measuring flow in Mavrozoumena stream located in southwestern part of the Peloponnese. It is the mean tributary of Pamisos river, located in RDB of Western Peloponnese (Figure 3-6). The site offers good measuring conditions. In four cases, measurements were made from a bridge while the rest were conducted directly in-stream. The sub-basin defined upward from the gauging site covers a total area of 445.0 km^2 while the length of the river concerning this part is 29.6 km. The basin's mean altitude is as high as 375.2 m and has a mean slope of 14.8°.

3.3 Catchment Descriptors

In this study, six geomorphological and climatic characteristics of the examined sites were selected as independent variables. These were: catchment area (A), length of main stem (L), mean annual precipitation (P), mean basin elevation (H), curve number (CN) and slope (S). The A, L, H and S convey information on the physical characteristics of the basin, P is the descriptor of precipitation while CN is an expression of joint geological and human impact indicators. Values for all independent variables were developed from raw datasets, as follows.

3.3.1 Curve Number (CN)

The Curve Number (CN) is an efficient and widely used method for determining the approximate amount of precipitation excess from a rainfall event, introduced by the Soil Conservation Service (SCS) -currently known as Natural Resources Conservation Service (NRCS)- of United States Department of Agriculture (USDA). In particular, the SCS method calculates the amount of runoff by three variables: the cumulative precipitation, antecedent soil moisture and the hydrological soil-vegetation complex. Each possible combination of the above three parameters, is expressed from a dimensionless number, the runoff CN. Prices theoretically range from 100 to 0, with high values expressing impermeable surfaces and high runoff. Practically the CN takes values from 30 to 98 and small deviations (of the order of 5 units) give large differences in runoff, up to 30-35%.

Given that the CN number for a basin can be estimated as a function of hydrological type of soil (permeability), land use/land cover and the previous moisture status, relevant geological and land cover data was acquired and used. At first every possible combination of land use/land cover and hydrological soil type in each grid cell was identified and then a unique 3-digit number was ascribed to each of them. This 3-digit number is a quasi-id for each cell, combining hydrological along with land use/land cover information. Then a lookup table was created that would match-up the 3-digit number to a CN value, according to US and Greek standards. The process is presented in a flow diagram (Figure 3-7) and described in detail below.

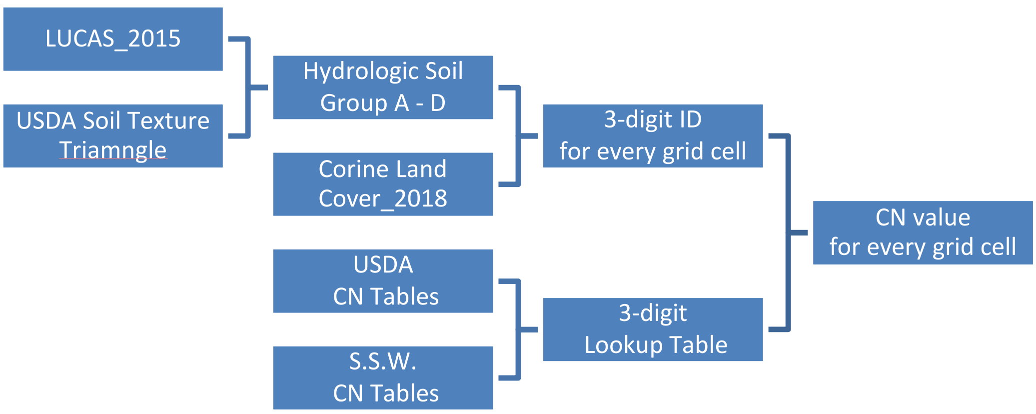


Figure 3-7: Flow diagram of the process used to acquire curve number (CN) values.

Setting up CN lookup table

The land cover and land use information was extracted from Corine Land Cover 2018 (*CLC_2018*) dataset. Corine Land Cover is a European program, monitoring land cover and land use changes across Europe (https://land.copernicus.eu/). *CLC_2018* dataset provides the information on land coverage and land use for Greece concerning the year 2018, according to the latest deliverables of the CORINE program.

The default categorization of *CLC_2018* is very extensive; comprising of 50 unique *CLC_Codes* for different land use/land cover types. The *CLC_Codes* are organized in general categories (*Label 1*), sub-categories (*Label 2*) and then specified even more precisely (*Label 3*). The first 11 *CLC_Codes* with description are presented in Table 3-2. To facilitate the workflow without significantly comprising the CN estimations, it was decided to group land use categories up to the second subcategory. This decision was made on the basis of scale that this research study was conducted and on the small variance of CN values for similar subcategories; i.e. in the scale of hundreds or thousands of square kilometers of basins examined, whether a small areas of some square kilometers would be interpreted as *"green urban area"* or *"sport and leisure facility"* (*Label 3*) would not have a significant effect in the final runoff estimation, as long as they were both interpreted *"artificial, non-agricultural vegetated areas"* (*Label 2*).

A simplification process was applied to screen out *Label 3* categorization, by subdividing with 10 all *CLC_Code* numbers and then keeping only the integer value. In this process, all *CLC_Code* numbers became 2-digit numbers. As an example *"port areas"* (*CLC_Code 123*) and *"airports"* (*CLC_Code 124*) would be regarded as the same land cover, from now on and denoted by the same code number of 12. By this process the *CLC* categories decreased from 50 initially, to 15 finally.

Table 3-2: Example of Corine Land Cover (CLC) classification. Connotation of each digit is done according to Labels 1 to 3.

CLC_Code	LABEL 1	LABEL 2	LABEL 3
111	Artificial surfaces	Urban fabric	Continuous urban fabric
112	Artificial surfaces	Urban fabric	Discontinuous urban fabric
121	Artificial surfaces	Industrial, commercial and transport units	Industrial or commercial units
122	Artificial surfaces	Industrial, commercial and transport units	Road and rail networks and associated land
123	Artificial surfaces	Industrial, commercial and transport units	Port areas
124	Artificial surfaces	Industrial, commercial and transport units	Airports
131	Artificial surfaces	Mine, dump and construction sites	Mineral extraction sites
132	Artificial surfaces	Mine, dump and construction sites	Dump sites
133	Artificial surfaces	Mine, dump and construction sites	Construction sites
141	Artificial surfaces	Artificial, non-agricultural vegetated areas	Green urban areas
142	Artificial surfaces	Artificial, non-agricultural vegetated areas	Sport and leisure facilities

Once the new *CLC_Codes* that would be used were acquired, a combination with hydrologic soil groups and previous moisture condition was needed to develop CN lookup tables. For this purpose the "Hydrologic Soil-Cover Complexes" of National Engineering Handbook of USDA (NRCS, 2004) was used, as it provides tables with estimated values for CN under different combinations of the above three factors, which are internationally used as standard values. The Flood Risk Managements Plans from Special Secretariat for Water of Ministry of Environment of Greece were also advised, as it specifies CN values for Greece.
As far as the antecedent moisture parameter is concerned, CN number is further divided into three categories: *poor, fair and good*. In lack of such information the number for *fair* hydrologic condition was used for all cases. Finally Table 3-3 was developed, matching up a CN number value for every combination of land use/land cover and hydrologic soil group.

Table 3-3: Developed CN values for different combinations of land cover and hydrologic soil groups.

	Curve Number for Hydrologic Soil Group			
Land Cover Group/Code	**A**	**B**	**C**	**D**
11	98	98	98	98
12	89	92	94	95
13	81	88	91	93
14	49	69	79	84
21	77	86	91	94
22	64	75	82	85
23	49	69	79	84
24	60	72	80	84
31	41	63	75	81
32	45	66	77	83
33	63	77	85	88
41	98	98	98	98
42	98	98	98	98
51	100	100	100	100
52	100	100	100	100

Finally using the Table 3-3 and assigning values for the soil type groups, designated as *GroupA=100, GroupB=200, GroupC=300* and *GroupD=400* a 3-digit number can be defined for every possible combination. In the new 3-digit number, the first digit indicates the soil type (*Group A-D*) while the next two digits correspond to land use/land cover. Consequently, *code*

233 would correspond to soil type of *Group B* and *land cover 33* (open space with little or no vegetation) giving a CN of 77.

Acquiring 3-digit number for each layer cell

The second step required to implement this method, was to get information on all possible combinations of hydrologic soil type and land use/land cover for each cell of the grid. To define soil type over the drainage basins the European Soil Dataset from program *LUCAS_2015* was incorporated. Program LUCAS is *"mechanism for the harmonized monitoring (common sampling procedure and standard analysis methods) of topsoils at the European Union (EU) level."* (ESDAC, 2020).

The LUCAS topsoil dataset used in this study was made available by the European Commission through the European Soil Data Centre managed by the Joint Research Centre (JRC), http://esdac.jrc.ec.europa.eu. This dataset provides information, over European Union countries, on the particle percentage of clay, sand and silt in the upper soil layer. This information is organized in shape layers, with a 1000 m x 1000 m cell size.

In general, soils are divided into four hydrologic groups (types) determined by their hydraulic conductivity (NRCS, 2009):

- *Group A*: Soils with low surface runoff potential. Soils in this group are characterized by more than 90% sand content and less than 10% clay, with sand, loamy sand and sandy loam textures. When saturated they have a high infiltration rate, 7.62 mm/h and above.
- *Group B*: Soils with moderate surface runoff potential. Soils in this group have in general 50% to 90% sand content and clay between 10% and 20% and have loam, silty loam and silty textures. They have a moderate infiltration rate 3.81-7.62 mm/h.
- *Group C*: Soils with relatively high surface runoff potential. Soils in this group range typically from 20% to 40% sand and less than 50% clay and have sandy clay loam textures. Their infiltration rate lies between 1.27-3.81 mm/h.
- *Group D*: Soils with very high surface runoff potential. Soils in this group have high content in clay, regularly over 40% and less than 50% sand. They have clayey loam, silty clay loam, sandy clay, silty clay and clayey textures. Their typical infiltration rate is less than 1.27 mm/h.

Having the needed information from the three layers of *LUCAS_2015* for sand, silt and clay a soil texture could be attributed to each cell. This procedure was based on the USDA soil texture triangle (Figure 3-8), which is a worldwide acceptable standard for texture categorization (USDA, 1987). To reduce the complexity and computation effort, each of the 12 textures described in the triangle is attributed in one of the four soil groups (Wang & Feddema, 2020), as categorized above. To do so, a code was created so that each cell, depending on the mixture of silt, sand and clay percentages, would be attributed to one texture class and consequently each texture class to one of the 4 hydrologic groups. Texture classes are defined in way to a) generate all possible combinations of sand, silt and clay percentages and b) eliminate overlapping of soil texture class boundaries (Benham et al., 2009).

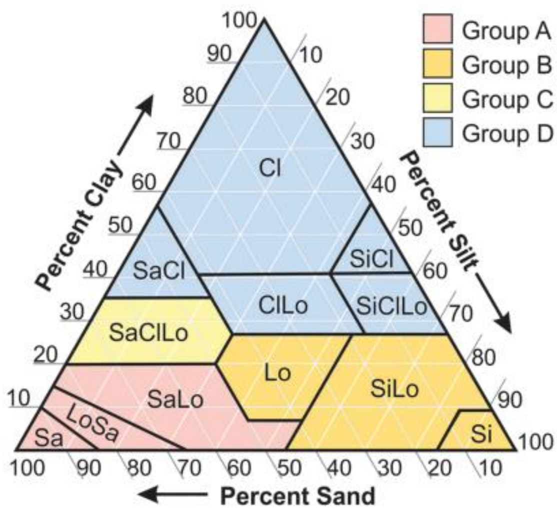


Figure 3-8: USDA soil texture triangle adopted with the reduced set of hydrologic soil groups (Sa = sand; Lo = loam; Cl = clay; Si = silt) used in this study (Wang & Feddema, 2020).

Once the four layers, each for every hydrologic soil group, were created they were merged into a single new layer, which aggregated the information of hydrologic soil type for each grid cell in every basin. Coupling of this layer with the land use/land cover layer, provided all possible soil types-land use/land cover combinations and 3-digit number were attributed to each grid cell. This 3-digit number and the lookup table of CN were matched and a single CN value was corresponded for each grid cell.

3.3.2 Other physical basin attributes (A, L, S, H)

Geomorphological and hydrological information for each site were acquired from geoprocessing of the Digital Elevation Map (DEM) of Greece with the use of Geographic Information System (GIS). The DEM used, was provided by the National Cadastre & Mapping Agency S.A. and it featured a 5 m x 5 m grid elevation dataset with a geometric accuracy RMSE of z ≤ 2.0 m and an absolute accuracy about 3.9 m for a 95% confidence level. GIS techniques along with the use of hydrological tools were incorporated to delineate the drainage basin up to the gauging site. Then, further analysis to acquire relevant information on catchment area (A), hydrographic network and length of mainstem (L), elevation (H) and slope (S) was done.

3.3.3 Precipitation

To acquire a mean annual precipitation (mm) value over the examined basins, the E-OBS dataset was used. E-OBS is a daily gridded observational dataset for precipitation from the European Climate Assessment & Dataset project (ECA&D). Observations are made from meteorological stations all over Europe, including Greece, and are subsequently processed in a spatial integration process. A continuously updated algorithm, accounting for errors and inconsistencies is then used to create the data. Information provided consists of: rainfall intensity, surface temperature, and atmospheric pressure at sea level. E_OBS data have a high spatial resolution of a 0.25 ° x 0.25 ° grid and are therefore considered to be the most reliable method for calculating precipitation values in sites where no measurement are available. The latest version issued (22.0e) was used, which was published in December of 2020. The dataset used, comprised of consecutive daily precipitation values in mm for 30 hydrologic years, namely from 01 October of 1989 up to 01 October of 2019.

Since the precipitation values were given in point measures/features (Figure 3-9), a surface interpolation technique was utilized to calculate the mean annual precipitation of each basin. For this process, the Thiessen method was used, a simple method according to which the weights of all measuring stations are regarded as equal, namely $w_i = 1/k$ y. Thiessen polygons were used to allocate area to the nearest grid point and then the daily precipitation for each basin was given as the sum of product of coverage percentage times the measured precipitation:

$$P_s = \sum_{i=1}^{k} w_i \, P_i \tag{1}$$

Monthly, annual and finally mean annual precipitation values were then estimated from the daily values derived from surface integration. The estimates of the method are better a) for a denser the network of rain gauges and b) for a longer time scale, e.g. over-annual estimations are more accurate than estimation referring just to one rainfall event (Mimikou & Baltas, 2018).

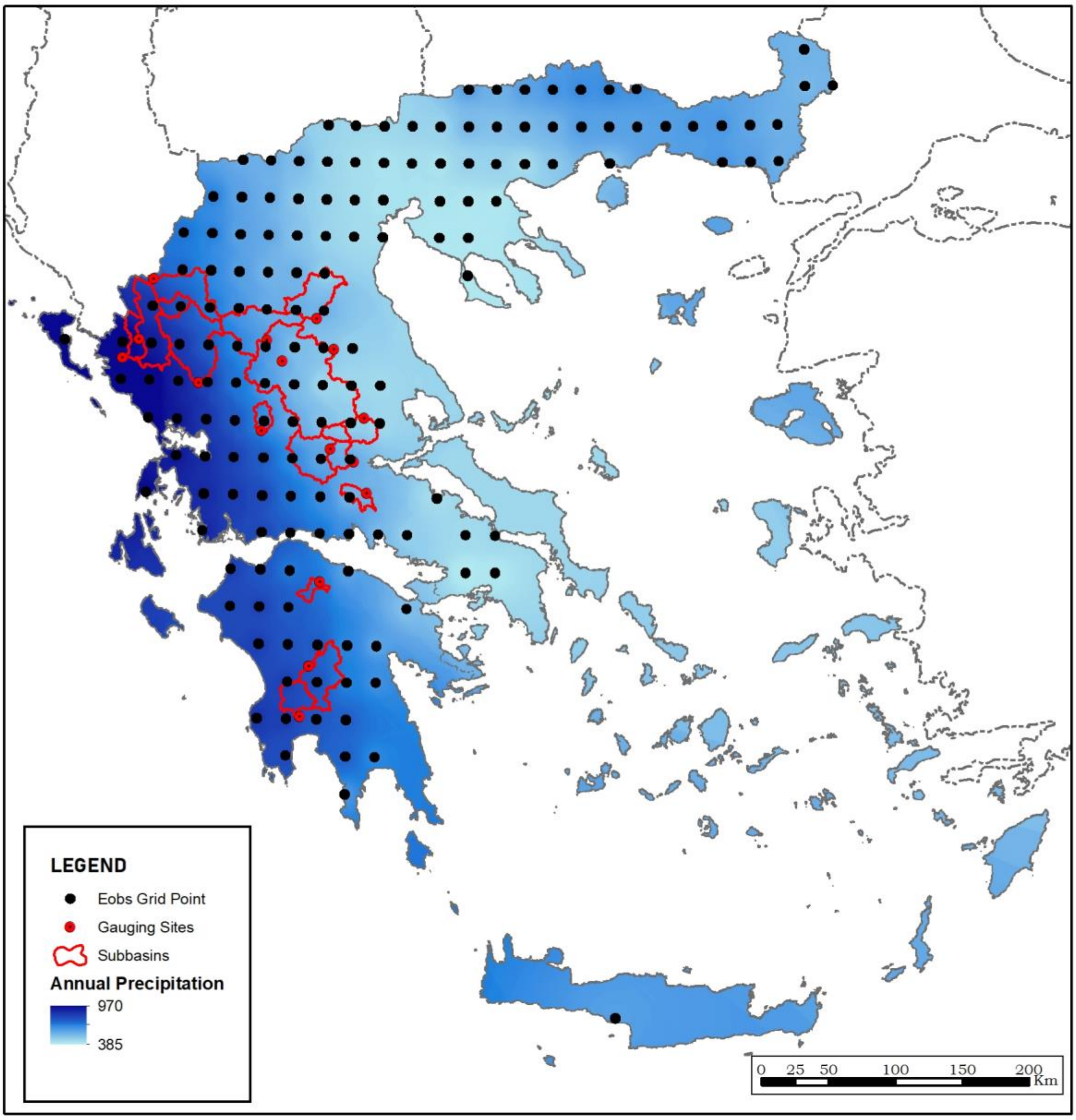


Figure 3-9: E-OBS grid points and the developed precipitation distribution map of Greece.

For most of the 16 basins, the dataset comprised of consecutive, positive numbers for the whole period of 30 hydrologic years. However *NoData* values, denoted as *-999.9*, were also present in some cases. Special care was taken each time, depending on the extent and the type of missing data, as described below.

For Mavria and Valyra, there was absence of data for all grid points concerning the first hydrologic year, from 01/10/1989 up to 01/10/1990. Therefore, the first year was excluded from the estimation process and the over-annual precipitation for these two basins was estimated on the basis of 29 hydrologic years.

Titar and Skopia, each had one *NoData* grid point. However, only a small fraction of the whole basin in each case, 2.3% and 1.4% respectively, was affected by these Thiessen polygons. Thus, their percentages were attributed to the nearest points with measured values, in such a way to both discard the *NoData* points but also be consistent to the 100% sum of weights.

Kalavrita and Kifissos were the most problematic cases, since grid points with absence of data summed up to 87.8% and 24.1% respectively. The percentages were considered as pretty high, to rely on the neighboring points solution that was applied before. A new process was implemented for both cases: the *NoData* grid points were deleted and new Thiessen polygons were created from adjacent grid points with full records of values. Then the standard process for daily, monthly and over-annual estimation of precipitation was employed.

4. METHODOLOGICAL FRAMEWORK

4.1 Q-H Curves Development

The development of a rating curve involves three main steps: a) the collection of field data, i.e. stage (H) and discharge (Q), b) the quality control of the data and c) the selection of the appropriate method to establish a mathematical model that associates the stage and discharge parameters (Othman et al., 2019). The process of curve fitting involves a generalized function, the coefficients of which will be optimized for the best fit between the measured equation and the gauging data (Chandrasekaran & Muttil, 2005).

The raw field data were made available by the monitoring program of the NMWN. Then to begin with the curve fitting process, a quality control scheme was implemented in order to audit the raw data for possible uncertainties and errors. Subsequently, three rating curves, from literature, were selected and examined over the selected sites. An application from MATLAB was used to perform the curve fitting and to evaluate the performance for each of the rating curves.

4.1.1 Quality control

Since the whole curve fitting process relies on the validity of the available Q-H measurements, a scrutiny process was implemented to account for outliers and erroneous measurements in the datasets. This procedure was used to determine if any measurements were to be deleted before the curve fitting or not. Scrutiny of measurements requires expertise knowledge, thorough examination of each single Q-H pair and sound hydrological reasoning for every exclusion done. Omitting measurement pairs is a risky process and should be used sparingly. For example, an extreme discharge observation should not automatically be excluded as an outlier, since this could be a measurement from a flooding event and, as such, not an erroneous measurement. Therefore not only this measurements must not be exclude, but provides with information regarding the formation of the rating curve for large stage values. On the other hand, over-refinement of the rating model has to be avoided and exclusion of measurements was done on the bare minimum extent and always with caution not to compromise hydraulic integrity.

Three fundamental criteria were implemented in this procedure. The first one concerned measurements that deviated more than 8% from the provisional rating curve. Different thresholds are given in literature for this criterion, ranging from 5% (Herschy, 1993; DeGagne et al., 1996) to 8% (Wilcock, 2016). The second criterion concerned measurements of discharge that varied greatly over the same or similar stage. The third criterion was the examination of the trendlines of discharge and stage, based on the concept of hydrological consistency. More specifically, observations of stage and discharge were sorted in a continuous chronological order and then plotted in the same set of *x,y* axis. It was expected that the two lines would follow similar trends, i.e. periods with increasing stage (rising curve) would correspond to increasing discharges as well. In that sense, if a measurement disrupted the consistency between the two trendlines, it was potentially erroneous and due to further examination.

An additional rule was applied for the minimum amount of measurements accepted per site, to develop a rating curve. Taking into account the data available and relevant international literature regarding this issue (ISO, 1998; WMO, 2010; Wilcock, 2016), the threshold value for this study was set to a minimum of ten measurements per site. It is also important to state that zero discharge values were not included in the set of measurement that would be used for curve fitting. Finally, since the rating curve is subject to changes with time, due to physical alterations of the river section geometry, the measurements were also examined to determine whether they were valid for use with a single curve or not. In the latter case, the need to use two rating curves was acknowledged and an effort to locate the possible breaking points in the dataset was made.

With the above criteria a combined examination of raw data, field notes and scatter plots, for each site, was used to locate dubious Q-H pairs. The available set of Q-H observations, for each site, was at first graphically represented in a scatter plot and a provisional curve was plotted. The visual representation of the field data makes it easier to locate Q-H pairs that deviate from a provisional curve and discharge values that vary greatly over same or similar stage measurements. In addition, stage and discharge values were plotted in continuous chronological order, in a combined diagram, and any inconsistency in the two trendlines was considered as an indicator and was further examined as potentially erroneous measurement. Finally, the audit of the measurements was completed by examining the field notes, which could explain certain deviations.

4.1.2 Stage-Discharge relationships examined

A large amount of different rating curves has been used worldwide to describe the stage-discharge relationship. However, the most widely used, in studies and in practice, is the power law function. The coefficients of the power law are estimated with non-linear regressions, but linear regression on the log-transformed dataset is also being used. However, other functions are also incorporated in the curve fitting process. It is known that polynomials of different degrees are frequently used (Chandrasekaran & Muttil, 2005). Higher degree of polynomials can capture more data variations, but become more unstable when increasing the degree level. Finally, polynomials of logarithms have also been occasionally used. For example, Pinter et al. (2008) made use of polynomial of logarithms relationships for constructing annual rating curves for the Mississippi River.

In order to determine which stage-discharge relationship has superior performance in the examined gauging sites, three relationships proposed were examined (Mimikou & Baltas, 2018):

a) Power law function,

$$Q = k(H - a)^b \tag{2}$$

where, Q = discharge (m³/s)

k and b = site specific constants

H = stage height (m)

a = stage height at which discharge is zero (m)

b) Second degree polynomial (2nd degree polynomial),

$$Q = A_0 + A_1H + A_2H^2 \tag{3}$$

where, Q = discharge (m³/s)

H = stage height (m)

A_0, A_1, A_2 = coefficients of the model

c) Second degree polynomial of the natural logarithm (ln-polynomial),

$$\ln(Q) = A_0 + A_1 lnH + A_2(lnH)^2 \tag{4}$$

where, Q = discharge (m³/s)

H = stage height (m)

A_0, A_1, A_2 = coefficients of the model

4.1.3 Curve Fitting

The curve fitting was performed with the Curve Fitting Toolbox of MATLAB®. The application performs regression analysis on a library of linear and non-linear models, as well as, on manually configured equations. Multiple fits can be run simultaneously and the results compared both graphically and through goodness-of-fit statistics. A typical example of the visual representation of model fit as well as the statistics of efficiency and the coefficients estimation is given in Figure 4-1 and Figure 4-2.

The Curve Fitting Toolbox also calculates confidence bounds for the fitted coefficients and prediction bounds for new observations. The bounds are defined by the user, with the typical value being 95%, although other percentages are also frequently used, such as the 90% and 99%. To compare the selected models, goodness-of-fit statistics, provided by the application, were selected.

For each dataset, the power law, the 2nd degree polynomial and the ln-polynomial were examined. The first two are available as presets of the application, while the latter was inserted manually. The curve fitting process was done with 95% level of certainty. These confidence levels concern the estimated Q values, when extrapolating is done within the range of observed stage values, and the fitted coefficients. Extrapolating values for stage higher than the highest gauged stage, will entail an even higher level of uncertainty for the estimated discharge (Clarke, 1999).

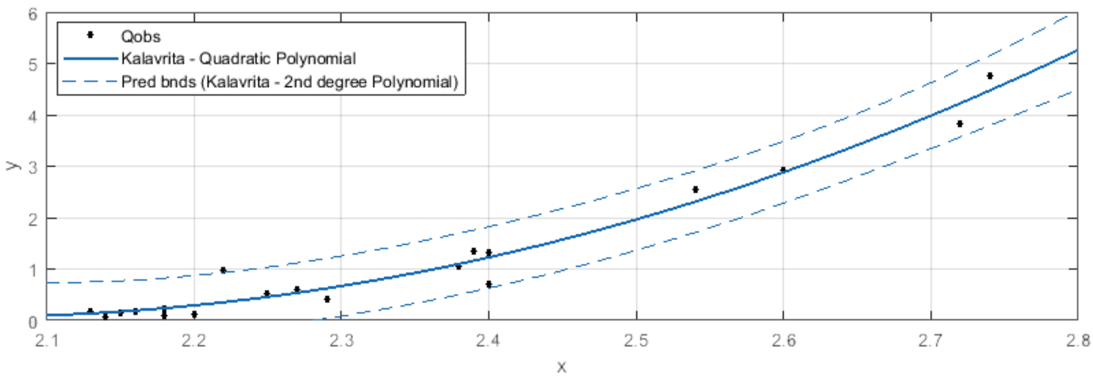


Figure 4-1: Curve fitting graph of 2nd degree polynomial rating curve with 95% confidence bounds, for gauging site Kalavrita in MATLAB Curve Fitting Toolbox.

```
Results

Linear model Poly2:
   f(x) = p1*x^2 + p2*x + p3
Coefficients (with 95% confidence bounds):
     p1 =       9.055  (5.109, 13)
     p2 =      -36.99  (-56.09, -17.89)
     p3 =       37.84  (14.88, 60.8)

Goodness of fit:
  SSE: 1.108
  R-square: 0.9675
  Adjusted R-square: 0.9634
  RMSE: 0.2631
```

Figure 4-2: Specified coefficients and goodness-of-fit statistics, concerning the 2nd degree polynomial rating curve for gauging site Kalavrita in MATLAB Curve Fitting Toolbox.

4.1.4 Goodness-of-fit measure

To evaluate and compare the efficiency of the rating curves, two goodness-of-fit measures were used: the coefficient of determination (R^2) and the Root Mean Square Error (RMSE). The R^2 is a statistical measure, representing the proportion of variance of the dependent value that is predicted from the independent value. The R^2 is widely used and is calculated as described below:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(y_{est,i} - y_{obs,i}\right)^2}{\sum_{i=1}^{N}\left(y_{obs,i} - \hat{y}_{obs}\right)^2} \qquad (5)$$

where, $\sum_{i=1}^{N}(y_{est,i} - y_{obs,i})^2$, is the sum of squares of the residuals, describing the total deviation of the response values from the fit to the response values and $\sum_{i=1}^{N}(y_i - \hat{y})^2$, is the sum of squares total describing the dispersion of the observed variables around their mean. The R^2 can take values from 0 to 1, often stated as percentages, with values closer to 1 indicating a better fit. R^2 has the advantage of being more intuitive, but it is a relative measure and is dimensionless.

The RMSE is the square root of the variance of the residuals and is an assessment of the model's predictive ability. It is a measure of how scattered from the regression line the residuals are. RMSE is calculated as described below:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{N}\left(y_{est,i} - y_{obs,i}\right)^2} \qquad (6)$$

RMSE has the same units as the dependent variable, with values closer to 0 indicating a better fit and is an important measurement of fit when the model is used for prediction (Irving et al., 2018).

4.2 Derivation of Environmental Flow Indices

The approach of this study on assessing e-flows is based on hydrological methods and therefore the FDC and MAF, the two most widely used hydrological methods, were selected and examined. In total, four low-flow indices were developed, two from using the FDC (Q_{90} and Q_{95}) and two from the MAF (10% and 30% MAF) methods. Subsequently, the four indices were compared through a selection process scheme, to the values proposed by Greek regulations. The low-flow index that produced the better approximations with the values determined by the Greek regulations, was selected as a representative e-flow index and was used into the regression model.

4.2.1 Data pre-process

To develop the e-flow according to Greek regulations and the four low-flow indices, for every site, all of the available Q-H pairs were used, i.e. including also all zero discharge measurements. This is in contrast with the procedure followed in the curve fitting process, where a number of Q-H pairs were discarded in order to ensure that erroneous and zero discharge measurements would be omitted. The basis of the different handling of the datasets, for these two processes, comes as a consequence of their different nature, i.e. the rating curves being a strict mathematical equation of two features and the flow indices being a rougher representation of the discharge range. In other words, small deviations and errors of measurements could render invalid a strict mathematical relationship, i.e. the rating curve, but could still be valuable information to get a rough representation of the discharge regime of a basin, i.e. the flow indices.

Also, unlike rating curves, where the input data were Q-H pairs, the required input for deriving the FDC and the MAF is solely discharge values. This fact alone was expected to reduce the degree of error, almost by 50%; making the assumption that errors come from both features (Q and H) with equal degree, omitting one feature, i.e. H, as a whole would also result in excluding all errors coming from that feature. For example, during the scrutiny process of input data, a pair of values with valid measurement of Q and error in the measurement of H would result in discarding of the Q-H pair. As a consequence, a perfectly good Q value would not be used because of flaws in stage measurements, although stage is a feature irrelevant in the FDC and MAF process.

However, this approach leaves open the possibility of errors coming from the measurement of discharge. For the scope of this study it was decided that all measurements of discharge, even when there are potential errors in the measurement, can be used as indicative values. This conjecture implies that values of discharge, even with some level of error, could still provide information on two very important factors a) the order of magnitude of a discharge measurement and b) on the frequency of occurrence. These two are merely the most essential information on the FDC and given the small amount of total observations, it was an accepted compromise.

Finally, zero discharge values should also be included in the input data processed in order for the FDC to capture seasonal dry-outs. A FDC is a signature of the streamflow and it is essential that any, or repeated, zero discharges are reflected in the FDC.

4.2.2 Greek regulations

The Greek regulations, define three different methods for calculating discharge, from which the biggest value should be regarded as the recommended e-flow. The first two methods, i.e. the 30% of the average supply of the summer months (June - July – August) and the 50% of the average supply for the month of September, were calculated for each site. The two values of discharge were compared to each other and the highest value was kept for each site, as the proposed e-flow according to Greek legislation. The third method of 30 l/s at least in each case (or 0.03 m^3/s) was also examined, but proved to be a rather low discharge value for the examined sites and was always exceeded by the other two methodologies, in all sites. The acquired discharge values according to Greek regulations were considered as target values, by which the fitness of the FDC and MAF methods were to be judged.

4.2.3 Q_{90} and Q_{95} (from FDC)

The FDC is developed by taking into account all discharge values during the examined period (2018-2019). The process of creating the FDCs is described as follows:

- Monthly discharges are gathered and sorted in a decreasing order of magnitude and
- A total number of measurements n is defined.
- A value rank m is assigned to each discharge, starting with 1 for the largest value.
- The exceedance probability is then calculated for each value by the equation:

$$P = \frac{m}{n+1} \times 100 \qquad (7)$$

Once a FDC is constructed the discharge values corresponding to 90% and 95% exceedance probability, denoted as Q_{90} and Q_{95} respectively, are acquired.

4.2.4 10% MAF and 30% MAF

The average discharge is calculated for each of the two years of records. Then the mean of the two is assumed as the mean annual flow for the sites. From this value, the designated percentages of 10% and 30% are acquired.

4.3 Regression analysis

The development of the regression model is based on the better performing low-flow index (dependent variable) and on geomorphological and climatic characteristics of the examined sites (independent variables). The raw hydrometric data of the 15 gauging sites were processed and the better performing low-flow index to be used in the regression analysis, was calculated for each of them. Sites that produced zero values for the better performing index were excluded from the regression.

To test the validity of the model, the remaining sites were divided in two datasets, one for calibration and one for validation purposes. A 75-25% rule was implemented for calibration and validation. Also a selection process was applied, to ensure that both datasets would include gauging sites covering all range of values of the independent variables. The variability of the gauging sites was mostly judged on catchment area and secondly on the magnitude of the selected low-flow index. Different combinations of gauging sites for the calibration and validation groups were examined in the process. Also clustering of gauging sites based on common features, for example catchment area or specific discharge was attempted.

The model was developed using stepwise regression and backward elimination approach with manual intervention. All six (A, L, P, H, CN, S) independent variables were initially included in the regression's analysis. Additionally, combinations of descriptors were also examined, like the catchment area divided by the length of main stem (A/L) and other variables such as the specific discharge (Q/A), namely the flow per unit surface area. The criteria for the chosen variables were, to be justifiable in terms of hydrology but also significant in terms of statistics (Eslamian et al., 2010).

The performance of each model produced was examined by the overall F-test. Statistically insignificant variables were determined by the individual t-test and they were eliminated with the stepwise process, from the regression analysis. Ultimately a certain allocation of the sites over the calibration and validation datasets was decided and the statistically significant independent variables were acquired.

4.3.1 Multiple Linear Regression (MLR) model

Multiple linear regression (MLR) is the extension of simple linear regression (SLR) to the case of multiple explanatory variables (Helsel and Hirsch, 2002). MLR is a statistical technique that uses several explanatory variables to predict, as much as possible, of the variation observed in the response y variable, leaving as little variation as possible to unexplained "noise".

The basic form of a linear multivariate model is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \tag{8}$$

where: y, is the response variable

β_0, is the intercept

β_1, is the slope coefficient for the first explanatory variable

β_2, is the slope coefficient for the second explanatory variable

β_k, is the slope coefficient for the kth explanatory variable

x_i, is the explanatory variable

The MLR is based on the assumptions that a certain linear relationship between the dependent and independent variables exists and that the independent variables are not highly correlated with each other. The Regression Tool of the Data Analysis toolpack of Microsoft Excel, which performs an ordinary least squares (OLS) regression, was used with 95% confidence intervals for coefficients estimate, while, the *p-value* of the *F-test* of overall significance was used to determine the validity of each regression model. The *F-test* examines the null hypothesis, which is (Helsel and Hirsch, 2002):

H_0: $\beta_{k+1} + \beta_{k+2} + \cdots + \beta_m = 0$, versus the alternative

H_1: at least one of these m-k coefficients is not equal to zero

The *p-value* for each independent variable indicates whether they are statistically significant. If the *p-value* is less than the selected significance level the null hypothesis can be rejected.

4.3.2 Performance measure

The prediction accuracy of the forecasting model was measured by the Mean Absolute Percentage Error (MAPE), R^2, RMSE and the Standard Error (SE). MAPE is a measure of size of error between actual and estimated value in percentage terms. By using the absolute error, MAPE possesses the advantage of avoiding positive and negative errors cancelling each other out. It is a widely used measure for prediction because it is expressed in percentage and is easy to interpret. Smaller values of MAPE indicate better prediction. MAPE is defined by the formula:

$$M = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{A_i - F_i}{A_i}\right| \quad (9)$$

where A_i is the actual value and F_i the predicted value.

The MAPE was applied to estimate the performance of the regression model to the validation group of gauging sites.

The SE indicates how precise the model's predictions are, using the units of the dependent variable. It gives a measure how far the data points are from the regression line on average. The smaller values of SE signify a better fit of the model. The SE is defined as:

$$SE = \frac{\sigma}{\sqrt{n}} \quad (10)$$

, where σ is the standard deviation and n is the sample population.

5. RESULTS & DISCUSSION

5.1 Q-H Curves Derivation

5.1.1 Raw Data & Quality control

The raw hydrometric data had to be audited and for that cause, a preliminary quality control process was applied to detect erroneous measurements (Table 5-1). In total out of 16 gauging sites examined, there was no exclusion of measurements in 4 of them (25% of total), minor intervention ranging from 1 to 3 pairs discarded in 5 of them (31.25% of total) and significant intervention by excluding from 4 up to 8 measurements in 5 of them (31.25% of total). In addition, the measurements from two gauging sites, Trikala and Titar (12.5% of total), were deemed as flawed altogether and were not included in the curve fitting process.

Table 5-1: Effect of the quality control process on the number of measurements.

Station name	Initial number of measurements	Final number of measurements	Excluded measurements
Arta	21	14	7
Gribovo	21	20	1
Kalavrita	21	19	2
Kifissos	21	21	0
Trikala	17	Rejected	-
Kryoneri	21	13	8
Makri	21	18	3
Mavria	15	15	0
Melisso	20	15	5
Pineios2	17	12	5
Pineios3	13	10	3
Skopia	15	11	4
Stenaki	17	17	0
T_Sper	21	21	0
Titar	18	Rejected	-
Valyra	21	19	2

Quality control of the measurements proved to be an essential step of the whole process, since only 25% of the total sites remained unaffected by it. For the rest 75% of sites the screening process either a) was necessary in order to obtain a rating curve or b) significantly improved the goodness of fit of a rating curve, although it was not necessary. The first case, apparent in sites where major interventions on measurements were done (four or more pairs removed), proved to be a decisive process as it prepared the dataset and made it suitable for the curve fitting process, in cases that otherwise a rating curve could not be fit. The second case, manifested in sites where only minor interventions were done (one or two pairs omitted) resulted in an important increase in R^2 and RMSE scores. However, it should be noted that for sites with minor interventions, even though exclusion of measurements contributed in the better performance of the rating curves, this step was not necessary; these rating curves could be developed even without the exclusions but with lower performances. The significance of the screening process can be highlighted by examining the results obtained here, in comparison to the performance of the rating curves in the gauging sites prior to any interference in the measurements. In this approach, namely without excluding any erroneous observations, five sites (instead of two) had R^2 values below 0.50 and were rejected (Skopia, Pineios3, Kryoneri, Trikala, Titar) as no reliable rating curve could be established. Also, for the rest 11 sites, a rating curve could be established and the R^2 ranged between 0.63 to 0.98, while in only five out the 11 sites the R^2 value was higher than 0.90. For the rest six sites, the R^2 value was below 0.90 and considerably lower than the R^2 value after the screening process was applied.

The quality control process is a step that should be done with care and to the minimum extent possible, since it introduces some level of arbitrariness and uncertainty in the whole process. As an example of the screening procedure, two representative cases of sites are discussed below, Kalavrita and Pineios3. Pineios3 is a gauging site located in an area subject to significant water pressures, as intakes for irrigation often result in zero flows during summer months and is presented here as a case representative for the gauging sites that exclusion of measurements was necessary in order to get an acceptable fit. A scatter plot including all Q-H pairs, 13 in total, and the provisional curve can be seen in Figure 5-1. The initial R^2 values were considerably low, 0.37 for power law and 0.19 for 2nd degree polynomial and could not propose any solid correlation between stage and discharge.

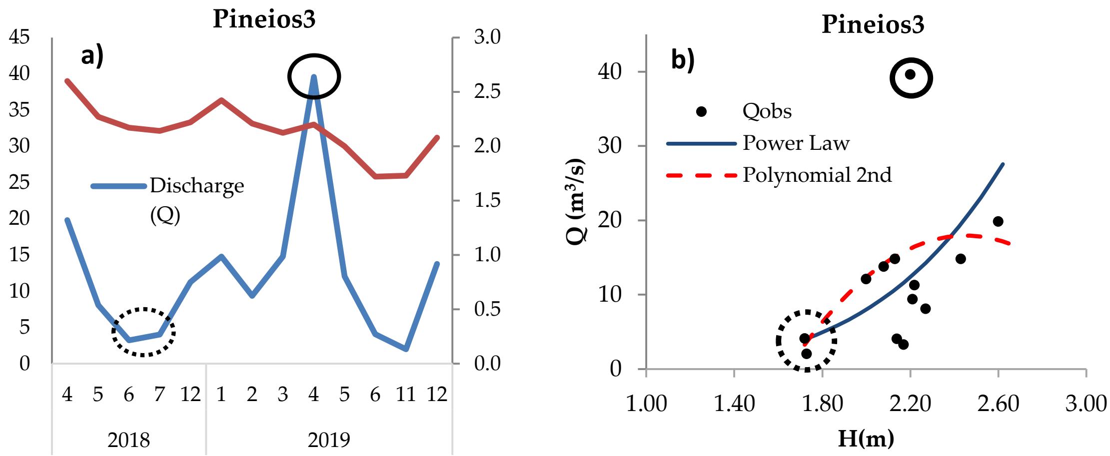


Figure 5-1: Quality control procedure for gauging site Pineios3; a) Combined graph of chronological timeseries for stage (H) and discharge (Q); b) initial scatter plot with provisional curves.

During the visual examination of both the initial scatter plot and the graph of chronological timeseries of stage and discharge, a measurement stands out, concerning the 4th month of 2019, highlighted in circle with solid line (Figure 5-1). The first visual indicator was further examined and confirmed that this measurement exceeded by far the 8% deviation from the fitting curve rule. Again, it can be seen that for a stage of 2.20 m it had a recorded discharge of 39.58 m^3/s when another measurement only 4 month prior and with the exact same stage had a discharge measured at 11.26 m^3/s. Examining the field notes, there was no description of a flooding or another event that would imply a cross-section alteration that could justify such a significant raise in the discharge measurement within 4 months. From the combined reasoning of the above justifications, the pair of observations concerning the 4th of 2019 was excluded. In a similar process two more measurements, concerning the 6th and 7th months of 2018 were discarded. They both had the same or similar stage measurement as other pairs of observation but with much lower discharge values and with considerable deviation from the fitting curve. These two measurements were excluded in order not to tamper the hydrological consistency of the data. In total three pairs of measurements were excluded and the fitting curve was created with 10 pairs. Through this process it became feasible to establish a rating curve for a site that would otherwise be omitted, since the provisional curve fitting did not produce acceptable results. The final R^2 values of this curve fitting, was 0.64 for power law and 0.67 for 2nd degree polynomial.

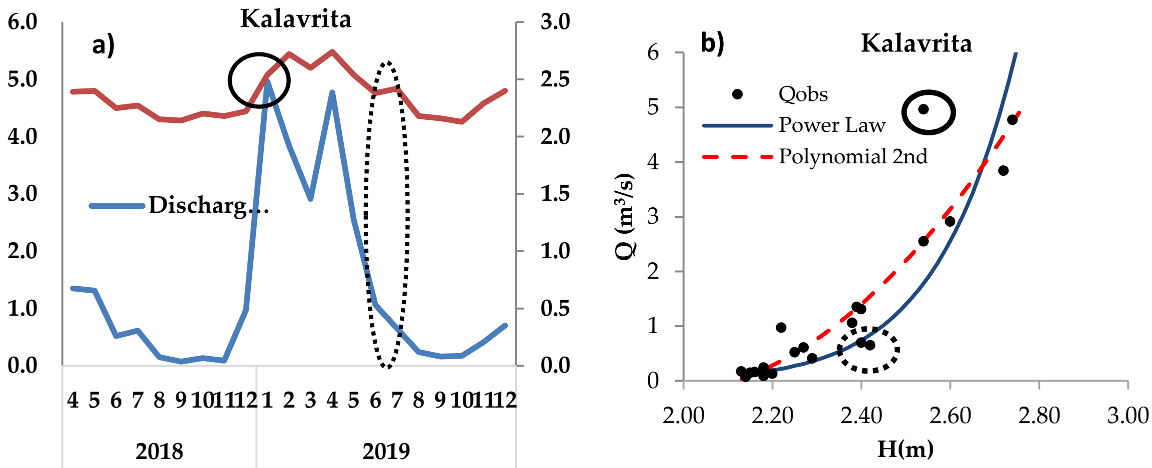


Figure 5-2: Quality control procedure for gauging Kalavrita; a) Combined graph of chronological timeseries for stage (H) and discharge (Q); b) initial scatter plot with provisional curves.

On the contrary, site Kalavrita represents one of the sites where quality control was not necessary, but rather only resulted in enhanced performance of the curve fitting. Already, prior to any intervention, the scatter plots for the site produced a pretty good provisional curve fit (Figure 5-2). That was evident both in the visual examination of the provisional curve and in the high R^2 values of the examined relationships of power law and 2nd degree polynomial, which were 0.84 and 0.83 respectively. However, two pairs of observations were excluded, after scrutiny of the dataset. The first measurement, concerning the 1st month of 2019 and highlighted in solid line circle (Figure 5-2), was considered to be an outlier as it exceeded by far the 8% deviation from the fitting curve rule. The second measurement, concerning the 7th month of 2019 highlighted in a dashed line circle (Figure 5-2), could not be easily identified as flawed form the scatter plot examination, but was highlighted as potentially erroneous from the stage and discharge trendlines disagreement. It can be seen that, from the 4th until the 9th months of 2019 there is a downward trend, both for stage and discharge, with the exception of a stage measurement for the 7th month of 2019. This alone, a unique measurement appearing to increase in a set of declining continuous measurement was a strong indication of inconsistency. However, this did not qualify as a reason for exclusion alone and further investigation had to be undergone. When further examined, this measurement had the same stage as another one but with considerable variation in the discharge value. The combination of these two indicators resulted in exclusion of this specific pair of observations. Totally two pairs of measurements were excluded for Kalavrita resulting in the use of 19 pairs of observation in total. The benefit of this procedure is also reflected in the improved R^2 values of the final curve fitting, 0.95 for power law and 0.96 for 2nd degree polynomial.

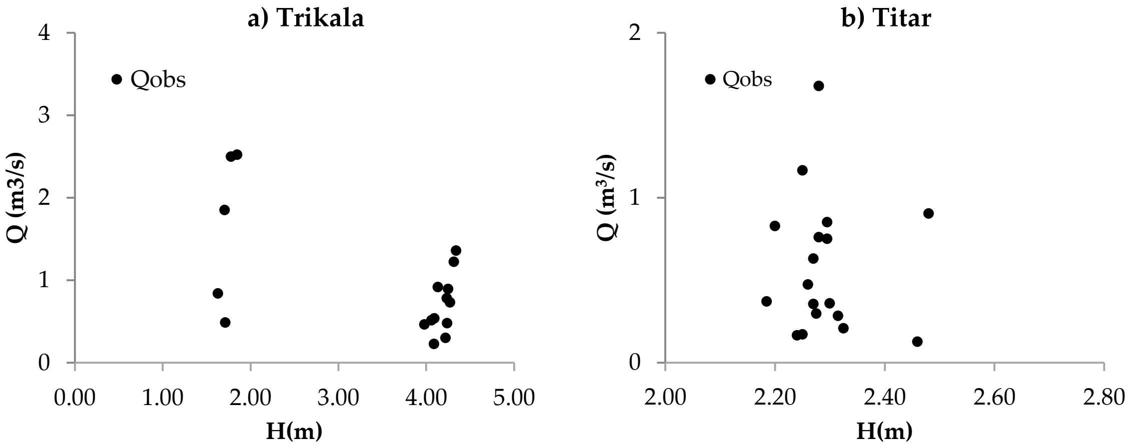


Figure 5-3: Trikala (a) and Titar (b), the two gauging sites that were deemed unsuitable and were omitted from the curve fitting process.

Trikala and Titar are the two gauging sites that after thorough examination were rejected and were not used in the curve fitting process. Trikala (Figure 5-3a) exemplified the case where the available data should not necessarily be excluded, but rather needed two different rating curves as they referred to different cross-section conditions. The existence of a breaking point was obvious from the visual examination of the scatter plot, suggesting that the measurements should be split in two groups and a distinct rating curve should be developed for each of them. Further examination of the data confirmed chronologically the stage shifting; that is the 5 measurements in the left side with an average stage of 1.74 m concern the first 5 month of gauging. Then, possibly a flooding event caused the alteration of the cross-section and from that point and on the stage has considerably shifted for all measurements, averaging a 4.19 m. Since the breaking point was identified, further action to create two different rating curves for each set of data was done, but with poor results. The measurements in the first group were insufficient, only 5 pairs in total and way below the 10 pairs threshold used in this paper overall. The second group comprised of enough pairs of observations (12 pairs) but produced values of R^2 below 0.50 for different stage-discharge relationships examined and thus was also rejected. This site was the most indicative case of a cross-section alteration reflected in the measurements.

The second gauging site rejected from the fitting curve process was Titar. Plotting of the Q-H pairs indicated a rather unsuitable dataset, with considerable variations of discharge over similar stage measurements (Figure 5-3b). A provisional curve produced extremely low R^2 value, as low as 0.015, suggesting that no relationship could be for this site. Further manipulation attempts, such as excluding certain Q-H pairs or splitting of the dataset, did not produce any reliable results and Titar was rendered as not fitting.

5.1.2 Q-H curves derivation for each gauge site

The performance for each of the three rating curves per site along with a scatter plot of the observed Q-H values, is given in Figure 5-4. The optimal rating curve for each of the 14 gauging sites is presented in Table 5-3.

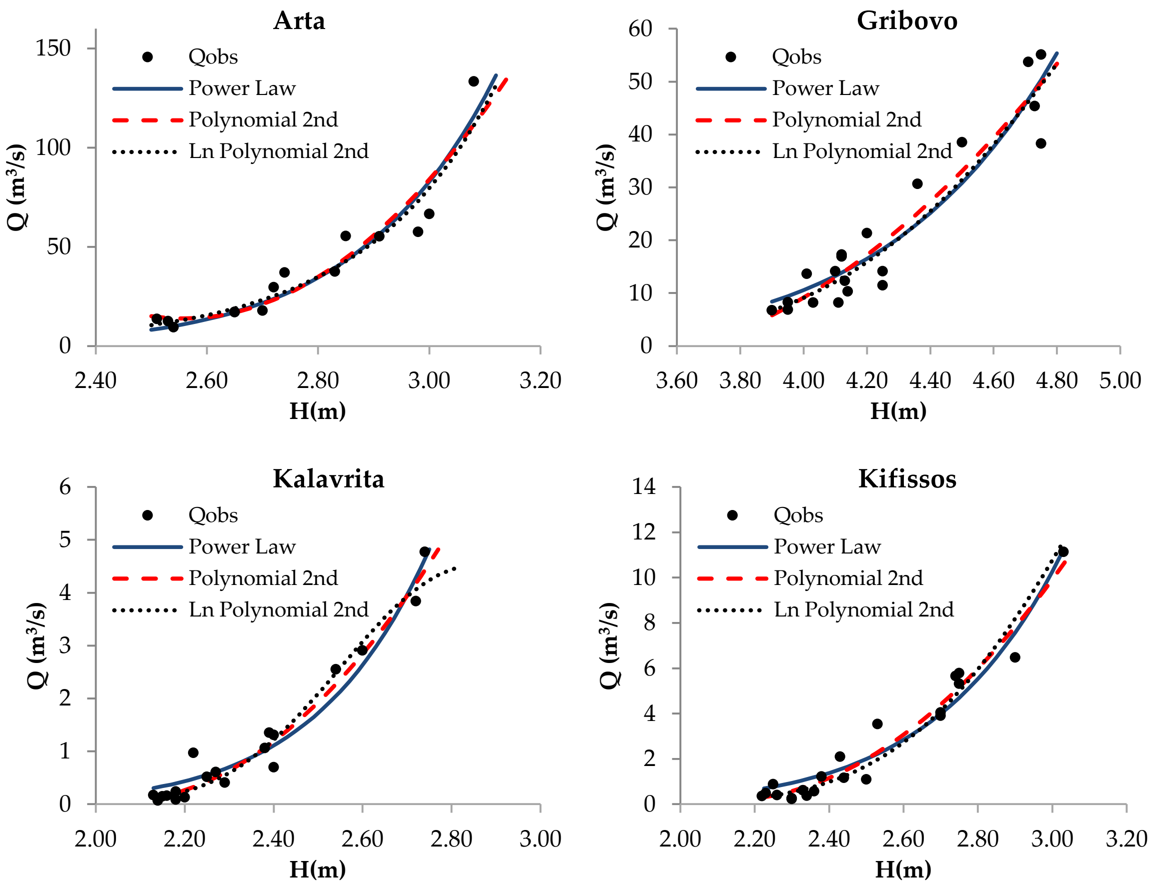
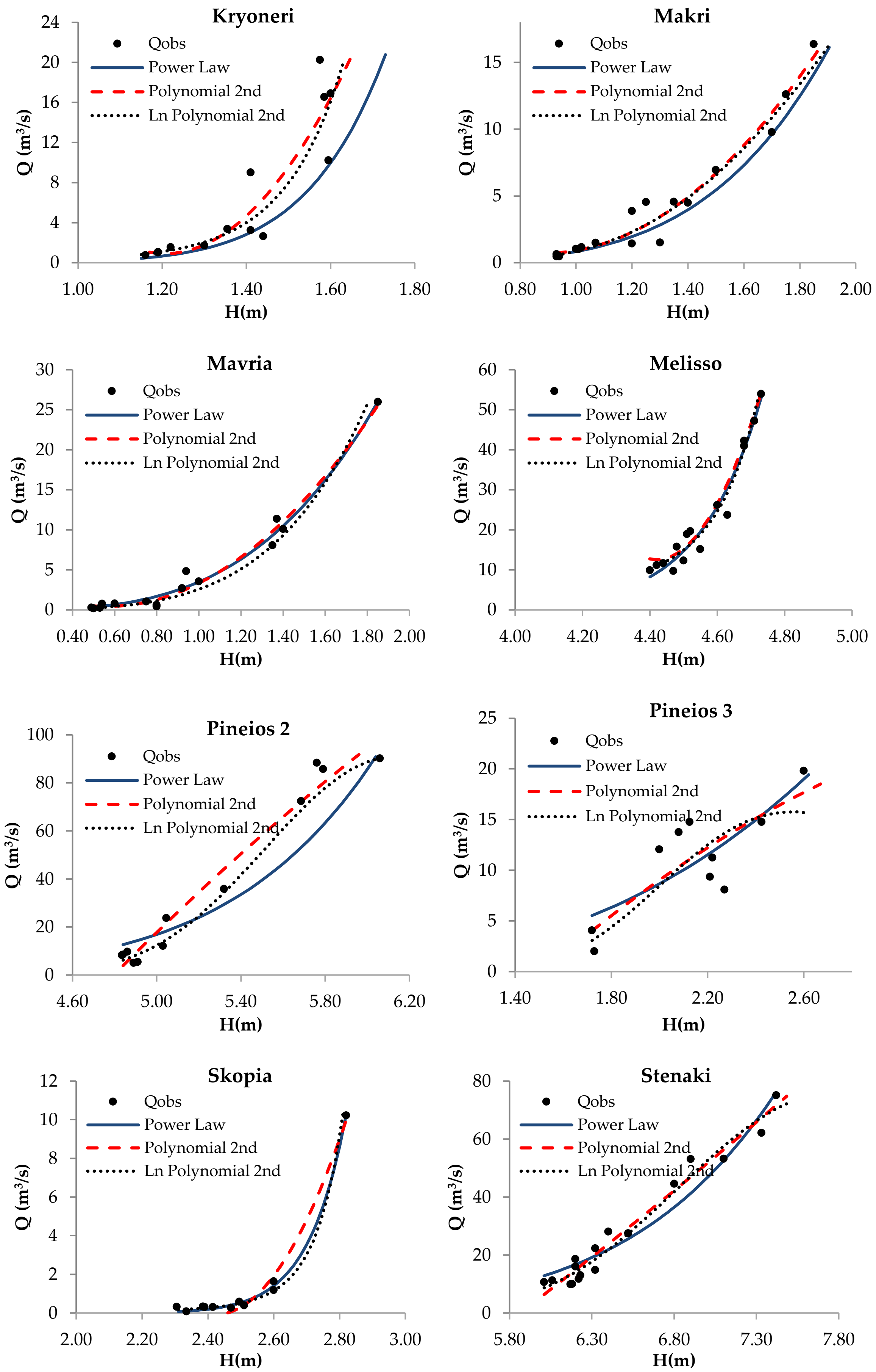


Figure 5-4: Performance of the three examined rating curves, for all 14 gauging sites (continued).


Kryoneri
Qobs
Power Law
Polynomial 2nd
Ln Polynomial 2nd
Q (m³/s)
H(m)
Makri
Qobs
Power Law
Polynomial 2nd
Ln Polynomial 2nd
Q (m³/s)
H(m)
Mavria
Qobs
Power Law
Polynomial 2nd
Ln Polynomial 2nd
Q (m³/s)
H(m)
Melisso
Qobs
Power Law
Polynomial 2nd
Ln Polynomial 2nd
Q (m³/s)
H(m)
Pineios 2
Qobs
Power Law
Polynomial 2nd
Ln Polynomial 2nd
Q (m³/s)
H(m)
Pineios 3
Qobs
Power Law
Polynomial 2nd
Ln Polynomial 2nd
Q (m³/s)
H(m)
Skopia
Qobs
Power Law
Polynomial 2nd
Ln Polynomial 2nd
Q (m³/s)
H(m)
Stenaki
Qobs
Power Law
Polynomial 2nd
Ln Polynomial 2nd
Q (m³/s)
H(m)

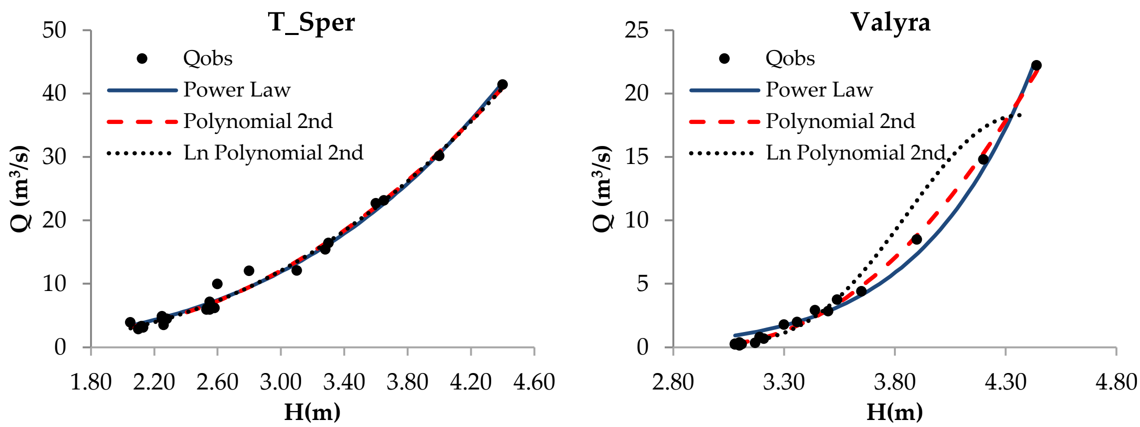


Figure 5-4: Performance of the three examined rating curves, for all 14 gauging sites.

In most of the sites, all three rating curves had high performances and also values of R^2 and RMSE similar to each other (Table 5-2). As a result of the similar performances, for one, and the diverse methods of calculation of R^2 and RMSE, for the other, the proposed best fitting rating curve per site, was not always the same for both measures of fit. A small discrepancy was observed in some cases (five sites), in which each of the measures-of-fit qualified over a different rating curve. The five sites where inconsistency between the measures-of-fit was observed were Kryoneri, Melisso, Pineios2, Pineios3 and T_Sper.

Table 5-2: The scores of R^2 and RMSE of all three rating curves, for each site.

Gauging site	R^2			RMSE		
	Power law	Poly 2nd	Ln-Poly	Power law	Poly 2nd	Ln-Poly
Arta	0.910	0.893	**0.932**	9.449	10.297	**9.411**
Gribovo	0.891	**0.901**	0.870	5.155	**4.907**	5.009
Kalavrita	0.955	**0.967**	0.884	0.282	**0.244**	0.261
Kifissos	0.943	**0.957**	0.877	0.672	**0.582**	0.656
Kryoneri	0.824	0.827	**0.903**	4.638	**2.803**	2.905
Makri	**0.966**	0.962	0.927	**0.825**	0.870	0.899
Mavria	**0.983**	0.982	0.897	**0.862**	0.896	1.507
Melisso	0.961	**0.962**	0.924	2.834	3.086	**2.674**
Pineios2	0.899	**0.968**	0.935	13.126	6.144	**5.711**
Pineios3	0.648	0.677	**0.757**	2.996	**2.867**	3.224
Skopia	**0.996**	0.982	0.888	**0.158**	0.371	0.453
Stenaki	0.934	**0.965**	0.927	5.233	**3.777**	3.790
T_Sper	**0.988**	0.988	0.967	1.037	1.023	**1.018**
Valyra	0.987	**0.997**	0.966	0.645	**0.291**	1.366

Eventually each of these sites was independently examined and the best fitting rating curve was determined in each case. The optimal rating curve for each of the 14 gauging sites is presented in Table 5-3.

Table 5-3: The optimal fitting rating curve for each site.

Gauging Site	Rating Curve	Performance index
Arta	$lnQ = 0.1525 - 4.829lnH + 7.895(lnH)^2$	R^2 + RMSE
Gribovo	$Q = 261.94 - 161.96H + 24.689H^2$	R^2 + RMSE
Kalavrita	$Q = 37.84 - 36.99H + 9.05H^2$	R^2 + RMSE
Kifissos	$Q = 56.751 - 53.371H + 12.586H^2$	R^2 + RMSE
Kryoneri	$lnQ = -1.012 + 4.773lnH + 7.008(lnH)^2$	R^2
Makri	$Q = 1.058H^{4.408}$	R^2 + RMSE
Mavria	$Q = 3.497H^{3.262}$	R^2 + RMSE
Melisso	$lnQ = 291 - 403lnH + 140.5(lnH)^2$	RMSE
Pineios2	$lnQ = -150 + 170.2lnH - 46.87(lnH)^2$	RMSE
Pineios3	$Q = -40.25 + 32.5H - 3.93H^2$	RMSE
Skopia	$Q = 9.75 * 10^{-11}H^{24.48}$	R^2 + RMSE
Stenaki	$Q = -205.3 + 26.288H + 1.4864H^2$	R^2 + RMSE
T_Sper	$Q = 0.3238H^{3.28}$	R^2
Valyra	$Q = 88.538 - 59.474H + 10.009H^2$	R^2 + RMSE

None of the three rating curve was found to absolutely over-perform over the others. A comparison of the better performing rating curve for each site suggests a rather even distribution, although a slight advantage was observed for the 2nd degree polynomial (Figure 5-5). More specifically, the 2nd degree polynomial has proved to have a better fit in 6 out of 14 sites (42.8%). The rest 8 sites are equally distributed between the other two rating curves, resulting in over-performance of power law and ln-polynomial in 4 sites (28.5%) each.

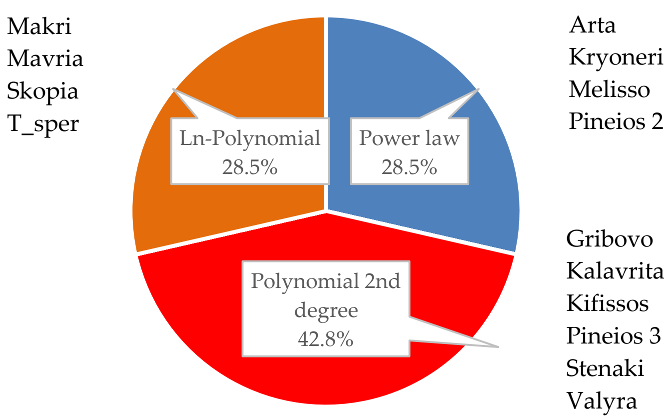


Figure 5-5: Distribution of best fitting rating curve, per site.

The spatial distribution of the best fitting rating curve over the 14 examined sites, is given in Figure 5-6.

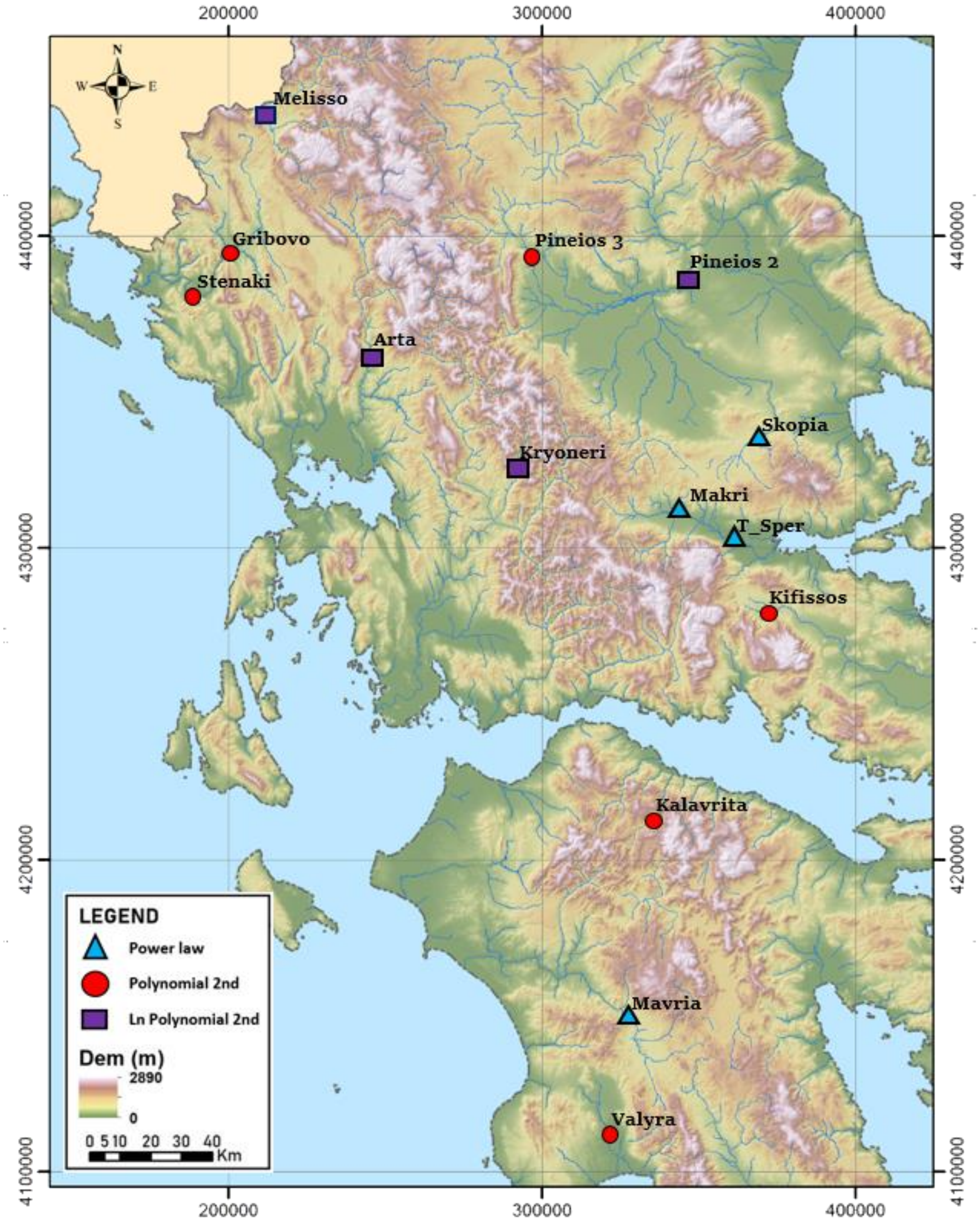


Figure 5-6: Spatial distribution of better performing rating curves, over the 14 sites.

Nonetheless, there were 9 out of the 14 sites (64.3%) that for both measures of fit there was agreement on the over-performing rating curve. These sites were Makri, Mavria and Skopia for the power law relationship, Gribovo, Kalavrita, Kifissos, Stenaki, Valyra for 2nd degree polynomial and Arta for the ln-polynomial. The consistency on the best fitting rating curves independently of the measure of fit, suggests higher levels of confidence for these sites. Undeniably, more reliable results from the rating curves for these sites are to be expected.

As stated above, for the 14 sites examined here the 2nd degree polynomial has a lead of better performance in slightly more cases. Nevertheless, it should be highlighted that although outperformed, the two other rating curves had for the most part good performances as well (Table 5-2). For example, in gauging site Kifissos the value of R^2 for the 2nd degree, which was the best fitting curve, was 0.95, while at the same time for the power law has a value of 0.94. This is to elucidate that "over-performed" does not necessarily mean that a relationship is not performing well. This remark applied for many sites and an examination of the total scores on R^2 shows that all basins and throughout all relationships examined the R^2 values were above 0.80, with the exception of one site (Pineios3). Even for this specific site, the scores of R^2 range from 0.64 to 0.75, scores that lie within an acceptable range since threshold R^2 value for rating curves in literature is slightly over 0.5. Furthermore, R^2 values were above 0.80 in 13 out of 14 sites, increasing the reliability of the rating curves.

The overall high R^2 values, at least to some extent, could be attributed to the exclusion of measurement pairs that resulted from the quality control process. However, high R^2 values as well in the sites where no exclusion of measurements was made, provide evidence that the quality control was not the only reason of high performance. In addition, the scrutiny of the datasets was conducted with great care, excluding the bare minimum amount of observations in an effort to avoid over-refinement of the rating models. Exclusion of measurements was not done solely on statistical measures; a methodology that could contribute to increased R^2 values. Statistics and visuals were used as indicators to highlight potential erroneous measurements and further scrutiny was carried out, based on the concept of hydrological consistency and the use of any relevant information available, in this case field notes.

Interestingly, after further examination of the R^2 performance for all three equations concerning all 14 sites, a certain trend could be pointed out; values for power law followed very closely the ones of 2nd degree polynomial. On the contrary the ln-polynomial was either relatively lower when the other two were high (Kalavrita, Kifissos) or relatively higher when the other two were low (Kryoneri, Arta), suggesting a complementary relationship. Consequently, it could be proposed that although the 2nd degree polynomial produced the better curve fitting results, the power law could also be widely used in these or new sites, as it had almost equally good performance as the 2nd degree polynomial. On the other hand, for sites where both power law and 2nd degree polynomial had moderate performances, the ln-polynomial should be incorporated as it proved to perform better in cases where the other two did not. Therefore, in most cases the power law and 2nd degree polynomial could be used with equally good results and when these do not perform well, the ln-polynomial could be used.

Another important observation, comes from the examination of the four sites (Arta, Kryoneri, Melisso and Pineios 2) that the ln-polynomial was the better fitting rating curve. Interestingly, these four sites are the ones that undergone the biggest intervention in terms of excluding measurements during the quality control process. In fact, 7 and 8 pairs of measurements were omitted from Arta and Kryoneri, respectively. Then for both Melisso and Pineios2, 5 pairs of measurements were discarded. This trend seems to suggest that, ln-polynomial produces a better fit for sites with few measurements or for sites where significant interventions of the hydrometric data has been done. In both cases, this trend suggests the ln-polynomial as the better fit in cases of relatively high uncertainty. Although the number of sites over which this assumption was made was not enough for any solid conclusion, a certain suggestion for future research could be made.

Finally, in this research study, the discharge was regarded as a function of stage solely. This is a valid conjecture, given that steady flow is assumed for the gauging sites. However, in reality the discharge is also a function of other factors, if the hysteresis effect was to be taken into account, some of the Q-H pairs of same or similar discharge over varying stage would not be excluded as they would be interpreted as valid rather than erroneous measurements. This would result into a different set of measurements to fit and also demand a new procedure to adjust factors that relate unsteady flow to steady flow. This is understood as another potential source of error in the final rating curves proposed.

5.2 Estimation of e-flows

The suitability and applicability of the four low-flow indices developed (Q_{90}, Q_{95}, 10% MAF, 30% MAF) as EFA, is estimated based on how efficiently they could approximate the discharge values derived from the current Greek legislation methodology, which were set here as target values. The method with the best performance would be the one that manages to estimate discharge values closer to the target values, as often as possible.

At first, discharges according to the three methodologies proposed for e-flow by the Greek regulations, were estimated (Table 5-4). The acquired values were compared, and the bigger was selected (in bold). This value was regarded as the target values, by which the performance of the four low-flow indices would be judged.

Table 5-4: Estimation of e-flow (in m^3/s) according to Greek regulations.

Gauging Site	30% Jun-Jul-Aug (m^3/s)	50% Sept (m^3/s)	At least 0.03 m^3/s, in each case
Arta	4.80	**7.22**	0.03
Gribovo	3.79	**4.77**	0.03
Kalavrita	**0.16**	0.06	0.03
Kifissos	**0.18**	0.16	0.03
Kryoneri	**0.78**	0.62	0.03
Makri	**0.35**	0.28	0.03
Mavria	**0.20**	0.14	0.03
Melisso	4.40	**4.69**	0.03
Pineios2	**3.41**	0.00	0.03
Pineios3	**0.57**	0.00	0.03
Skopia	**0.10**	0.04	0.03
Stenaki	4.70	**5.90**	0.03
T_Sper	1.34	**1.60**	0.03
Titar	**0.13**	0.04	0.03
Valyra	**0.22**	0.12	0.03

Subsequently, the four low-flow indices from hydrological methods were estimated. Two of them were acquired as percentiles of the FDC (Q_{90} and Q_{95}) while the other two as percentages of MAF (10% and 30% MAF). Results of the four low-flow indices and the target values according to Greek regulations are presented in Table 5-5.

Table 5-5: Discharge values estimated for the four low-flow indices and target values for all sites.

Gauging Site	Target Value (m^3/s)	Q_{90} (m^3/s)	Q_{95} (m^3/s)	10% MAF (m^3/s)	30% MAF (m^3/s)
Arta	7.22	6.52	5.33	3.32	9.96
Gribovo	4.77	7.13	6.78	2.19	6.57
Kalavrita	0.16	0.10	0.07	0.12	0.37
Kifissos	0.18	0.28	0.23	0.25	0.76
Kryoneri	0.78	1.03	0.78	0.70	2.09
Makri	0.35	0.48	0.47	0.35	1.04
Mavria	0.20	0.22	0.00	0.41	1.23
Melisso	4.69	7.76	7.60	2.29	6.87
Pineios2	3.41	0.00	0.00	3.77	11.31
Pineios3	0.57	0.00	0.00	0.58	1.74
Skopia	0.10	0.06	0.00	0.13	0.39
Stenaki	5.90	9.96	0.00	2.41	7.23
T_Sper	1.60	3.14	2.90	1.09	3.26
Titar	0.13	0.00	0.00	0.05	0.15
Valyra	0.22	0.22	0.15	0.32	0.97

On a comparative analysis (Table 5-6) of the discharge value of the four low-flow indices (Q_{90}, Q_{95}, 10% MAF, 30% MAF) to the target values, Q_{90} proved to be the preferred index. The Q_{90} had a consistent and acceptable estimation error in all examined sites, with 32% error in sites of overestimations and 39% error in sites of underestimation. The Q_{90}, was equaling or slightly exceeding the target values in the majority of the sites and only underestimated discharge in three sites.

Table 5-6: Percentage error for each of the four methods examined, compared to the discharge target values, set by Greek regulations.

	Q_{90}	Q_{95}	10% MAF	30% MAF
Overestimation Error	32%	30%	24%	53%
Underestimation Error	-39%	-80%	-92%	0
Sites where target value was equaled or exceeded	9	7	7	15
Sites where target value was underestimated	3	2	8	0
Sites with estimated zero values	3	6	0	0

On the other hand, both Q_{95} and 10% MAF have error percentages equal to Q_{90} in sites of overestimation but had significantly higher percentage errors in sites of underestimation deviating from target values, by 80% and 92% respectively. Finally, 30% MAF appears to be, in general, a rougher approximation, suggesting discharge values that lied out of the order of magnitude of the rest methods.

To recapitulate the above results and to facilitate visual interpretation of the relationship among the four low-flow indices, the FDCs for each site are presented in Figure 5-7 where Q_{90}, Q_{95}, 10% MAF and 30% MAF are plotted. The conclusions of the comparative analysis done above, can also be seen visually and be more easily interpreted. At first, the position of the Q_{90} index on the curve overall, can give a rough estimate of the magnitude of the proposed discharge. Then and more importantly the positions of the other low-flow indices highlight their unfitness as EFA methods. Indeed, Q_{95} and 10% MAF often went beyond the lowest discharges of the basin (right end of the curve) while it was also evident that they often reached zero values. On the contrary, 30% MAF proposed in all sites a significantly higher discharge and was almost in another order of magnitude than the target values. In fact, approximately in half of the gauging sites, the 30% MAF was as high as the median discharge.

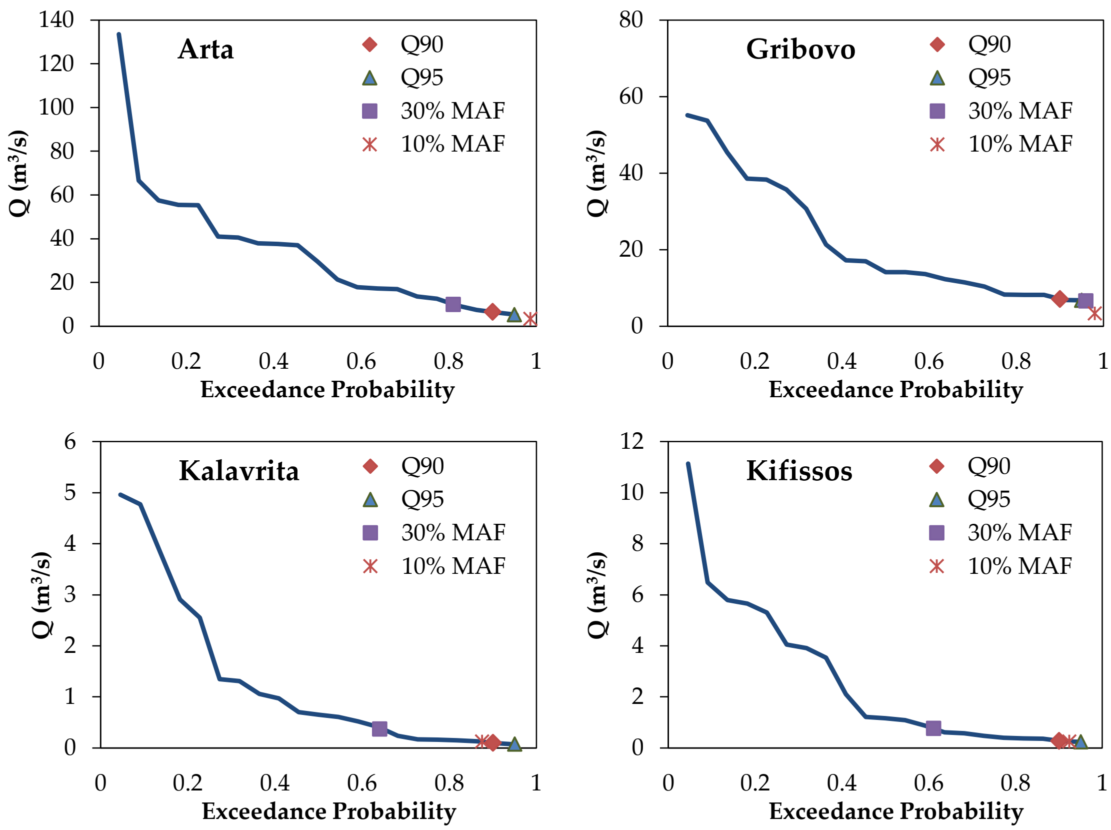


Figure 5-7: Distribution of the four examined low-flow indices on flow duration curves (continued).

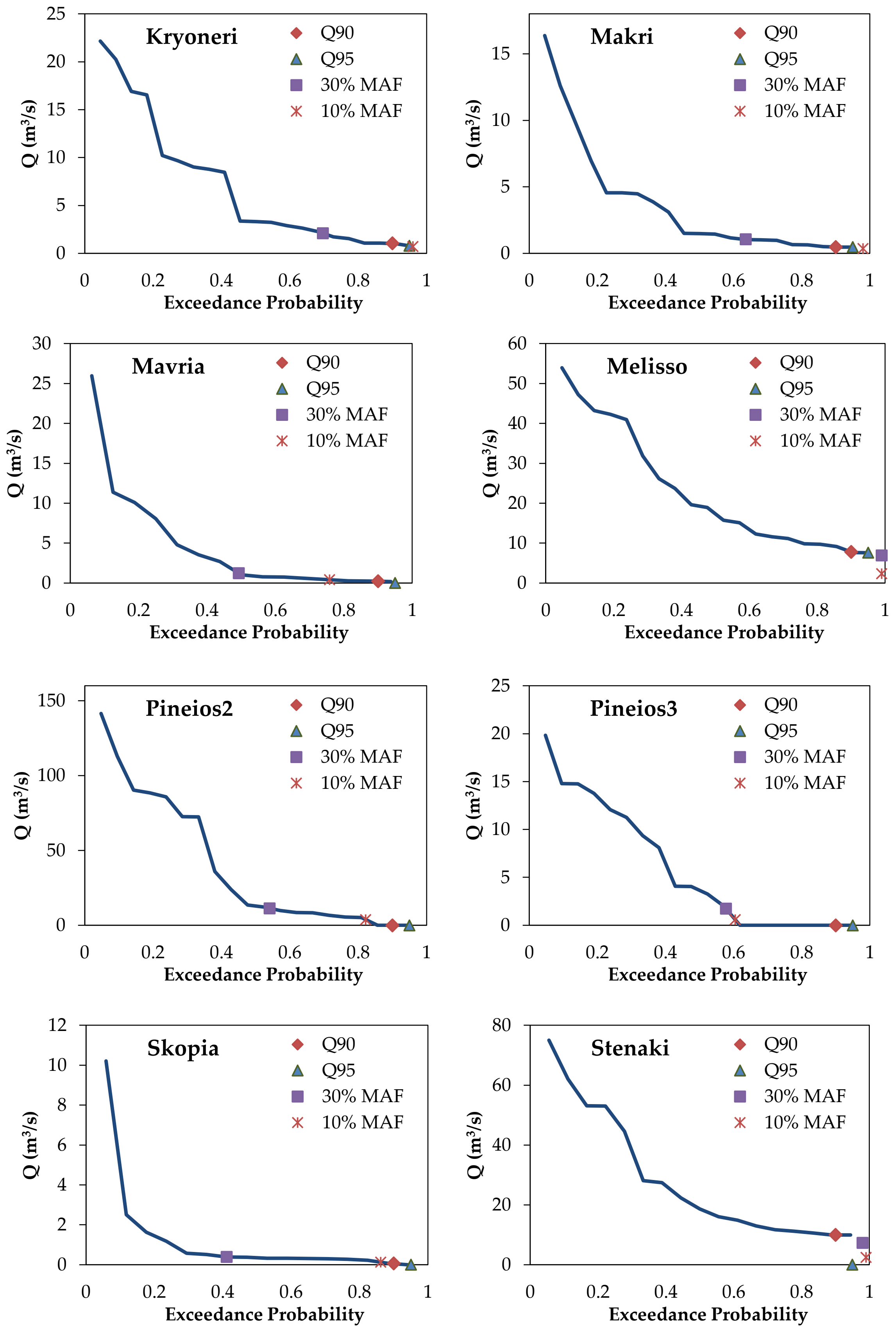


Figure 5-7: Distribution of the four examined low-flow indices on flow duration curves (continued).

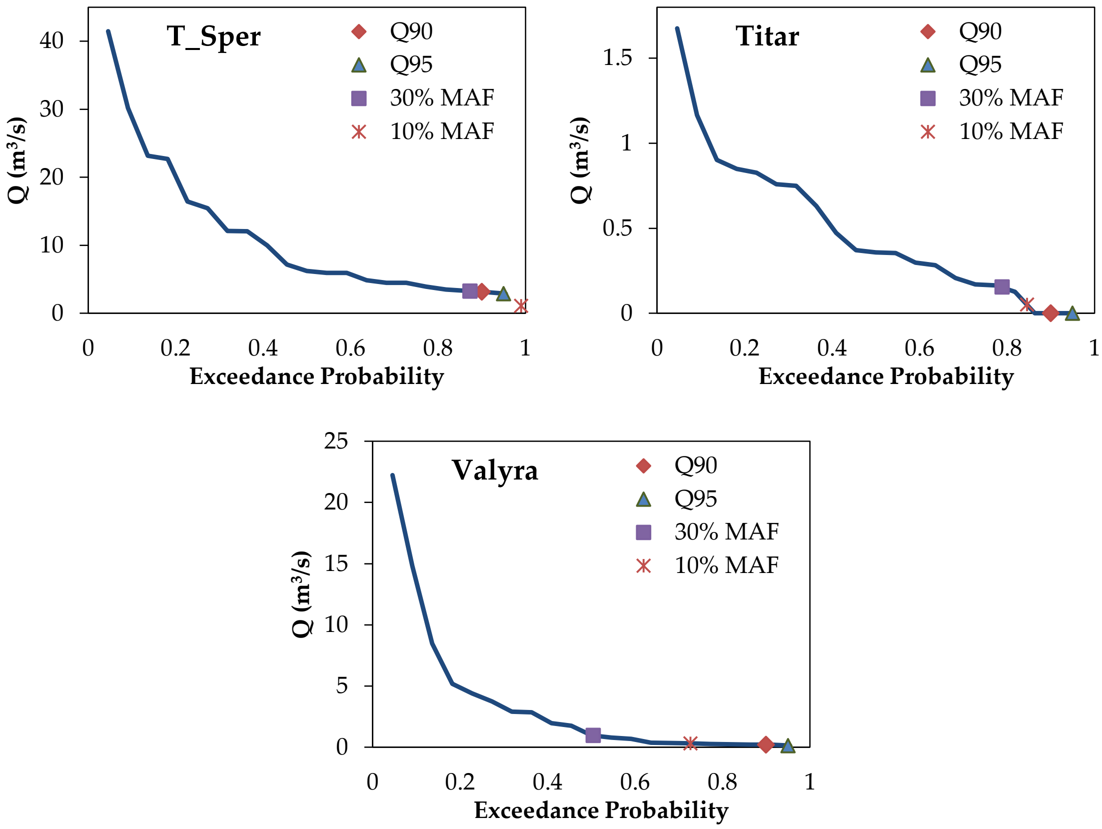


Figure 5-7: Distribution of the four examined low-flow indices on flow duration curves.

As far as Q_{90} is concerned, in 9 out of 15 cases the proposed e-flow equaled or moderately exceeded the target value, presenting 60.0% efficiency. More specifically it equaled the target value for one site (Valyra), slightly overestimated discharge in eight sites and underestimated the discharge in six sites. By average, the percentage of error in the eight sites of overestimation was 32% while the respective value for sites of underestimation was 39%. In three of the underestimated cases, Q_{90} had a value of zero, and this could be attributed to specific characteristics of these sites. In fact, all three concerned sites are located in the same prefecture of Thessaly, which is under significant water extractions for irrigation affecting the water regime of these rivers.

Concerning Q_{95}, only in 5 out of 15 cases examined the estimated e-flows equaled or exceeded the target values, which means that underestimation of e-flows is most likely to happen if Q_{95} is employed. Assessed zero discharge values are doubled in relation to Q_{90}, namely from three sites with zero discharges for Q_{90}, they increased to six for the Q_{95} index. Even when sites of zero discharge values were excluded and the remaining sites were examined, the Q_{95} index failed to equal or exceed target values. The efficiency was as low as 55.5% and rendered the Q_{95} index as a rather insufficient index.

The 10% MAF method was also examined but with poor results as in eight out of 15 times it underestimated the e-flow target value, resulting in 53.3% efficiency. This method had the lowest error (24.0%) in sites of overestimation, but only slightly lower than the percentage error of Q_{90} and Q_{90}. On the other hand, it had the highest error of all methods, in sites of underestimation (92.0%). This means that in more than half of the sites (8 out of 15), this method would produce very low discharge values, most likely in a range of values that would fail to ensure ecological integrity.

Finally, the 30% MAF was also calculated and proved to overestimate discharge values in all sites. Although at first this could be a good indication, the degree of overestimation is also important and should be addressed before selecting the suitable method. It was found that the 30%MAF is in many cases proposing double or triple values compared to the target values, with an extreme case for Mavria suggesting a discharge value that was six times higher (1.23 m^3/s) than the target value (0.20 m^3/s). The average overestimation error is 53%, which is also pretty high to be accepted. Therefore the 30% MAF method, could not be regarded as a representative estimation method and was excluded from any further analysis.

Taking into consideration that, a low-flow index would not equal the target value but most likely would be an approximation of it, a consensus was made that at least this variation should be on the positive side (overestimation) rather than the negative side (underestimation). The method that estimated equal or higher discharge values than the ones proposed by Greek legislation would be preferred, as long as severe overestimations were avoided. Although greater discharge values offer safer environmental conditions, it should not be overlooked that EFA is an attempt to balance water contrasting needs. Therefore, proposing indiscriminately big discharge values (overestimations) would render the EFA method invalid. On the other hand, methods that underestimate discharge, compared to target values, were to be evaluated lower and even rejected. This approach ensures that the proposed discharge will be environmentally sound and therefore moderate overestimations are to be preferred over underestimations.

A significant limitation of the Q_{90} index was found to be the fact that, it produced zero values for three out of the 15 sites. Contrarily, 10% and 30% MAF presented the comparative advantage of proposing a greater than zero discharge, for every site examined. This was a result of the different calculating processes employed for each method. However, even with this limitation taken into account, the Q_{90} was the higher performing index. A compromise was made to exclude the 3 sites of zero Q_{90} value from the regression analysis and use this index for the rest of the sites. If the Q_{90} index, was evaluated without the three sites of zero discharge, then in 9 out of 12 sites it equaled or exceeded target values. This provides a consistent hydrologic tool with an efficiency of 75.0%.

5.3 Regression Model

The regression model was developed with the Q_{90} index as the dependent variable, since it proved to be the better performing low-flow index for e-flow approximation. The climatic and geomorphological characteristics of the basins that were examined, can be seen in Table 5-7. Gauging station Trikala was rejected, due to its very small extend of catchment area.

Table 5-7: Catchment descriptors examined in the regression analysis as independent variables.

Gauging Site	Catchment Area (km²)	Length of main stem (km)	Mean Annual Precipitation (mm)	Mean Basin Elevation (m)	Curve Number	Slope (degree)
Arta	1602.0	86.7	736.25	914.5	63	21.3
Gribovo	1049.5	78.8	828.87	603.4	67	18.2
Kalavrita	143.6	25.0	598.17	1054.7	62	22.0
Kifissos	220.4	27.8	474.59	997.3	70	21.6
Kryoneri	219.9	27.2	511.08	1190.0	60	35.0
Makri	864.2	45.5	483.40	795.2	61	20.6
Mavria	848.7	49.0	652.90	768.0	60	15.4
Melisso	915.0	86.5	702.49	1291.2	68	24.9
Pineios2	5027.8	146.40	479.67	433.01	73	12.6
Pineios3	1059.5	56.70	551.37	822.80	72	20.1
Skopia	368.0	36.6	418.33	664.6	75	12.7
Stenaki	1380.3	104.1	831.15	581.4	65	19.6
T_Sper	1146.8	74.3	479.77	716.4	63	19.2
Titar	839.3	51.0	482.42	725.0	63	15.3
Valyra	445.0	29.6	667.46	375.2	68	14.8

Catchment area (A), Length of main stem (L), Mean annual precipitation (mm), Mean basin elevation (m), Curve number (CN) and Slope (S).

Different combinations of catchment descriptors were examined as independent variables, in the stepwise regression process. Following numerous trials, the optimal model for the prediction of e-flows from climatic and geomorphological characteristics, was:

$$Q_{90} = -41.984 + 0.0059 * A + 0.0117 * P + 0.3836 * CN + 0.4280 * S \qquad (11)$$

The scores on the performance measures of the regression model were 0.967, 0.937 and 36.32% for the R^2, SE and MAPE, respectively.

The high R^2 (0.967) and adjusted R^2 (0.935) values suggested a good regression model and were a manifestation that the regression succeeded in identifying the driving forces for the discharge index (Table 5-8). The four descriptors, that proved by the stepwise process to be statistically decisive were catchment area (A), precipitation (P), curve number (CN) and slope (S). The four final geomorphological and climatic characteristics, could describe 0.967 of the variance of the discharge, which is pretty high. Even the adjusted R^2 which penalizes the use of additional independent variables and is always smaller than R^2, remains quite high. Adding more variables, would not necessarily result in a higher performance but could rather lead to an unstable and overfitting model. Furthermore, incorporating more independent variables would produce a more complex model, which is ill-advised; the simpler a model can be the better it is.

Table 5-8: Regression statistics for the optimal model.

Measure	Value
Multiple R	0.983
R Square	0.967
Adjusted R Square	0.935
Standard Error	0.937
Observations	9

The validity of the model was assessed by its performance over a set of gauging sites that were not used in the calibration process. The MAPE for the validation group was 36.3%, which was moderately high but, nonetheless, an acceptable percentage of error (Table 5-9). Given the small number of sites, i.e. 12 sites, on which the regression analysis was performed, and the uncertainty in the initial measurements, the MAPE value was considered as acceptable. Actually, the regression model was created on a calibration set of nine basins, with a certain degree of variability on their physical characteristics. If relevant data on other basins were available a bigger calibration set would have been used for the model and a higher performance (smaller error) should be expected. Nevertheless, having an approximation by almost 35% accuracy for ungauged basins, relying solely on readily obtained data should be an acceptable compromise.

Table 5-9: Performance of the regression model on the validation dataset.

Gauging Site	Observed Q_{90} (m^3/s)	Estimated Q_{90} (m^3/s)	Percentage Error
Kryoneri	1.03	3.33	69.10%
Melisso	7.76	8.46	8.26%
Arta	6.52	9.53	31.59%

Furthermore, the model was also positively evaluated on the fact that the errors in estimating target values, was in all validation sites an overestimation error. This is important, as deviations from the target values are always expected, to a greater or smaller degree, in any prediction model but preference on either over or under-estimations is decided on the context and the specific characteristics of the issue addressed by each model. The consistent overestimation in this case is favored strongly over underestimations, as estimated discharge values with this model would only result in safer and more robust environmentally solutions.

Also, 36.32% was the overall MAPE but if the three sites used for validation were examined individually, the error varied significantly. It was found that, for site Melisso the percentage error was quite low (8.26%) and for site Arta the error was close to the mean error (31.59%). On the contrary the error was quite high only for one site, Kryoneri with 69.10%, which increased the overall MAPE and reduced the overall performance of the model.

Possible justification on the heterogeneity in error values of the validation sites, was sought after in the variation of their physical attributes. As a matter of fact, Kryoneri station had a rather small catchment area (219.9 km^2), actually the second smallest of all gauging sites, with steep relief characteristics (35°) while both Melisso and Arta stations lied in the upper side of the basin size spectrum and also had a more gentle relief (24.9° and 21.3° respectively). This finding could suggest that the regression model had a good performance in sites where the hydrological responses were more typical of bigger catchments and mild reliefs. In fact, if only the first two gauging sites were used in the validation set, they would produce a MAPE of 19.92% which is suggestive of a much better performing model.

Extending on the similarity observation, the big range of the catchment area values of the datasets examined, could suggest that clustering of the sites would produce more accurate results, as small flashy catchment have different driving forces and hydrologic responses than big ones. Clustering is being used to find inherent grouping within datasets and has been used in different studies, with positive results (Sanborn & Bledsoe, 2006; Kuentz et al., 2017). In the same approach, other characteristics that have proved to be important or representative of the basins, like the specific yield could be examined.

Both indicators, i.e. catchment area and specific yield, were considered for clustering in this paper, but trials of such regression models produced poor results and this approach was abandoned. This should be attributed to the small number of sites available rather than the validity of this method. For example, clustering of sites with big catchment area, e.g. larger than 800 km^2, resulted in only five sites available for calibration, which was not sufficient to establish a valid regression model. However, if more sites could be incorporated in such a prediction scheme, considering clustering of the dataset is highly advised.

The three rejected sites Titar, Pineios2 and Pineios3, which all had zero Q_{90} values, bring to light a certain limitation to the use of Q_{90} index as e-flow. It was found that under certain circumstances and as a result of its computation method, the Q_{90} index can correspond to zero values. This fact renders the Q_{90} unfit as a low-flow index for flashy streams or rivers with cease-to-flow characteristics, since it can often result in zero discharge values.

Hence, the possibility of zero Q_{90} value remains as a significant and relevant limitation of the method especially for hydrologic conditions in Greece. Streams with ephemeral flow regimes or rivers typical in the Mediterranean climate, is quite possible that will have zero Q_{90} values. This could impair the application of the regression model, at least in small flashy catchments with seasonal dry-outs. This remark is in accordance with the observation of reduced performance of the regression model in sites with small catchment areas used in the validation process. What is more, this point adds to the suggestion that the regression model developed is more suitable for bigger catchments with perennial flow regimes.

On the other hand, these three gauging sites (Titar, Pineios2 and Pineios3) are all located in the Thessaly prefecture, the area most heavily affected by water intakes for irrigation needs.

In all other 12 examined sites, where water intakes are moderate to minimal, there is no zero Q_{90} value. Therefore, assuming that these three sites were a deviation from the norm, since in all the other cases examined here the Q_{90} index was non-zero, could be a valid point.

Two descriptors, i.e. the length of mainstream (L) and the average catchment elevation (H), were eliminated from the individual *t-test* of the regression. In all regression trials, the length of main strem (L) was always the first to be indicated as statistical insignificant. This could be attributed to its correlation with the catchment area, which had a more significant effect as a descriptor but also conveyed similar information for the model. Therefore, the L parameter was easily excluded. The second independent variable discarded was the average catchment elevation (H). A point could be made for correlation between average elevation and precipitation, but this is more of a hypothesis and no certain proof of that could be made from these datasets. It is more likely that average elevation just proved to be statistically insignificant for this model. Removing both these descriptors improved the performance of the model, since having uncorrelated descriptors in the regression analysis, is adding to the reliability of the model.

Finally, in the absence of long timeseries of daily streamflow data, unique monthly values were treated as indicative mean values for each month. This assumption is expected to have an important effect on the quality of the results and increase the levels of uncertainty. To overcome this, it is common practice to use synthetic timeseries based on historic timeseries, especially in Greece where lack of flow series is the norm. However, this practice has the disadvantage that often relies on out-dated gauging programs from previous decades, which may not be representative of present hydrological condition. Indeed, the validity of this technique should be under investigation as in many cases the flow regimes, cross-sections and land use/land cover have greatly changed in catchments over the past decades. It was instead preferred, to work with up-to-date measurements and the monthly step resolution was an acceptable compromise. Daily streamflow data would have resulted in more robust and of higher precision results. However, the results on the rating curves and the regression model could be regarded as robust and useful. Even if they cannot be used for accurate prediction, at the very least, they highlight certain trends and provide initial estimation, while at the same time constitute a solid basis to make suggestions on future research.

6. CONCLUSIONS & FUTURE RESEARCH

6.1 Summary

This research study was based on recent (2018-2019) raw hydrometric data, made available by the NMWN, which provided the opportunity to apply a set of different hydrologic tools, over significant rivers, in six RBD of Greece. The use of actual measurements instead of synthetic timeseries, was highly valued and is expected to result in increased validity of the results. The study focused, on the examination of a) the dominant rating curve, over Greek rivers and b) the development of a regional model for determination of e-flows in ungauged basins.

Three rating curves (power law, 2^{nd} degree polynomial, ln-polynomial) were examined, to define the better performing one, over the selected gauging sites. This question was also addressed with the intention to estimate, if a certain rating curve exists, that describes better the stage and discharge relationship for Greek rivers.

The study focused on the development of a regional model, for the determination of e-flows based on recent (2018-2019) raw hydrometric data. Raw data employed, concerned 16 gauging sites, with a wide spatial distribution over mainland Greece. Given that all hydrologic tools used in this research study, are primarily affected by the quality (and quantity) of the input data, a quality control process was implemented to audit the raw data. The quality control resulted in exclusion of erroneous measurement in most of the gauging sites.

To define the e-flow, four low-flow indices from hydrologic methods were acquired for each site. Two indices were developed with FDC method and two from MAF method. Selection of the most representative low-flow index was judged on the better approximation of the target e-flow values, set by Greek regulations. Subsequently, geomorphological and climatic characteristics of each basin were obtained and a link to the selected low-flow index (Q_{90}) was established, through a multiple linear regression. A 75-25% rule for calibration and validation was applied over the gauging sites, to assess the efficiency of the model. The developed model could be used to predict e-flows in ungauged basins, on the concept of transfer of hydrologic information.

6.2 Conclusions

The main conclusions derived from this research study are:

Rating Curves

- The 2nd degree polynomial was the better fitting rating curve in most cases, but only within a small majority on the examined sites, as it proved to have better performance in 6 out of 14 sites (42.8% of total). The rest 8 sites were evenly distributed over the other two rating curves examined; i.e. the power law and ln-polynomial had the better fit in 4 sites each (28.5% of total).
- None of the rating curves examined proved to be dominant over the others. It is therefore unlikely that a single rating curve could describe the stage and discharge relationship for Greek rivers.
- Although outperformed in many cases, the power law rating curve performed well overall, and had only slightly lower R^2 and RMSE values than the 2nd degree polynomial. This suggests that the power law could be equally often used in Greek rivers as the 2nd degree polynomial.
- Contrarily, the ln-polynomial performed well when the other two had moderate performance and vice-versa. In addition, the ln-polynomial proved to perform better in sites with few measurements and/or sites of high uncertainty. This remark, suggests a complementary relationship between power law and 2nd degree polynomial for the one side and ln-polynomial for the other.
- Furthermore, the quality control of raw data proved to be an essential step of the rating curve process, as it affected 75% of the sites. It excluded erroneous measurements and significantly improved the performance of the rating curves and therefore its extrapolation ability and confidence.
- The monthly time step resolution used in this study, cannot accurately describe the flow variability of a river. This should be expected to entail a level of uncertainty in the developed FDCs and therefore on the Q_{90} index values.

Regression Model

- The regression model developed had high performance, with R^2 of 0.967 and adjusted- R^2 of 0.935. The validity of the model, was given by the 36.32% overall MAPE of the validation dataset.
- Catchment area (A), mean annual precipitation (P), curve number (CN) and slope (S) proved to be the statistically significant characteristics for the model. The fact that the four aforementioned characteristics are readily available information, adds to the effectiveness of the model.
- Other basin characteristics examined, like length of main stem (L), mean catchment elevation (H) as well as different combination of them, mostly resulted in increasing the complexity of the model without enhancing its performance. Instead, this simpler model was preferred, as simpler is regarded as better.
- Further examination on the physical attributes of the gauging sites, suggested that the model had better performance in sites with bigger catchment areas and mild reliefs. The performance of the model estimated only for such sites improved significantly and MAPE was reduced to 19.92%.
- The error of the model, in estimation of the e-flow for the validation gauging sites, was in all cases an overestimation error. This finding, adds to the robustness of the model, as higher estimations would produce more environmentally safe discharge values.
- The Q_{90} proved to be a good indicator for environmental flow assessment, as it had the better approximation of the discharge values set by the Greek regulations, out of the four examined low-flow indices.
- The use of Q_{90} as indicator of the e-flow sets certain limitation to the applicability of the model, since sites with Q_{90} zero value render the model invalid. However, this is most likely expected in sites with small catchment areas and flashy regimes, strengthening the suggestion that the proposed model is more appropriate for large (<800 km^2) catchment areas.

6.3 Future Research

Based on the conclusion drawn as well as on the limitations that became evident from this research study, future research could focus on the following:

- Acquire longer period of measurements, to produce more reliable results. The on-going gauging program, of the NMWN, ensures the availability of relevant measurements. Models based on small time series are dependent on the specific conditions of the calibration period and furthermore a two-year timeseries is a considerably small period for hydrologic predictions. It should be expected that additional measurements, from the same gauging sites, would essentially improve the validity of the conclusions of this study.
- Applying the fitting curve process in more sites, to evaluate both conclusions of this study, namely that power law has similarly high performance to the 2nd degree polynomial and that ln-polynomial is more appropriate for sites of few measurements and/or high uncertainty. Either confirming or rejecting the above is crucial, since rating curves are essential in providing critical information for discharge in rivers.
- Another suggestion could be to apply the process of curve fitting by taking into account the hysteresis effect. As stated above, a steady state was assumed for the examined sites and therefore a single-valued relationship rating curve was developed. The steady state assumption also resulted in the exclusion of measurements that had the same stage value but varied over their discharge. However, if the hysteresis effect is taken into account the curve would have a loop shape and many measurements that were discarded in the quality control process, would be regarded as valid. Developing rating curves under this assumption is expected to have significantly different results than this study and would help to determine the sites with valid rating curves.
- Using clusters of sites and developing individual regression models for each of the clusters could significantly improve performance. It is proposed that grouping of the examined sites should be based on catchment area size, as it proved to be one of the

most deciding factors of the model. Additionally, flow regime or specific discharge values could be used to cluster datasets.

- Apply the model to sites where an e-flow is already implemented in order to assess the validity of the regression model. The evaluation of the model under real situation conditions is very important, as it could reinforce its validity or lead to supplementary calibration.

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