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Hydraulic Modelling of Suspended Sediment Deposition in an Inundated Floodplain of the Nemunas Delta

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Floods of meadows in the delta of the river Nemunas contribute to the deposition and retention of sediments and nutrient that would otherwise deposit in the Curonian Lagoon. In grassland area of the Nemunas delta the formation of alluvial soil occurs according to the flood dynamic rules: water discharging into the valley leaves suspended sediments on the soil surface. By mathematical modelling it was established that about 35% of suspended sediments inflow deposited there. Due to sand particles deposited during the study period (1950-1991), the natural river bank levee rose by 0.3 m. Fine clay and silt particles deposited uniformly within the entire model area and formed a 4-6 mm thick layer there. It contained about 50-60 t/ha of silt deposits. The valley soils were naturally fertilized with 250 t of potassium, 950 t of phosphorus, 38,000 t of calcium, and even 147,000 t of organic matter saturated with nitrogen. Certain amount of heavy metals also deposited there.

The deposition process has not yet been adequately investigated under the conditions of flow bed covered by grass. It was established that grass cover intensified the sediment deposition in the floodplain. Considering calculation results and measurement data, the process of suspended sediment deposition was analysed and new formulas were derived. It was established that in order to increase sedimentation in the valley, it would be necessary to increase water discharge overflowing from river bed into the delta valley.

Introduction

Water quality in the Curonian Lagoon depends on water flowing into it from the Nemunas watershed area of 91,800 km^2. The river Nemunas is a great source of pollutants of the Lagoon, bearing nutrient (salts) and suspended agricultural sediments (wash load). Nutrients brought by the river with water and sediments caused such a violent explosion in algae populations that water plants started starving for lack of light and died (Maniukas 1959). The bottom of the deepest parts of the Lagoon was covered by silt and mud (Gudelis 1982; Pustelnikovas 1997).

Saline water flowing due to the strong west wind from the Baltic Sea into the Lagoon through the Klaipeda Strait makes less than 7.6% of fresh water inflow from Nemunas (Cervinskas 1959; Gailiusis *et al.* 1997). As a result, eutrophication problem is now getting very urgent in the Curonian Lagoon (Larsson *et al.* 1985). Thus, the impact of water condition of the Nemunas river on that in the Lagoon becomes dominant.

When water runs high in the river Nemunas, it overflows its banks and floods the meadows in the delta. This contributes to the sediment deposition and retention of nutrient salts and mud that would otherwise deposit in the Curonian Lagoon. Accumulation as well as erosion can occur in river flood plains. Accumulation processes prevail on flooded meadows. Alluvium is formed on soil in grassed area of the Nemunas delta. Water flowing into the valley is purified by leaving a sediment layer (Malisauskas and Sileika 2001; Gipiskis 2000; Vaikasas and Rimkus 1997).

Significant impact of sediment (mud) and nutrient (salt) retention was estimated by the elaboration of the restoration project in the Skjern river delta of the Ringkobing Fjord in Denmark. It was determined that depositing suspended sediments reduced the river's load to the Fjord by 6%, phosphate and iron loads were reduced by 12% and 25% respectively (The Skjern River Restoration Project 1999).

Thus, the retention of nutrients during the flooding of valley is positive for both soil fertilization and water quality improvement. Sedimentation process occurring in an inundated river valleys (and in the Nemunas delta) is many-facet. Old riverbeds, channels, and lakes remain in the valley. Some spots are turning into wetlands.

The volume and distribution of deposited sediment depend on floodplain relief, flow distribution, flood duration, dike density, vegetation, concentration of the suspended sediments, hydrological and other conditions. Thus, the investigations of processes occurring in the Nemunas delta were the purpose of our investigations. Results of this work are discussed in this paper.

Calculation Method for the Distribution of Flow Velocities and Deposits

The known sediment deposition calculation methods were elaborated for flow on a sandy bottom. In the case of flow on meadows there are other boundary conditions.

However, the same methods are employed in most recent hydraulic mathematical models. Consequently, we found it necessary to study the peculiarities of the flow and sediment motion under these conditions and develop equations for these calculations.

A quasi-2D model of slowly exchanging flow stripes with constant water discharge was created for the calculations of flow velocity distribution in the flooded meadows of the Nemunas delta (Rimkus and Vaikasas 1999). For our investigations the part of the Nemunas floodplain most efficient for sediment deposition was chosen, in which the field investigations of water turbidity were performed. Because of flat relief in this interval, flow stripes in this model were treated as one-dimensional ones. Excluding shear stresses between the flow stripes, the flow velocities can be calculated according to one-dimensional Saint-Venant equation:

$$v = C_{ch} \sqrt{h \left(I - \frac{v}{g} \frac{\partial v}{\partial l} \right)} \tag{1}$$

In this formula Chezy coefficient was calculated according to Manning:

$$C_{ch} = h^{1/6}/n \tag{2}$$

where v – depth averaged flow velocity; C_{ch} – Chezy coefficient; h – water depth; I – water surface slope; n – Manning coefficient; g – coefficient of gravity.

Change of water level between the adjacent cross-sections was calculated by iteration method. It was chosen so that the water discharge evaluated by integration of velocities calculated with Eq.(1) across the flow cross-section would be equal to the given water discharge. Thus the continuity equation was suitable as well.

$$Q = \int_{\omega} v \, d\omega \tag{3}$$

where ω – are of flow cross-section.

Subsequently, the whole water flow was divided into the flow stripes with equal discharge.

The suspended sediment deposition formulas for river beds area based either on concepts of transportable sediment concentration, bed shear stress critical for deposition, or critical flow velocity. To calculate sand particle sedimentation, the suspension transport capacity or transportable sediment concentration is usually applied:

$$D = \frac{q_s - q_{tr}}{q} w = \left(1 - \frac{C_{tr}}{C}\right) C w, \quad C_{tr} < C \tag{4}$$

where D – deposition rate per unit of the bottom area (kg/m^2/s); q_s – sediment flow rate per unit width; q_{tr} – sediment transport discharge per unit width; q – water flow discharge per unit width; C – actually existing sediment concentration; C_{tr} – transportable sediment concentration; w – sediment particle fall velocity.

In the case of silt and clay sediments, the formula containing the critical for sediment deposition flow velocity is usually applied:

$$S = \left(1 - \left(\frac{v}{v_{cr}}\right)^2\right)\frac{Cw}{h_*}, \qquad v < v_{cr} \tag{5}$$

where S – reduction of sediment flow rate caused by sediment deposition (kg/m^3/s); v_{cr} – average stream velocity critical for sediment deposition, h_* – distance from the bottom to the center of sediment weight.

When applying Eqs.(4) and (5), one must know the effective sediment transport capacity of the flow. A lot of different formulas have been proposed for the calculation, because q_{tr} depends on a number of factors that form the flow structure. Besides, these factors vary depending on different conditions. The transport capacity or transportable sediment concentration of suspended sediment can be calculated applying the known methods (Bagnold 1966; Van Rijn 1984, 1993; Karaushev 1969; Velikanov 1958; Young *et al.* 1987; Yang 1973; Grishanin 1969; Chanson 1999).

Using these formulas for meadow flows, calculated sediment deposition values do not coincide with the measurements. The reason is that flow conditions near the bottom in riverbed and in flood plain under grass are different.

Stream velocities are low in-between the grass of flooded meadows, and each sediment particle settles down when it gets in-between the vegetation. Thus, the ability of grass to entrap the sediments is revealed. As a result, sediment deposition takes place even when the flow velocities are rather high and sediment concentration is low. Therefore, the concept of transportable concentration or critical stream velocity cannot be used for calculation due to certain sediment deposition, which always takes place in the meadows. The term in brackets of Eqs.(4) and (5) evaluating the flow saturation with sediments cannot be applied. Instead, it is necessary to include a factor that estimates mixing capacity of the flow, as the sediment deposition can be reduced and sediment can be transported only due to a mixing process caused by turbulence. Sediment deposition is proportional to their concentration and fall velocity. Such relationship can be expressed by the following formulas proposed by A. Rimkus (Rimkus and Vaikasas 1999):

$$D = k_{mix} C w \tag{6}$$

$$k_{mix} = \frac{1}{1 + k(u_*/w)} \tag{7}$$

where D – deposition rate per unit of bottom area; C – the existing sediment concentration; u_* – shear velocity; k_{mix} – factor defining the mixing process; k=0,00018 – empirical coefficient.

The ratio of velocities u_*/w is found in all formulas used for the calculation of transportable suspended sediment discharge. It is great help when estimating the mixing capacity.

Both Eqs. (6) and (7) can be used for mud (silt and clay) as well as for sand particles. Difference in the behavior of these particles can be estimated by calculating their fall velocity by different formulas (Van Rijn 1993; Maidment 1992).

Model Calibration

We have investigated and modelled the upstream of the Nemunas delta, which is a watershed of the river Gege (Fig.1). This part of the delta has been chosen because of the fact that here the flow length makes up to 24 km in the inundated valley and this section is long enough for clay particles to deposit.

Major part of the sediments brought into the Nemunas delta deposit there. According to the data of our field investigations (the study period covered the years 1987-1996), there were about 1.71-17.56 t/ha of sediment deposited within the watershed of the river Gege per year (at the distance of 50 km from the Nemunas mouth) (Katutis 2002; Vaikasas and Rimkus 1999; Vaikasas 2001). Meanwhile, this amount decreased to 0.79-1.45 t/ha in the cross-section that was located at a distance of 24 km from the river mouth. In profile near the river Sysa, which was 10 km away from the river mouth, it decreased even to 0.48-0.83 t/ha. This clearly illustrates the efficiency of deposition near the tributary of the river Gege.

Valley interval used for the calibration, water sampling posts and their numbered cross – sections and flow strips used for computing are shown in Fig. 2. The turbidity measurements were taken during the spring flood of 1996.

Measured turbidity values of 38 mg/l defined at the flow entering the valley (at cross-section XXI), turbidity values of 17.4 mg/l measured in the valley bridge orifice (at the second strip of cross-section XVI), and the average turbidity values of 12.2 mg/l measured in the main part of cross-section III (5 measurement points) were used for calibration.

Eq.(4) was tested by applying Zamarin's formula for the calculation of transportable sediment concentration (Grishanin 1969):

$$C_{tr} = 0.022 \frac{v}{w_0} \sqrt{\frac{Riv}{w}} \tag{8}$$

where C_{tr} – transportable sediment concentration kg/m^3; v – average stream velocity m/s; R – hydraulic radius m; i – energy gradient;

$w_0 = 0.002$, when $w < 0.002$ m/s (for silt and clay);
$w_0 = w$, when $w \geq 0.002$ m/s (for sand).

According to this formula, no sediment deposition occurred in the Nemunas delta valley during this flood. However field measurements indicated certain sediment

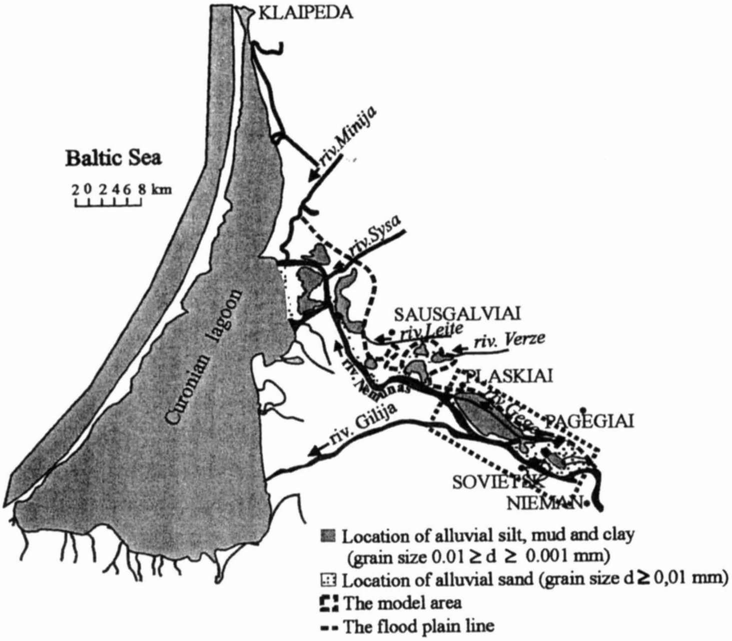

Fig. 1. Scheme of flood plain of the Nemunas delta and the Curonian Lagoon (The model area is indicated by a rectangle).

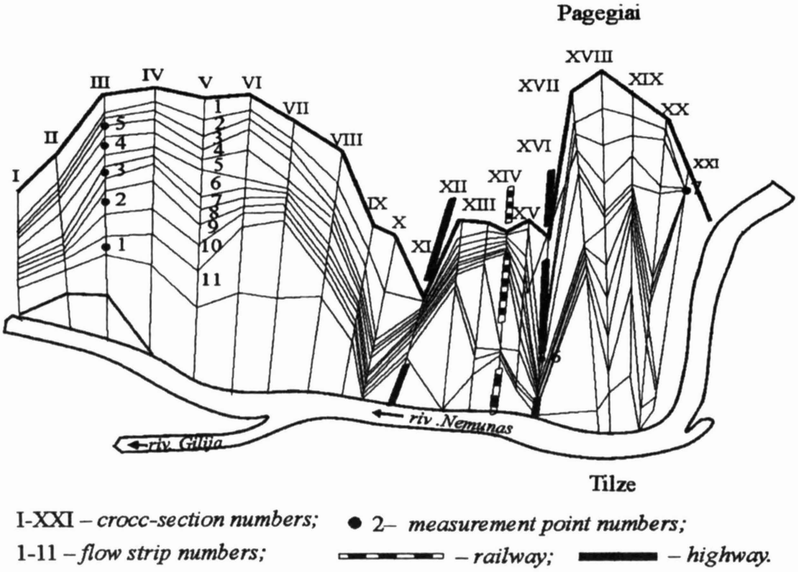

Fig. 2. Distribution of flow lines and sedimentation process of suspended sediment according to the mathematical model developed for spring flood on April 11th, 1996 (V.L. altitude z= 7,71m; Q_{sl} = 700 m^3/s).

deposition. This was due to the fact that transportable concentration C_{tr} calculated by Eq.(8) was greater than the actual one existing in the flooded valley.

To check Eq.(5) usually applied for silt and clay particles (only such particles were observed in our case), critical deposition velocity v_{cr} can be calculated as follows:

$$v_{cr} = 1.25\, w \frac{h^{1/6}}{n\sqrt{g}} \tag{9}$$

When applying these formulas, no sediment deposition was noticed either. Thus, test results showed that formulas confirmed for the flow in riverbeds should not be used for the flow in flooded meadows, where sediment deposition is much greater.

Suitability of Eq.(4) for sediment deposition calculation was also checked by applying Bagnold's formula adjusted by R. A. Young (1987) to calculate sediment deposition in small channels and in concentrated storm water streams from agricultural fields:

$$q_{tr} \equiv \frac{\eta k \tau v^2}{w} \tag{10}$$

where q_{tr} – effective sediment transport capacity, kg/s m; η – effective transport factor; k – transport capacity factor; τ – shear stress, kg/m^2.

$$\eta = 0.74 \left[\frac{(\gamma_s - \gamma_w)\, d}{\tau} \right]^{1.98}, \qquad k = 0.001 \tag{11}$$

where γ_s and λ_w – specific weight of sediment and water, kg/m^3; d – particle diameter, m.

We expected the conditions in agricultural field for which these formulas were made to be similar to flooded meadows. Consequently, applying Eqs.(10) and (11), the sedimentation process should also be confirmed in the delta valley. Calibration was performed by estimating the composition of sediment fraction brought by the river stream into the valley. The composition was chosen so that the calculated concentrations would be equal to the measured ones in cross-sections and points along

Table 1 – Sediment concentration values in cross-sections XVI and III as determined by calibration according to Eqs. (4), (6), (7) and (10), mg/l.

Cross-section XVI	Cross-section III	Notes
17.4	12.2	Measured during the 1996 flood
17.4	12.2	Calibration by Eqs. (6) and (7)
17.4	7.3	Calibration by Eqs. (4) and (10), variant 1
25.2	12.2	Calibration by Eqs. (4) and (10), variant 2

the valley stream. Only applicable formulas can satisfy this requirement.

Turbidity values measured and calculated by calibration are compared in Table 1. As it is seen, only applying our Eqs.(6) and (7) the calculated turbidity values in both sections III and XVI were obtained to be equal to the measured ones. Using Eqs.(4) and (10), these values could be received equal only in one or the other of two mentioned sections. In the other section these values turned out to be different. In Table 1 these cases are shown as two variants. This was because these formulas were invalid under the conditions of flooded meadows either.

Thus the application of our formulas allowed us to obtain equal calculated and measured turbidity values in all floodplain sections. When applying another Eq. (10), these values were obtained to be different from the actual ones because this formula is not valid for water flow over the grassed bottom.

Modelling Results and Discussion

By the calculations of the flood sediment deposition made for 42 years, it was established that water had left 2.25×10^6 t of sediment within the study area in this period. This sediment amount deposited in the flooded area of 16×10^3 hectares in a watershed of the river Gege (Fig. 1). It contained on the average about 14.3 kg/m^2 of deposited silt, clay and sand particles. Since the bulk density of this dry soil was 1.30 t/m^3, it made up a layer of only 1.0-1.1 cm thick. That was not essential in view of the relief changes, but such deposit volume decreased water turbidity in the Curonian Lagoon. Besides, both tiny clay and silt particles were capable of absorbing various nutrients and heavy metals. Thus, the transportation and sedimentation processes of these contaminants were proportional to those of fine sediments. Consequently, the volume of this matter brought in with silt and deposited within the delta can be calculated. There are 0.11 kg K_2O; 0.42 kg P_2O_5; 17 kg Ca, and 65 kg of organic matter per deposit ton on the average (Vaikasas *et al.* 1999). Thus, the valley area was naturally fertilized with 250 t of potassium, 950 t of phosphorus, 38,000 t of calcium and even 147,000 t of the organic matter saturated with nitrogen over the study period of 42 years. The maps on both the distribution of heavy metals and deposition of tiny clay and silt particles were found very similar and comparable (Gipiskis 1999).

When comparing the amount of various kinds of sediment deposited during different flood periods to the run-off of suspended sediments measured in the Hydrometeorological station, it was established that the deposited suspended sediment discharge made up about 35% of suspended load of sediments transported by the river Nemunas (Fig. 3).

The analysis of the sum of sediments showed that the largest deposited sediment amount (752,000 t) was observed in 1958. Rather large amounts of sediment de-

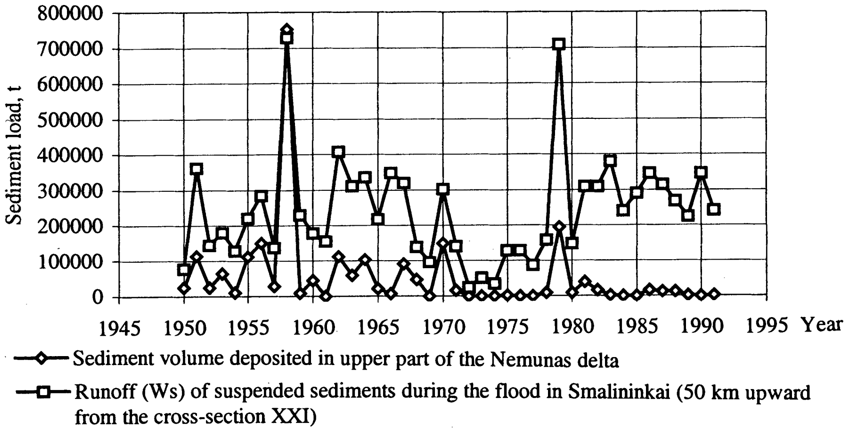

Fig. 3. Comparable amount of sediments deposited within the study area in the Nemunas delta during spring floods in 1950 – 1991

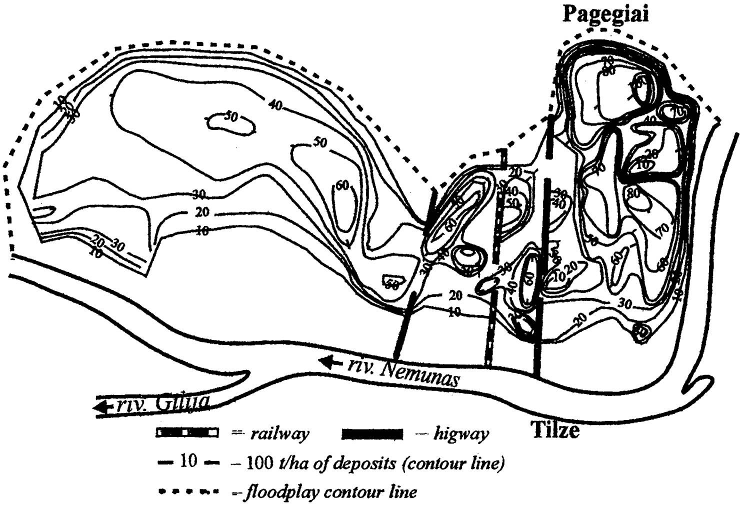

Fig. 4. Distribution of sediment of clay fractions deposited in the upper part of the Nemunas delta during spring floods in 1950-1991, t/ha (results of mathematical modelling).

posited in the years 1979, 1956, 1970, 1962, 1955, and 1964. This was the result of water discharge and floodwater turbidity, which coincided with the flood peaks. During the years less abundant in water – in 1961, 1969, 1972, 1973, 1974, 1976, 1977, 1984, 1985, and 1990 – the valley was not inundated.

The largest total amount of sediment with different particle size (1000-3000 t/ha) deposited near the natural mound near section XX. Such a large sediment amount was caused by fine sand and large aggregate particles.

Thus our modelling demonstrates the process of filling the bank levee by sand sediments when the river overflows its banks. Both fine clay and silt particles deposited much more uniformly.

The mentioned fine particles deposited more intensively in the areas where the major current was slower. Therefore more sediment deposited in deeper spots. Deposited clay amounted to about 50-60 t/ha in the entire area over the study period (Fig 4). Silt particles deposited more unevenly: about 200 t/ha of silt particles deposited in the upstream part, while downstream this amount varied from 100 t/ha to 80 t/ha. Thus, twice as much of silt sediment deposited in the upstream part of the Nemunas delta. More fine clay and silt particles were found downstream; therefore soil texture was somewhat better improved.

A mathematical model was also employed to select some factors that show how to increase the sedimentation in the valley. It was estimated how much the sediment amount would increase if the water discharge entering the valley would be increased. This could be achieved either by removing and/or cutting out bushes from the flow entrance point on the bank section or by making this bank section lower in some areas.

In view of our modelling data, we can see the importance to investigate the intensified sedimentation process occurring in grassed floodplains of rivers. This can be done by the means of proposed formulas.

Conclusions

1) Having derived formulas for the calculation of suspended sediment deposition in grass covered floodplains and having created a mathematical model "Delta" for the investigation of flood performance, we established that about 35% of suspended sediments carried down by hydrometric station at Smalininkai deposited in the investigated part of floodplain of the river Nemunas, containing a watershed of the river Gege. These sediments have a fertilization effect on the soil of the valley and they do not enter the Curonian Lagoon.
2) It was established that about $2.25\text{x}10^6$ t of sediment deposited in the modelled section during the study period in 1950-1991. Most of sediments are deposits in the form of sand, clay and small aggregates during great floods of 1-3% probability, when more than a half of flood water flows down the valley. The greatest amounts of sediments (about $75\text{x}10^4$ t) deposited in 1958.
3) Sand particles deposited near the riverbanks. Fine clay and silt particles deposited in the entire model area and formed about 4-6 mm thick sediment layer. It contained about 50-60 t/ha of silt sediments.
4) The increment of water discharge entering from riverbed into the flood plain of delta would effectively increase the amount of sediments depositing in the valley.
5) Flood plane meadows of rivers significantly increase the deposition of suspended sediment. Therefore, their existence and extension are to be estimated by suspension transport calculations.

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