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Hydrological 2D Modeling of Lithaios River Flows (Greece), Using GIS and Geostatistics for Environmental and Agricultural Water Resources Administration †

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Abstract: The goal of our investigation is the hydrological 2D modeling of Lithaios river (Central Greece) streamflow, using GIS and geostatistics for studying water velocity and discharge, stage elevation and the hydraulic features (streamflow depth, water flow area, wettable circumference, hydraulic radius and deep, n Manning's coefficient, Chow's composite n, froude number, etc.). Moreover, compilations and validations of rating curves (RC) were performed from a series of stage h(t)–discharge Q(t) couples metrics, aiming to use these as a river toolkit to aid environmental and agriculture surface water resources management, help environmental flows calculation, streamflow tracking and irrigation programming in regional basin range. The statistical results pointed that froude number during the study period was $Fr < 1$ showing that the Lithaios streamflow is classified as subcritical. Models' validation outcomes by using various statistics and geostatistical alternative methods, models simulate and statistics errors criterions, were conjuncted that the retrieved power models' streamflow data matching for the RC curves and 2D GIS modeling and mapping of river velocity and discharge relationships were highly satisfying since stabilities of the deployed relationships were solid. Outcomes of the study results are recommended to provide a hydrological serving toolkit for environmental water resources administration and irrigation programming. This toolkit could assist water supply principalities to calculate fast and precisely the streamflow volumes and features with a minimal cost rate and workload, and it could be engaged in water supply and agricultural watering administration, calculation of environmental flows, flood protection, groundwater recharge and other objectives.

Keywords: Hydrological 2D streamflow modeling using GIS and geostatistics; flow velocity; discharge rate; n Manning's coefficient and Chow's composite n; hydraulic properties; rating curve.

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1. Introduction

Streamflow velocity and discharge rate, water elevation, hydraulic deep and flow form are main themes in hydrology and are closely linked to water supply, quality and administration, flood protection, dewatering, irrigation, dam construction, and other related themes [1–3]. Streamflow velocity and discharge rate have a significant effect on water's retention period and quality [2,4,5]. So, these variables are typically needed for hydro-systems modeling. Unfortunately, the streamflow ongoing monitoring on a river's cross-section is commonly unfeasible or very costly [2–6]. The fast and accurate discharges calculation is of high importance for a great amount, of environmental-engineering projects (real time flood forecasting, water resources administration, etc.) [2,5–7]. The goal of our research is the hydrological 2D streamflow modeling of Lithaios river (Central Greece), using GIS and geostatistics for studying water velocity and discharge, stage elevation and hydraulic features (streamflow depth, water flow area, wettable circumference, hydraulic radius and deep, n Manning's coefficient, Chow's composite n, froude number, etc.).

2. Materials and Methods

2.1. Lithaios River Measurements, Instruments Used and Specifications

The study was conducted in Lithaios river (top width = 15 m) at Trikala monitoring station (M-S), region of Thessaly in Central Greece. A propeller current flow [7,8] meter (OTT) was employed together with a modern electronic metering system including a flow computer, data logger and a real-time display monitor, all calibrated by the manufacturer. River flow data were computed by averaging over a 60 + 60 s measured couple. Vertical measurements of water depths and velocities were performed for temporal monitoring of the cross-section's velocity and discharge variation [8].

2.2. Hydrological Methodology

The river's streamflow velocity, depths and widths of the defined segments were measured and engaged for the estimation of cross-section's mean discharge of every segment [2–8]. The overall discharge [2–8] was estimated by the mid-section methodology [5–8]. The features of the cross-section, the water flow velocity of the defined segments and the overall mean flow velocity were metered, computed, modeled and depicted in diagrams and GIS maps respectively, building up a hydrological toolkit for Lithaios river. Water stage elevation and flow measurements were taken monthly for a period of 1 year (January to December). Also, more measurable variables (streamflow depth, defined segments' wide, overall river width, water stage elevation) were measured, and more hydraulic features (streamflow depth, water flow area, wettable circumference, hydraulic radius and deep, n Manning's coefficient, Chow's composite n, froude number, etc.) were computed and depicted in diagrams and saved in the hydrological toolkit. The equation 1 was applied in order to calculate the river flow velocities.

$$V_{i=1}^{n} = a + (b_{eq} \times N_{eq}) \tag{1}$$

where $V_{i=1}^{n} =$ streamflow velocity (m s^{-1}), n is the number of cross-section segments, a = initial speed to overcome mechanical resistance, b_{eq} = system's calibration constant, and N_{eq} = equipment's rotations per second.

The equation 2 was used for the river's cross-section total discharge.

$$Q_T = \sum_{g=1}^{n} V_{i=1}^{n} A_{J=1}^{n} \tag{2}$$

where Q_T = Total discharge (m^3 s^{-1}) of the river's cross-section, g = 1...n is the number of cross-section segments, $V_{i=1}^{n}$ = Mean flow velocity of each cross-section segment (m s^{-1}), and $A_{J=1}^{n} =$ Wet flow area of each cross-section segment (m^2).

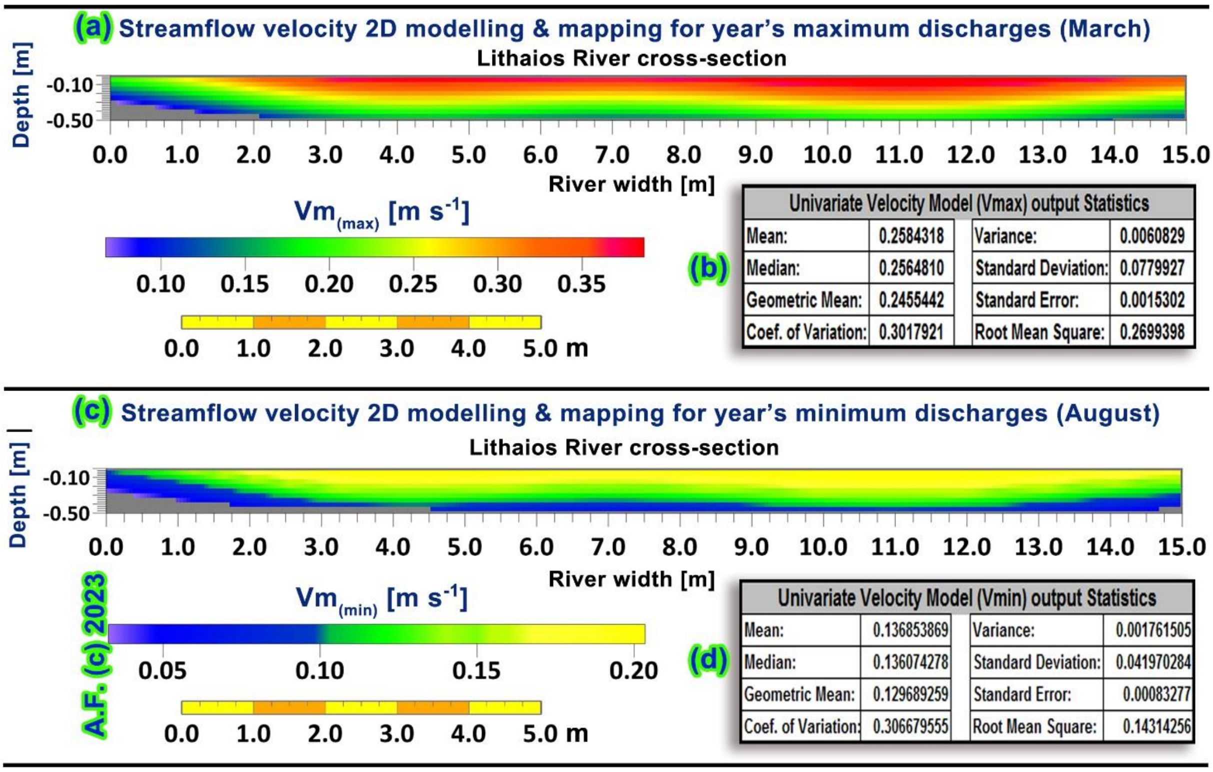
Couples of stage water elevation *h(t)* and discharge *Q(t)* measurements were utilised to develop mathematical relationships between them. Lithaios river rating curves (*h(t)* − *Q(t)*) [2–8] and changes in the riverbed were computed on the basis of the measured variables using various model equations for regression, the ANOVA statistical analysis and the model's fit F test by utilizing the IBM SPSS v.26 statistics software [2,3,9–25].

2.3. Statistical and Geostatistical Data Analysis, Flow Velocity and Discharge Modeling and 2D Mapping Methodology

Data were analysed by the use of IBM SPSS v.26 [2,9,11,12] statistics software. The results are the observations averages. The ANOVA (Analysis of variance) [2,3,9,11–25] was used to assess velocity ($V_{i=1}^{n}$), discharge (Q_T) and hydraulic depth effects. In the present study, we used geostatistics (Kriging method with power model) [2,11–25] for modelling and GIS (Geographical Information System) hydrological 2D mapping of Lithaios river water velocity and discharge. Furthermore, the validation of Q_T and $V_{i=1}^{n}$ involves analysis of residual errors, that is the gap between predicted and observed data values and the bias forecast between over- and underestimates. For this purpose, we applied the statistical criteria described by other studies [2,11–16,18–20,22–28], such as the equations for Residual Sum Squares (RSS), Standard Error (SE), and Root Mean Square Error (RMSE).

3. Results and Discussion

Streamflow velocity 2D modelling [2,27] results of Lithaios river cross-section for year's maximum (March) and minimum (August) water discharges and the univariate velocity model output statistics are depicted in Figure 1a–d. The Lithaios river mean water flow velocity ($V_{i=1}^{n}$) of cross-section segments for year's maximum (March) and minimum (August) water discharges results showed that $V_{i=1}^{n}$(max) ranged 0.199–0.329 (m s^{-1}) and $V_{i=1}^{n}$(min) ranged 0.098–0.177 (m^3 s^{-1}) respectively.



Univariate Velocity Model (Vmax) output Statistics			
Mean:	0.2584318	Variance:	0.0060829
Median:	0.2564810	Standard Deviation:	0.0779927
Geometric Mean:	0.2455442	Standard Error:	0.0015302
Coef. of Variation:	0.3017921	Root Mean Square:	0.2699398

Univariate Velocity Model (Vmin) output Statistics			
Mean:	0.136853869	Variance:	0.001761505
Median:	0.136074278	Standard Deviation:	0.041970284
Geometric Mean:	0.129689259	Standard Error:	0.00083277
Coef. of Variation:	0.306679555	Root Mean Square:	0.14314256

Figure 1. (**a**) Streamflow velocity 2D modelling results on a digital 2D $\boldsymbol{V_{i=1}^{n}}$ map of Lithaios river cross-section (Trikala M-S) for year's maximum discharges (March), (**b**) Univariate velocity model (Vmax) statistics, (**c**) Streamflow velocity 2D modelling results on a digital 2D $\boldsymbol{V_{i=1}^{n}}$ map of Lithaios river cross-section (Trikala M-S) for year's minimum discharges (August), and (d) Univariate velocity model (Vmin) statistics.

The flow velocity ($V_{i=1}^{n}$) statistics [$\bar{x}$ (mean), median, geometric mean, Coefficient of Variation (CV), s^2 (variance) and s (standard deviation)] for year's maximum discharges

(March) are presented in Figure 1b and for year's minimum discharges (August) are presented in Figure 1d. Velocity fluctuation of a river's cross-section can be specified by means of descriptive statistics [2,3,9,27–29] and of all the descriptive statistics, the coefficient of variation (CV) is the most important measure. [2,9]. Results for both CVs' of the cross-sections velocity variability for year's maximum (March) (CV = 0.302) and minimum (August) (CV = 0.307) discharges were classified as moderate variability $V_{i=1}^{n}$. The resulting spatial distribution of water flow velocities obtained using river cross-section measurements was best fitted using Kriging with Power model, that resulted in minimum residual sum squares (RSS = 0.0001694) and the RSS used as one of the criteria to choose the greatest model. The other criteria used included Standard error (SE) and Root mean square error (RMSE), as in other studies. [2,27]. The best SE for March's velocities modelling was the one using Kriging with Power model (SE = 0.0002236) and for August was also the same model (SE = 0.0008328). The RMSE using Kriging with Power model for March's velocities modelling was found as the best RMSE = 0.0406329 and for August was found as the best RMSE = 0.1431426. These results are acceptable since the SE and RMSE scores should be close to zero for an accurate prediction and classified Kriging with Power model as the best model. The above mentioned outcomes, prove the validity and accuracy of the generated 2D digital velocity maps (Figure 1a,c). The relationships between the n Manning's coefficient [2,3,5,7], the Chow's composite n coefficient [5] and the river's water discharges modeling (power model) resulted in high coefficients of determination (R^2) [2,9,12,13,16], for the 12 months measurements study period (Figure 2a,b). The diagrams of discharges power model (resulted as the best model), Darcy-Weisbach f coefficient multinomial model and shear linear model for year's maximum (March) and minimum (August) water discharges are depicted in Figure 2c,d. The R-squared gives a measure of how accurately the observable outputs are reproduced by the model, based on the percentage of the total variance that is explained by the model [2,9].

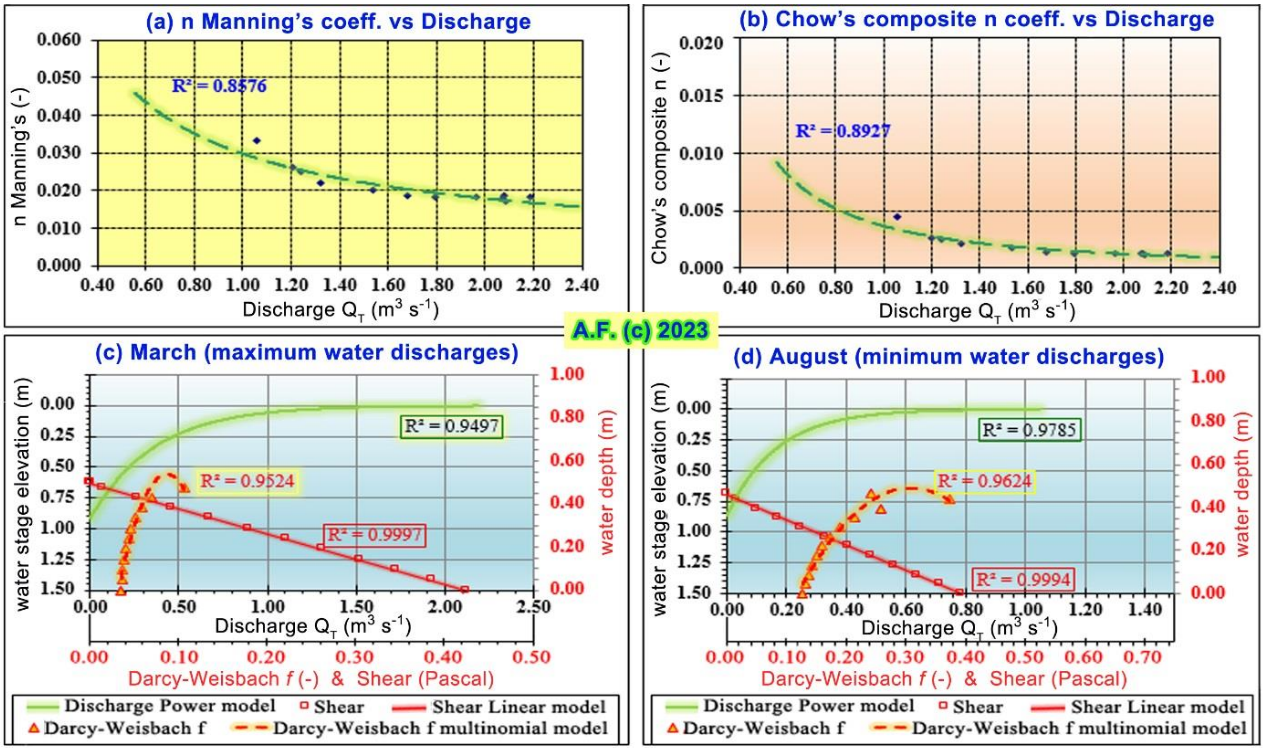


Figure 2. (**a**) Diagram of n Manning's coefficient vs. Discharge, (**b**) Diagram of Chow's composite n coefficient vs. Discharge, (**c**) Diagram of Discharge power model, Darcy-Weisbach f coefficient multinomial model and shear linear model for year's maximum Q_T (March), and (**d**) Diagram of Discharge power model, Darcy-Weisbach f coefficient multinomial model and shear linear model for year's minimum Q_T (August).

The R squared output results for the n Manning's coefficient vs. discharge showed a high $R^2 = 0.8576$ and for the Chow's composite n coefficient vs. discharge also resulted a high $R^2 = 0.8927$. The n Manning's coefficient and Chow's composite n coefficient results are showing a high degree of correlation with the river's water discharges, with the Chow's composite n coefficient found to have a higher correlation. These results indicate that Chow's composite n [5]—which is built on the hypothesis that the overall force resisting streamflow in the cross-section is equivalent to the summation of the resisting forces of streamflow in each of the defined segments regions [2,5]—more accurately approximates the force resisting water flow of the Lithaios river. Finally, the statistical results pointed that froude number during the study period was $Fr < 1$ showing that the Lithaios streamflow is classified as subcritical [2,3,5].

4. Conclusions

The RSS and the prediction errors (SE, RMSE) results of spatial and geostatistical 2-dimensional modeling, mapping and validation of Lithaios river water flows confirmed the validity and accuracy of the generated 2D digital GIS velocity maps of the river's cross-sections. These outcomes have proven that the kriging power model had a good performance and is regarded as very appropriate for 2-D streamflow modeling and digital mapping, as well as suitable for other hydraulic parameters (n Manning's coefficient, Chow's composite n coefficient, Froude Number, shear, Darcy-Weisbach f coefficient, hydraulic radius, etc). Outcomes of the study are recommended to provide a hydrological toolkit for environmental water resources administration and irrigation programming. This toolkit could assist water supply principalities to calculate fast and precisely the streamflow volumes and river's features with a minimal cost rate and workload, and it could be engaged in water supply and agricultural watering administration, calculation of environmental flows, flood protection, groundwater recharge and other objectives.

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