SEDIMENT MANAGEMENT IN RESERVOIRS IN ORDER TO REDUCE SHORELINE EROSION: THE CASE OF NESTOS RIVER, GREECE

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ABSTRACT

Nestos River is the 71th biggest transboundary river in the world. At early nineties, two major hydroelectric reservoirs, at the locations “Thisavros” and “Platanovrysi”, in the Greek part of the considered river basin, were constructed. In a previous work, the authors have found that the construction of these reservoirs induced a dramatic reduction (more than 80%) in the sediment yield that reaches the outlet of Nestos River basin. This resulted to a major increase in the erosion rates at the river delta and the adjacent shorelines. In the present paper the effect of sediment dredging and flushing from the “Platanovrysi” dam downstream is investigated, in order to evaluate the increase in the sediment budget that reaches the outlet, which can contribute to the reduction of shoreline erosion. For this purpose a mathematical model is modified accordingly in order to take into account sediment dredging and flushing. A wide series of parametric simulation scenarios is performed, aiming to identify the optimum periods that dredging and flushing can be applied for maximizing the sediment amount that reaches the basin outlet. A definite classification of the months in “effective” and “ineffective” as well as to “consistent” and “inconsistent” with respect to the total amount of sediment that reaches the basin outlet is made. It is also found that the considered river has a maximum transport capacity regardless the further increase of the dredged and/or flushed sediment quantity from the identified limiting value. Finally, flushing is identified to be slightly more effective than dredging.

Keywords: sediment management, reservoir, mathematical modelling, Nestos river

1. INTRODUCTION

Coastal erosion constitutes one of the main environmental problems in many parts of the world. Especially in the case of deltaic regions, the construction of dams in the river basin impedes sediment supply at the river mouths and therefore the rates of shoreline retreat and sea level rise may exceed the corresponding rates of vertical shoreline accretion, resulting to the increase and in many cases the predomination of deltaic and coastal erosion. Over the last decades, many investigations have been directly or indirectly focused on the assessment of reservoir sedimentation and its effect on sediment yield reduction and coastal erosion, in the wider coastal regions of various rivers worldwide, using varying investigation methodologies and techniques (e.g. [1]-[6]).

Nestos river is one of the most important transboundary rivers, characterized by its great biodiversity. Nestos River flows through two European countries, Bulgaria and Greece, and discharges its water into the Aegean Sea. It originates from Mount Rila (2,716 m) in South Bulgaria between the mountain chains of Aimos and Rodopi, where the river is called Mesta. Its total length reaches 234 km and the river basin covers an area of 5,749 km^2, 130 km (<56 per cent) and 2,280 km^2 (<40 per cent) of which lie in Greek territory [7]. In the Greek part of the river, two reservoirs, the Thisavros reservoir and the Platanovrysi reservoir, have already been constructed and started operating in 1997 and 1999, respectively. A previous work by the authors [8] constitutes one of the first attempts, where the assessment of reservoir sedimentation effect on the coastal erosion for the case of the Nestos River delta and the adjacent shorelines was addressed in detail, through mathematical modeling, modern remote sensing techniques and field surveying. It was found that the construction and operation of the considered reservoirs have caused a dramatic decrease (about 83%) in the sediments supplied directly to the basin outlet and indirectly to the neighbouring coast, and that this fact has almost inversed the erosion/accretion balance in the deltaic as well as the adjacent shorelines. Before the construction of the reservoirs, accretion predominated erosion by 25.36%, while just within five years after the construction of the reservoirs, erosion predominates accretion by 21.26%.

It has been estimated that every year 1-2% of the effective volume of reservoirs worldwide is lost, due to the accumulation of sediment. This is an unavoidable process which however can be reduced, quantified and incorporated to the design and operation of a reservoir [9].

The sediment management methods in reservoirs can be classified in three main categories: a) methods that minimise the inflow of sediment into the reservoirs, b) methods that minimise the accumulation of sediment in the upstream of the reservoir and c) methods that maximise the overall sediment discharge that passes downstream of the reservoirs. The application of this last class of methods could serve as a possible treatment for the reduction of shoreline erosion which has been mainly caused by the construction of the above mentioned reservoirs in the case river Nestos. Two of the most widely applied methods of sediment removal from reservoirs are the processes of dredging [10] and flushing [9].

In the present paper the effect of sediment removal by dredging and flushing from the “Platanovrysi” reservoir downstream is investigated, in order to evaluate the increase in the sediment budget that reaches the outlet of the river, as this increase can contribute to the reduction of shoreline erosion. For this purpose, a previously validated and applied [8] mathematical model (RUNERSET- RUNoff ERosion SEdiment Transport), is modified accordingly in order to take into account sediment dredging and flushing applications. The proposed modifications involve the addition of different amounts of eroded material (sediment) in the sub-basin that lies directly downstream of “Platanovrysi” reservoir for dredging processes as well as the inclusion of a flushing discharge. In more detail, a parametric investigation is conducted using a wide series of simulated scenarios, aiming to identify the optimum periods that dredging and flushing can be applied in order to maximize the increase of the sediment that is transported and reach the basin outlet.

2. APPLICATION OF SEDIMENT DREDGING AT PLATANOVRYSI RESERVOIR

In order to investigate the possible contribution of the mechanical removal (dredging) of sediment from the reservoir of Platanovrysi, and their deposition in the sub-basin of Toxotes, at the outlet of Nestos river, the mathematical model RUNERSET [8] was accordingly modified. The proposed model consists of three submodels: a rainfall-runoff model, a sediment erosion model and a sediment transport model. In more detail, the proposed modification involves the addition of different, additional, eroded sediment amounts at sub-basin number seven (Figure 1) for specific months of each year, for the time period 1980 to 1990. The proposed sub-basin lies directly after the reservoir of Platanovrysi.

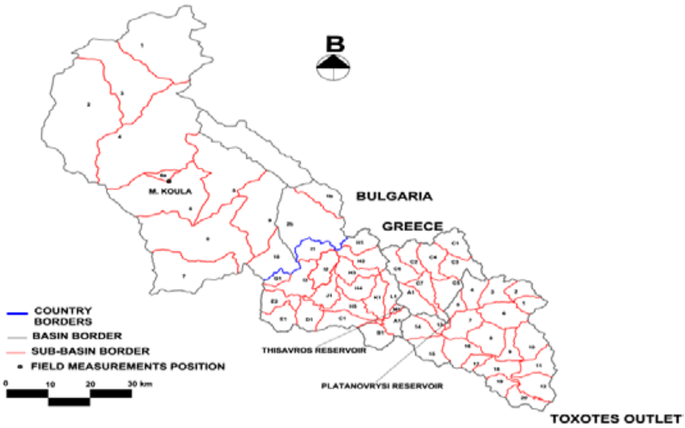

Figure 1: Sub-basin map of Nestos river hydrological basin.

A total number of 888 simulations were conducted for the years 1980 to 1990 assuming the following scenarios: application of dredging at each month of each year and for various amounts of sediment removal. Initially, diagrams of the total annual amount of sediment that reaches the outlet of the river, versus the amount of sediment that were removed by dredging from Platanovrysi reservoir, were constructed. Figure 2, illustrates indicatively these diagrams for two of the considered years.

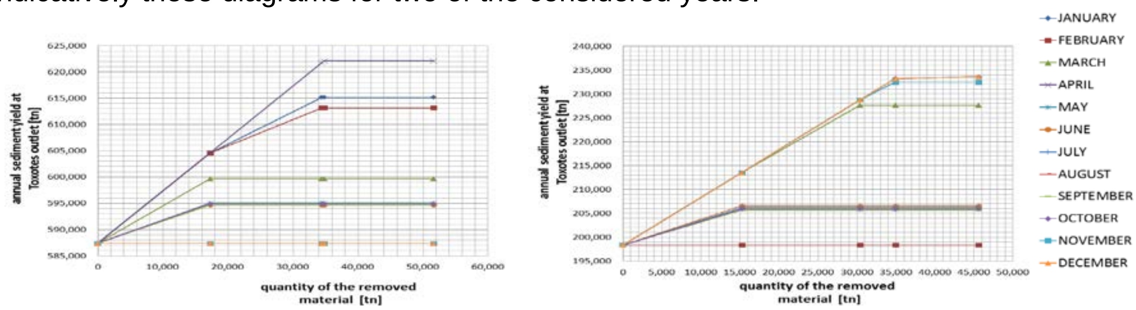

Figure 2: Indicative results from simulated dredging scenarios for the years 1981 (a) and 1986 (b).

From these diagrams it is obvious that for dredging scenarios in specific months of the year, the total annual sediment amount that reaches the outlet of the river is higher than the corresponding dredging scenarios in the rest of the months. Therefore, the months of the year can be clearly classified in “effective” and “ineffective” for a dredging application. In more detail, from the overall analysis of the simulation results, it can be concluded that January, February, March, April, November and December can be, in general, characterised as “effective” months, while for the time period from May to October (ineffective months), a potential dredging application would not alter significantly the annual sediment amount that reaches the outlet of the river. The month classification in “effective” and “ineffective” is summarised schematically in Figure 3 (a), where the additional annual amount of dredged sediment that reaches the outlet of the river (Toxotes outlet, see Figure 1), is plotted against the amount of sediment that was removed at the specific month of the year in each case, for the overall simulated scenarios.

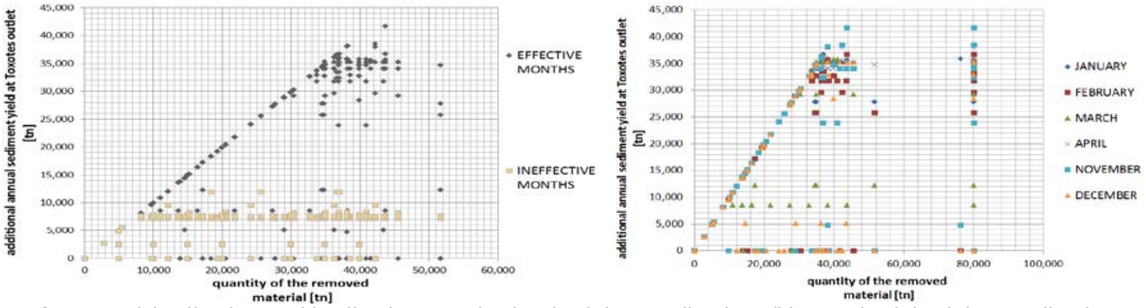

Figure 3: (a) Effective and ineffective months for dredging application, (b) Result of dredging application during the effective months of the year (the data points represent the overall simulated scenarios)

It is should also be mentioned that for amounts of sediment removal up to 35,000 tn and for dredging scenarios in the effective months of the year, the ratio of the additional sediment amount that reaches the outlet of the river to the removed sediment amount, is equal to unity. This indicates that generally, up to a limiting value of 35,000 tn of dredged sediment from Platanovrysi reservoir, in an effective month, all of this removed amount of sediment will reach the outlet of the river. Moreover, from a certain amount of removed sediment and above, there is not any change in the amount of sediment that reaches the outlet of the river. This indicates that there is a maximum transport quantity of dredged material, that Nestos river can transport up to its outlet. This limiting amount varies accordingly for each month. Therefore, it is vital to define, the month of the year in which this sediment transport quantity is maximized. Figure 3 (b) indicates, that the maximum value of sediment surplus that reaches the outlet of the river, takes place if dredging is applied in November.

However, for November there are also a lot of simulations that resulted in a zero sediment surplus at the outlet of river Nestos (in some of the overall simulated years). This means that while river Nestos can transport the maximum amount of sediment that reach its outlet if the dredging application is performed during November for a certain year, it is also possible at a different year that no sediment at all to reach the outlet. Therefore, an additional classification of the “effective” months in “consistent” and “inconsistent” must be conducted. According to the diagram of Figure 3 (b), the months January and April can be characterised as “consistent”, while February, March, November and December can be characterised as “inconsistent”.

In order now to investigate the most “effective” and “consistent” month of the year for applying sediment dredging, between January and April, a direct comparison of these two months was conducted. For this purpose the overall results from all the simulated years (1980-1990) and for all the amounts of dredged sediment were collected, for January and April. The quantitative analysis of the proposed simulation results indicated that the overall sediment dredging performance of these two months can be classified in three distinct parts. The first part refers to dredging scenarios with sediment removal up to 34,400 tn, in which the performance of each month with respect to the amount of sediment surplus that reaches the outlet of the river is the same, having a value of 100%. The second and third parts consist of dredging scenarios with sediment removal from 34,400 tn up to 36,150 tn and greater than 36,150 tn, respectively. In these last two parts of the collected data, the performance of each month is different, having values also lower than 100%. Taking into account the fact that river Nestos cannot in generally transport to the outlet dredged sediment amounts greater than 35,000 tn, the third part of the resulting data was neglected from the comparison process. For the proposed comparison, the mean value of the dredged sediment amount that did not reach the outlet of the river was taken as the effectiveness criterion, while the corresponding standard deviation was used as the criterion for consistency. The overall analysis from the comparison between January and April can be summarised in Table 1. It is obvious that April can be assumed as the most suitable month of the year, for a dredging application at Platanovrysi reservoir. It is also worth to be mentioned that the sediment amount of 35,000 tn that is the maximum amount of dredged sediment that can reach the outlet of Nestos river, is equal to 2.46% of the mean annual sediment yield of the river at its outlet, before the construction of the considered reservoirs, and the 10,95% of the mean annual yield of the river after the construction and operation of the reservoirs. Finally, this sediment amount also constitutes the 11,53% of the mean annual sediment yield that reaches the reservoir of Platanovrysi.

	quantity of removed material [tn]	**additional annual sediment yield at Toxotes outlet [tn]**			
		JANUARY	**non delivered sediment quantity [tn]**	**APRIL**	**non delivered sediment quantity [tn]**
	34, 400	27,806	6,594	34,400	0
	34,625	34,626	-1	34,625	0
	34,744	27,806	6,938	34,744	0
	34,825	34,825	0	34,102	723
	34,903	34,902	1	34,101	802
	36,150	35,238	912	36,150	0
mean value	**34,941.17**	**32,533.83**		**34,687**	
mean attribution [%]	**-**	**93.11**		**99.27**	
		mean value	**2407,33**	**mean value**	**254,17**
		standard deviation	**3396,38**	**standard deviation**	**394,55**

Table 1: Comparison of effectiveness and consistency between January and March for dredging application

3. APPLICATION OF SEDIMENT FLUSHING AT PLATANOVRYSI RESERVOIR

In order to investigate the possibility of minimising shoreline erosion due to the construction of the proposed reservoirs, with the application of flushing the mathematical model RUNERSET was accordingly modified, in order to take into account the corresponding flushing discharge. Also in these series of simulations the model was applied for the years 1980 to 1990. For the calculation of the flushing discharge equation (1) was used [9] assuming that the sediment flushing discharge is known:

$$Q_f = \left(\frac{Q_S}{3,5\cdot10^{-3}\cdot(S\cdot10^4)^{1,8}}\right)^{1/1,2} \quad (1)$$

where Q_s is the removed sediment discharge from the reservoir during a flushing event (tn/sec), S is the bottom slope along the flushing channel, assuming that the flow is uniform and therefore the slope of the energy line and the flow line coincide and Q_f: is the flushing discharge (m^3/sec).

In order to determine the optimum month of the year for the application of flushing in the reservoir of Platanovrysi, a series of simulations were performed with a sediment flushing discharge of 0.0135 tn/sec (that corresponds to the value of 35,000 tn) and for flushing events occuring in diffrent months. The results are summarised in Table 2. It is obvious that he optimum month for the aplication of a flushing event, in order to maximise the overall flushed sediment amount that reaches the outlet of the river, and therefore decrease the indirect shoreline erosion, is January and not April (as in the corresponding investigation for the application of dredging). However, April is found to be the second most effective month. In the literature it is stated that in order to maximase the amount of sediment that are removed from a reservor and therefore restore its storing capacity, a flushing event will be more effective if it occurs at the beginning of the ice melting period [9]. Therefore, from this point of view, April could be characterised as the optimum month of the year for the application of a flushing event.

	PERCENTAGE OF FLUSHED SEDIMENT THAT REACHES TOXOTES OUTLET [%]										
	1980	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**
JAN	**99,99**	**79,50**	**100,00**	**100,00**	**100,00**	**99,99**	**99,88**	**99,99**	**99,91**	**100,00**	**100,00**
FEB	95,71	73,78	90,94	93,72	0,00	99,99	0,00	0,00	84,48	90,86	90,97
MAR	99,99	35,20	100,00	100,00	0,00	24,55	83,59	99,99	0,00	100,00	100,00
APR	**99,99**	**99,22**	**99,22**	**97,44**	**100,00**	**97,42**	**97,59**	**0,00**	**99,91**	**97,43**	**97,45**
MAY	34,26	21,77	24,06	22,88	21,46	21,98	21,58	22,54	27,61	21,70	21,55
JUN	20,83	20,91	20,92	0,00	20,89	20,83	23,58	23,68	0,00	20,84	20,86
JUL	21,40	21,48	21,78	7,45	21,46	21,69	22,43	21,68	21,61	21,70	21,55
AUG	21,40	21,48	21,49	21,56	21,46	21,69	21,58	21,68	21,61	21,70	21,55
SEP	20,83	20,91	20,92	20,85	20,89	20,83	20,72	20,82	20,75	20,84	20,86
OCT	21,40	21,48	21,49	21,56	21,46	21,69	21,58	21,68	20,75	0,00	21,55
NOV	92,56	0,00	68,36	99,15	97,48	99,99	97,59	13,68	99,91	0,00	97,45
DEC	0,00	0,00	0,00	81,18	100,00	99,99	99,88	0,00	0,00	94,00	14,58

Table 2: Results from simulations of flushing scenarios for different months of the year

In order to calculate the river's maximum transport quantity of flushed sediment at the outlet of its basin, additional scenarios of continuous through each year flushing events were simulated. For this purpose the mathematical model RUNERSET was further modified in order to take into acount sediment flushing discharge equal to 0.1 tn/sec, a value much greater than the previously identified critical value of 0.0135 tn/sec. From the analysis of the results it is found that Nestos River could tranport at its outlet aproximatelly 200,000 tn of additional sediment, if the flushing of sediment was applied continuously during the whole year. It worths to be mentioned that this amount constitutes the 62% of the mean annual sediment yield today.

Taking into account that the application of flushing could be more effective, at least from the point of view of limiting shoreline erosion, during certain months of the year (time period from November to April) additional continuous flushing scenarios were simulated for the period of the six more effective months of the year for each of the concidered years (1980 to 1990). The overall results are summarised in Figure 5.

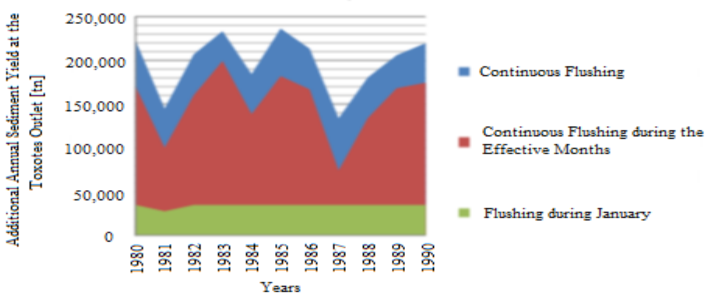

Figure 5: Results from simulated flushing scenarios**.**

Examining Figure 5, it can be concluded that in the case that the continuous flushing event happens during the six of the most effective months of the year, the amount of sediment that reaches the outlet of river Nestos reaches the 76.5 % of the corresponding amount at the case of continuous flushing thoughout the whole year. Moreover, at the case that the sediment flushing event is applied only during January the amount of sediment that reaches the outlet consitutes the 17.35 of the maximum possible amount (continuous flushing thoughout the year). This amount is also equal to the 73.5% of the amount that whould reach the outlet of the river, in the case of a continuous flushing event during the non-effective months of the year (period from May to October).

4. COMPARISON OF THE CONSIDERED SEDIMENT REMOVAL METHODS

In order to select the optimum of the two examined methods a comparison was conducted, by collecting the maximum amount of sediment that reach the outlet of river Nestos, that are attributed, if ist method is applied at ist optimum adentified month of the year: April for the application of mechanical sediment removal or dredging, and January for the application of flushing.

In order to calculate these quantities, a sediment discharge (dredging/flushing) much more greater than the previously used values of 35,000 tn for the case of dredging and 0.0135 tn/sec for the case of flushing, was assumed. In more detail, the mathematical model was further modified in order to take into account a sediment discharge of Q_s=289,200 tn and q_{sf}=0,1 tn/sec, since it was proven that for values, generally above 35,000 tn (approximatelly 0,0135 tn/sec for the case a flushing event with a duration of 30 days), the results of the simulations did not change. The results of the proposed comparison are summarised diagramatically in Figure 6.

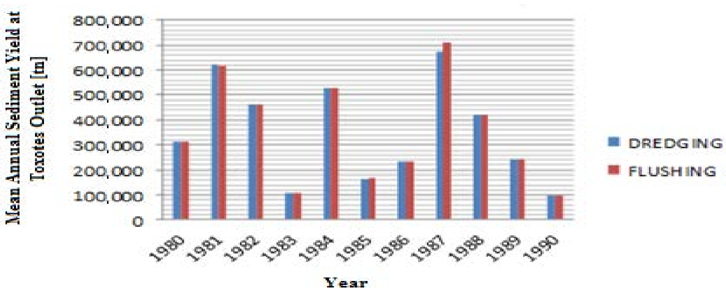

Figure 6: Comparison between dredging and flushing.

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It can be seen that flushing seems to perform slightly better than dredging but in a degree that can not be chosen as the optimum method. Therefore, in order to chose which is the optimal method, for the aim of the present investigation, other criterions, such as technical difficulties in their application as well as cost of application, should be taken into consideration.

5. CONCLUSIONS

In the present paper a previously validated and applied mathematical model [8] is modified accordingly in order to take into account the application of sediment dredging and flushing at a reservoir of river hydrological basin. The modified model is applied for the case of Nestos River (Greece) in order to identify the optimum sediment removal scenario at a certain reservoir (Platanovrysi reservoir) upstream of the considered river outlet (Toxotes outlet), in order to maximise the amount of sediment that reaches the delta of the river. In more detail, a wide series of parametric simulation scenarios is performed, aiming to identify the optimum periods that dredging and flushing can be applied. From the overall analysis of the simulation results, a definite classification of the months in “effective” and “ineffective” as well as to “consistent” and “inconsistent” with respect to the total amount of removed sediment that reach to the basin outlet is made. It is also found that the considered river has a maximum transport quantity of the removed material, regardless the further increase of the dredged and/or flushed sediment quantity from the identified limiting value. A comparison between the two considered methods, identified flushing to be slightly more effective than dredging. Finally, the overall results of the present investigation indicate, that the proposed modified mathematical model can serve as a quite effective and usefull tool that can be applied for similar investigations at various river basin worldwide and it could also be incorporated in the early design stages of new reservoirs that are going to be constructed, estimating the amount of sediment descharge that needs to pass through the reservoir in the downstream part of river basin in order to minimise the unavoidable deltaic and adjacent shoreline erosion.

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