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Comparison between Calculation and Measurement of Total Sediment Load: Application to Nestos River †

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Abstract: Measurements of stream discharge, bed load transport rate and suspended sediment concentration in the Nestos River (northeastern Greece) were conducted by the Section of Hydraulic Engineering, of the Civil Engineering Department, Democritus University of Thrace. In addition to those measurements, the total sediment concentration was calculated by means of the formulas of Yang. The comparison between the calculated and measured total sediment concentration was achieved by means of several statistical criteria and the results were deemed satisfactory.

Keywords: total sediment load; total sediment concentration; bed load transport rate measurements; suspended sediment concentration measurements; Yang formulas

1. Introduction

Stream sediment transport still stands out as a challenging problem for hydraulic engineers. Despite the leaps that have been made in the last century in the understanding and modeling of river load transport, the problem remains largely unintelligible and insoluble, due to the complexity of the physical processes that describe it.

Sediment transport affects riverine systems, either directly or indirectly, through erosion and deposition. Excessive depositions, as a result of soil erosion, affect the cross sections, increase the risk of flooding and can lead to a deterioration of water quality. This problem can be exacerbated in the case of agricultural basins where sediments may be carriers of infectious particles due to the use of fertilizers and pesticides [1].

Total sediment transport in streams is classified into bed load transport and suspended load transport on the basis of two different motion patterns. The sum of bed load and suspended load is equal to the total load [2].

In the recent decades, the Section of Hydraulic Engineering of the Civil Engineering Department, Democritus University of Thrace (Greece), has conducted bed load transport rate measurements and suspended sediment concentration measurements at the outlet of the Nestos River basin [3], Kosynthos River basin [4,5], and Kimmeria Torrent basin [5].

This study aims to redetermine the coefficients of Yang's (1973) and Yang's (1979) sediment transport formulas using multiple regression. In the past, nonlinear regression equations between bed load transport rate and stream flow rate, as well as between suspended load transport rate and stream flow rate, were established for the outlet of the Nestos River basin [3]. In the present study, 111 pairs of measured stream flow rate, measured bed load transport rate or measured suspended load transport rate in the Nestos River were used. The sum of measured bed load transport rate and measured suspended load transport rate provides the measured total load transport rate from which the total sediment concentration can be estimated. Apart from those measurements, total sediment concentrations were calculated by means of Yang's formulas [6,7]. This made it possible to compare calculated to site-measured total sediment concentrations.

2. Study Area

The Nestos River springs from the Rila Mountains in southwestern Bulgaria and is one of the main watercourses of Eastern Macedonia and Thrace (Greece). Its Greek part covers approximately 130 km and the mountainous part of the Nestos River basin extends to an area of 840 km^2. The basin is covered by forest (48%), bush (20%), cultivated land (24%), urban area (2%) and areas of no significant vegetation (6%), and has an altitude between 38 m and 1747 m. The basin is divided into 20 sub-basins with coverage areas between 13 km^2 and 80 km^2 and the mean land slope is between 23% and 58%. The mean slope of the main streams of the sub-basins ranges between 2.5% and 20%, whereas the mean slope of the Nestos River is 0.35%.

3. Stream Flow Rate and Sediment Transport Rate Measurements

All measurements were conducted at a location between the outlet of the Nestos River basin (Toxotes) and the river's delta [8,9]. The average width of the cross sections of all measurements is 26.7 m.

The stream flow rate measurements were conducted using the following procedure: the site cross section was divided into sub-sections and the average stream flow velocity was measured at the middle of each sub-section, at 40%, approximately, of the flow depth from the bed, using a Valeport open channel flow meter. The stream flow rate of the entire cross section was taken as the sum of the individual sub-sections stream flow rates.

The bed load transport rate measurements were conducted in the middle of each cross section using a Helley–Smith bed load sampler. In order to determine the bed load transport rate, the trapped bed load sample is dried out and the mass is divided by the trap width and the measurement time duration [8,9].

The suspended sediment concentration was determined by obtaining a sample of water at the middle of the section and subsequently filtrating the sample through retention paper filters to obtain the net weight of the suspended load [8,9].

4. Calculation of Total Sediment Concentration

"Unit stream power", as defined by Yang [6], is the amount of dynamic energy consumed by gravitational flow per unit of time and per unit weight of water, and is expressed by the product of the flow rate and the energy slope:

$$\frac{dY}{dt} = \frac{dx}{dt}\frac{dY}{dx} = us = \text{unit stream power} \tag{1}$$

where Y is the elevation above a datum, equal to the potential energy per unit weight of water; x is the horizontal distance; and t is the time.

4.1. Yang (1973)

Yang's [6] formula for the total sediment transport in a river is given by:

$$\log c_F = 5.435 - 0.286\log\frac{wD_{50}}{v} - 0.457\log\frac{u_*}{w} + \left(1.799 - 0.409\log\frac{wD_{50}}{v} - 0.314\log\frac{u_*}{w}\right)\log\left(\frac{us}{w} - \frac{u_{cr}s}{w}\right) \tag{2}$$

where c_F is the total sediment concentration in parts per million (ppm) by weight; w is the terminal fall velocity of sediment particles (m/s); D_{50} is the median particle diameter (m); ν is the kinematic viscosity of water (m^2/s); s is the energy slope; u is the mean flow velocity (m/s); u_{cr} is the critical mean flow velocity (m/s); and u_* is the shear velocity (m/s).

If the following auxiliary variables x_1, x_2, x_3, x_4 and x_5 are considered:

$$
\begin{aligned}
x_1 &= \log(wD_{50} / \nu) \\
x_2 &= \log(u_* / w) \\
x_3 &= \log(us / w - u_{cr}s / w) \\
x_4 &= \log(us / w - u_{cr}s / w)\log(wD_{50} / \nu) \\
x_5 &= \log(us / w - u_{cr}s / w)\log(u_* / w)
\end{aligned} \quad (3)
$$

then Yang's formula can be written as follows:

$$\log c_F = 5.435 - 0.286x_1 - 0.457x_2 + 1.799x_3 - 0.409x_4 - 0.314x_5 \quad (4)$$

White et al. [10] calculated the terminal fall velocity of the particles using the following equations:

$$w = F\sqrt{\varrho' g D} \quad (5)$$

$$F = \sqrt{\left(\frac{2}{3} + \frac{36}{D^{*3}}\right)} + \sqrt{\frac{36}{D^{*3}}} \quad (6)$$

$$D^* = \sqrt[3]{\frac{\varrho' g}{\nu^2}} D_{ch} \quad (7)$$

$$\varrho' = \frac{\varrho_F - \varrho_w}{\varrho_w} \quad (8)$$

where F is the correction factor for suspended load; D is the grain diameter (m); D* is the Bonnefille number; D_{ch} is the characteristic grain diameter (m); ϱ_F is the density of sediment particles (kg/m^3); and ϱ_W is the density of water (kg/m^3). The kinematic viscosity v (m^2/s) of water is given by the equation:

$$\nu = \frac{1.78 ?\ 0^{-6}}{1 + 0.0337T + 0.00022T^2} \quad (9)$$

where T (°C) is the temperature of the water.

4.2. Yang (1979)

In 1979, Yang concluded that the critical unit stream power term in Equation (2) can be neglected without causing much error when the measured sediment concentration is greater than 20 ppm by weight [7]. The simplified unit stream power equation was derived as:

$$\log c_F = 5.165 - 0.153\log\frac{wD_{50}}{\nu} - 0.297\log\frac{u_*}{w} + \left(1.780 - 0.360\log\frac{wD_{50}}{\nu} - 0.480\log\frac{u_*}{w}\right)\log\left(\frac{us}{w}\right) \quad (10)$$

Similarly, if the following auxiliary variables x_1', x_2', x_3', x_4' and x_5' are considered:

$$
\begin{aligned}
x_1' &= \log(wD_{50}/\nu) \\
x_2' &= \log(u_*/w) \\
x_3' &= \log(us/w) \\
x_4' &= \log(us/w)\log(wD_{50}/\nu) \\
x_5' &= \log(us/w)\log(u_*/w)
\end{aligned} \quad (11)
$$

Equation (10) can be written as a linear multiple regression equation:

$$\log c_F = 5.165 - 0.153x_1' - 0.297x_2' + 1.780x_3' - 0.360x_4' - 0.480x_5' \quad (12)$$

5. Development of Yang's Equations on the Basis of Nestos River Data

On the basis of the Nestos River data, the arithmetic coefficients of the original formulas of Yang [6,7], (Equations (2) and (10)), are modified, respectively, as follows:

$$\log c_F = 2.595 - 0.560\log\frac{wD_{50}}{v} - 6.649\log\frac{u_*}{w} - \left(1.380 - 0.534\log\frac{wD_{50}}{v} + 2.315\log\frac{u_*}{w}\right)\log\left(\frac{us}{w} - \frac{u_{cr}s}{w}\right) \quad (13)$$

$$\log c_F = 3.301 - 0.697\log\frac{wD_{50}}{v} - 14.367\log\frac{u_*}{w} - \left(1.214 - 0.537\log\frac{wD_{50}}{v} + 7.301\log\frac{u_*}{w}\right)\log\left(\frac{us}{w}\right) \quad (14)$$

In concrete terms, the new arithmetic coefficients of Equations (13) and (14) were determined by means of the conventional least square-based regression.

The measured stream flow rate (m^3/s), the measured total sediment concentration (ppm), as well as the corresponding calculated total sediment concentration (ppm), by means of Equations (13) and (14), are provided in Table 1.

Table 1. Measured stream flow rate and total sediment concentration—Calculated total sediment concentration in the Nestos River.

No.	Stream Flow Rate (m³/s)	Total Load $\log c_F$ (meas.)	Total Load $\log c_F$ (calc.) Yang 1973	Total Load $\log c_F$ (calc.) Yang 1979	No.	Stream Flow Rate (m³/s)	Total Load $\log c_F$ (meas.)	Total Load $\log c_F$ (calc.) Yang 1973	Total Load $\log c_F$ (calc.) Yang 1979
1	14.17	2.4064	2.3272	2.4124	**31**	3.16	2.4852	2.1243	2.1413
2	17.44	2.3929	2.2086	2.3058	**32**	2.56	1.6531	2.1818	2.1209
3	19.50	2.1160	2.1335	2.1819	**33**	3.95	2.0033	2.0120	2.0609
4	16.65	2.5769	2.2280	2.3020	**34**	4.22	2.1990	2.0149	2.0704
5	18.49	2.3163	2.1567	2.2284	**35**	3.66	2.3754	2.0099	2.0559
6	2.44	1.3789	2.0625	2.1273	**36**	4.80	2.2213	1.9135	1.9778
7	2.73	1.3806	1.9514	2.0150	**37**	2.06	2.0066	1.7068	1.7695
8	2.69	1.2852	1.9321	1.9866	**38**	1.46	2.2493	1.8468	1.9173
9	2.84	1.2712	1.8949	1.9532	**39**	1.88	2.1066	1.7164	1.7854
10	3.09	1.3444	1.9260	2.0052	**40**	1.49	2.1652	1.8366	1.9067
11	17.89	0.9300	1.3330	1.4140	**41**	1.75	2.1639	1.7815	1.8486
12	15.45	1.5009	1.4583	1.5803	**42**	1.66	1.7420	1.8333	1.9043
13	20.62	1.4076	1.2519	1.3096	**43**	2.29	1.7200	1.6467	1.7179
14	16.15	1.2719	1.4327	1.5588	**44**	1.55	2.1600	1.8386	1.8937
15	14.14	0.8808	1.5299	1.6691	**45**	1.24	1.8919	1.9283	1.9875
16	58.98	−0.4977	0.7454	0.4515	**46**	1.65	2.6312	1.7926	1.8650
17	52.94	0.3224	0.8856	0.7877	**47**	1.56	1.5917	1.8406	1.9286
18	50.14	1.0832	0.8405	0.5748	**48**	2.03	1.1085	1.7015	1.7641
19	48.27	0.6214	0.9100	0.7553	**49**	0.80	1.4741	1.9474	2.0033
20	45.72	0.5341	0.9570	0.8348	**50**	0.69	1.0102	1.9347	1.9919
21	44.45	0.9808	0.9586	0.7920	**51**	0.69	1.1868	2.0170	2.0654
22	62.41	1.2658	0.7342	0.4807	**52**	0.90	1.5753	1.8987	1.9769
23	55.30	0.5716	0.8122	0.5924	**53**	3.27	2.1887	1.9611	2.0192
24	2.62	2.6540	1.9164	1.9354	**54**	3.70	2.4867	1.7769	1.8147
25	3.95	2.6132	2.0149	2.0704	**55**	2.48	2.2356	2.0437	2.0747
26	4.22	2.5023	1.9973	2.0650	**56**	2.23	2.6100	2.0533	2.0860
27	4.13	2.4793	1.9776	2.0225	**57**	0.85	2.0211	2.3816	2.2171
28	6.20	2.4870	1.8488	1.9273	**58**	0.64	2.3324	2.0842	1.9663
29	4.80	2.6715	1.8485	1.8979	**59**	0.55	2.2624	2.3519	2.2803
30	3.76	2.5385	1.9707	2.0092	**60**	2.83	2.0921	1.9500	2.0009

No.	Stream Flow Rate (m³/s)	Total Load $\log c_F$ (meas.)	Total Load $\log c_F$ (calc.) Yang 1973	Total Load $\log c_F$ (calc.) Yang 1979	No.	Stream Flow Rate (m³/s)	Total Load $\log c_F$ (meas.)	Total Load $\log c_F$ (calc.) Yang 1973	Total Load $\log c_F$ (calc.) Yang 1979
61	3.40	2.2798	1.9355	1.9988	**87**	0.90	1.9402	2.0299	1.9359
62	3.29	2.0411	1.9162	1.9825	**88**	0.88	1.9007	1.6822	1.6011
63	1.77	2.7604	2.1373	2.1580	**89**	0.97	1.4280	1.8835	1.8606
64	1.06	2.7836	2.4887	2.3048	**90**	0.47	1.7540	2.2480	2.1496
65	0.60	2.5666	2.4785	2.1120	**91**	0.52	1.8291	2.3018	2.2275
66	0.39	2.3439	2.7624	2.3083	**92**	0.29	2.0208	2.3191	2.1865
67	0.64	2.8455	2.5643	2.2200	**93**	1.39	0.0803	2.2672	2.2396
68	2.67	1.6012	2.0161	2.0783	**94**	1.36	0.2972	2.0320	1.9492
69	3.68	2.0237	1.8693	1.9422	**95**	0.93	2.4222	2.7206	2.7267
70	2.45	1.7286	2.0470	2.0960	**96**	1.15	2.2505	2.5983	2.6155
71	2.62	2.5135	2.0109	2.0678	**97**	2.05	2.6852	2.3236	2.3769
72	2.95	2.5891	2.0145	2.0770	**98**	0.87	1.9359	2.2107	2.0739
73	0.84	1.7919	2.0595	2.0582	**99**	0.85	2.4092	2.7146	2.6828
74	1.76	1.4119	1.7486	1.8104	**100**	1.06	2.0224	2.1208	2.0151
75	1.81	2.0826	1.7312	1.7866	**101**	1.26	2.4699	2.2245	2.1058
76	1.09	2.2863	1.9924	2.0559	**102**	0.49	2.5759	2.1305	2.1176
77	0.59	2.3232	2.3234	2.2569	**103**	0.34	2.7771	2.3937	2.3719
78	1.06	2.2265	1.7887	1.8405	**104**	1.34	1.7905	1.9632	2.0090
79	0.75	2.3269	1.8485	1.8623	**105**	0.68	2.4427	2.1192	2.1378
80	1.43	2.2886	1.6653	1.7245	**106**	0.10	2.9859	1.9198	2.1113
81	1.47	1.8679	1.7191	1.7927	**107**	17.28	1.8167	1.5857	1.6423
82	0.64	2.1852	1.9814	1.9869	**108**	8.24	2.2106	2.0268	2.1808
83	0.55	1.4934	2.1193	1.9905	**109**	0.94	2.0663	1.8149	1.9314
84	0.83	1.9176	2.1437	2.0544	**110**	9.83	1.9549	1.7134	1.8098
85	0.85	1.7439	1.9873	1.9228	**111**	0.76	2.0425	1.8485	1.9434
86	0.51	1.5108	1.9665	1.9298					

6. Comparison between Calculated and Measured Total Sediment Concentration

The comparison between calculated and measured total sediment concentration is made on the basis of the following statistical criteria [11]. At this point, it should be noted that the total sediment concentration was calculated by means of both the original and the modified Yang's formulas.

6.1. Root Mean Square Error (RMSE)

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{n}} \tag{15}$$

where y_i is the measured total sediment concentration; $\hat{y}_i$ is the calculated total sediment concentration and n the number of data. The RMSE ranges between 0 and +∞. The lower the RMSE, the better the correlation between measured and calculated values.

6.2. Mean Relative Error (MRE) (%)

$$\mathrm{MRE}=\frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)}{n}100 \tag{16}$$

Mean Relative Error (MRE) provides the relative size of the error. It is an index of how good an approximation between the predicted and measured value is, in relation to the magnitude of the physical quantity's value.

6.3. Nash –Sutcliffe Efficiency (NSE) [12]

$$\mathrm{NSE}=1-\frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{\sum_{i=1}^{n}(y_i-\bar{y})^2} \tag{17}$$

where $\bar{y}$ is the average value of y_i. NSE indicates how well the plot of observed versus simulated data fits the line of agreement (1:1 line). Nash –Sutcliffe efficiency ranges from −∞ to 1, with 1 being the optimal value.

6.4. Linear Correlation Coefficient r

$$r=\frac{\sum_{i=1}^{n}(y_i-\bar{y})(\hat{y}_i-\bar{\hat{y}})}{\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}\sqrt{\sum_{i=1}^{n}(\hat{y}_i-\bar{\hat{y}})^2}} \tag{18}$$

where $\bar{\hat{y}}$ is the average value of $\hat{y}_i$. The coefficient r expresses the degree of mutual linear dependence between the variables y_i and $\hat{y}_i$, and ranges between −1 and +1. The values $r = \pm1$ represent the ideal occasion, when the marks representing the pairs of values y_i and $\hat{y}_i$ depicted on an orthogonal coordinate system, lie on the regression line, with positive or negative slope, respectively.

6.5. Determination Coefficient R^2

The determination coefficient R^2 yields the percentage of change of the calculated values, which can be explained by the linear relationship between calculated and measured values. It ranges between 0 and 1. A value of 0 states that there is no correlation, whereas the value of 1 states that the variance of the calculated values equals the variance of the measured values [11].

6.6. Discrepancy Ratio

The discrepancy ratio represents the percentage of the calculated total sediment concentration values lying between pre-determined margins of the corresponding measured total sediment concentration values. As far as the present study is concerned, the discrepancy ratio represents the percentage of the calculated total sediment concentration values that lies between the double and the half of the corresponding measured total sediment concentration values.

The values of the above-mentioned statistical criteria are displayed in Tables 2 and 3.

Table 2. Statistical criteria of Yang's formulas—original and calibrated (1973).

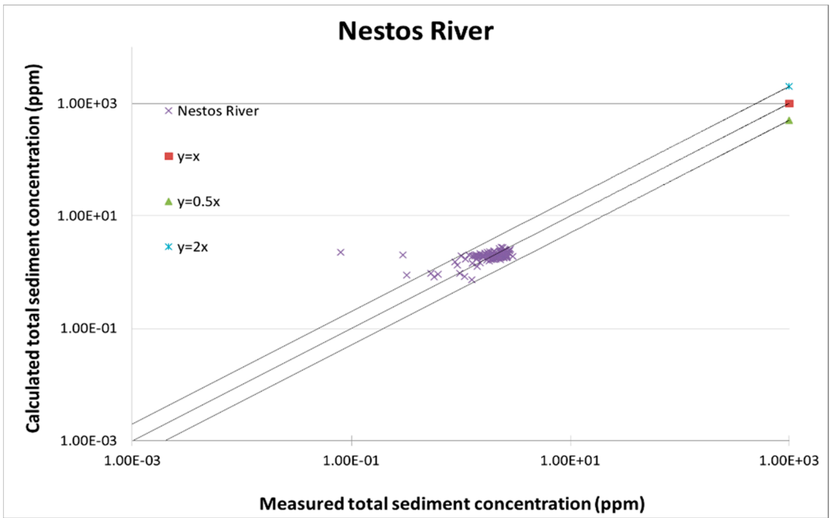
	RMSE	MRE (%)	NSE	r	R^2	Discrepancy Ratio
Original	1.324	−98.339	−3.240	−0.338	0.114	0.757
Calibrated	0.506	−31.734	0.381	0.617	0.381	0.964

Table 3. Statistical criteria of Yang's formulas—original and calibrated (1979).

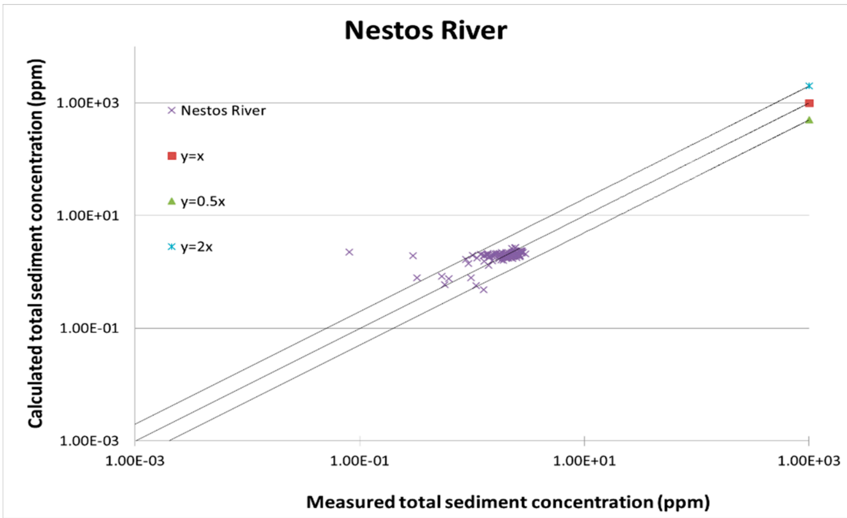
	RMSE	MRE (%)	NSE	r	R^2	Discrepancy Ratio
Original	1.390	−115.039	−3.673	−0.449	0.201	0.739
Calibrated	0.492	−31.185	0.415	0.644	0.415	0.955

The values of the RMSE and NSE, on the basis of the calibrated formulas, can be considered fairly satisfactory. Additionally, the degree of linear dependence between calculated and measured total sediment concentration is acceptable. As expected, the values of NSE and R^2, on the basis of the calibrated formulas, are identical and obviously non-negative.

The plot of Figure 1 represents the discrepancy ratio between measured and calculated values of total sediment concentration. At this point, it should be noted that both coordinate axes are in logarithmic scale; therefore, the equations y = x, y = 0.5x and y = 2x are graphically represented by parallel straight lines. Especially the values of the discrepancy ratio, on the basis of the calibrated formulas, are very satisfactory.



(**a**)



(**b**)

Figure 1. Discrepancy ratio plot between measured and calculated values of total sediment concentration by means of: (**a**) calibrated Yang's formula (1973) and (**b**) calibrated Yang's formula (1979).

7. Discussion—Conclusions

In this paper, an attempt was made to redefine the coefficients of Yang's formulas based on field measurements data in the Nestos River, between 2005 and 2015. A deviation between the calculated and measured total sediment concentration was observed for this specific case. For the correct application of Yang's formulas [6,7] to the Nestos River, the calibration of the independent variables' coefficients was deemed necessary.

As presented above, all statistical criteria of both calibrated Yang's formulas were improved in comparison to the ones of Yang's original formulas. More specifically, the RMSE approached zero for the calibrated equations, whilst the MRE displayed a notable decrease. Regarding the NSE, the linear correlation coefficient, r, and the determination coefficient, R^2, came closer to the optimal value. Particularly, the discrepancy ratio was very near to the optimal value (100%). Overall, the results can be considered satisfactory.

It is noted that the application of Equations (13) and (14) should be bound to the Nestos River.

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