Full Length Research Paper

Apprehending the potential effect of sediment deposition due to dredging in Laonong River upstream, Southern Taiwan

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The use of dredging at an appropriate location is a common practice introduced to maintain the flood capacity and the safety of the bridge. The effective zone and characteristics of sediment transport after dredging are important issues that need to be investigated. This study analyzes the fluvial processes in a selected river, Laonong River, by using the NETSTARS numerical model. The hydrodynamic behavior and sediment transport under flood of different return periods are investigated. The results show that Laonong River remains the trend of deposition in the present condition. The deposition accumulates at the upper reach, as the Laonong River is divided into the lower, middle and upper reaches. Great variation in the volume of deposition is observed at different reaches while different dredging locations are applied. However, the upper reach has a steady trend of deposition and is the main segment of deposition. Scenarios of dredging with different lengths and depths at different reaches are analyzed. From the comparison results, it is concluded that the effectiveness of dredging is influenced by the volume of deposition under the circumstances of this study site, in Southern Taiwan. Furthermore, it is also found that dredging at the lower reach is the most effective method for reducing the sediment deposition in the river.

Key words: Dredging, sediment transport, deposition potential, NETSTARS.

INTRODUCTION

The hydraulics and sediment behavior of river bed in alluvial channels has been studied using numerical approach during the past decades (Bennet and Nordin, 1977; Yang and Molinas, 1982; United States Army Corps of Engineers and Waterways Experiment Station, 1996; Lee et al., 1997; Lee and Hsieh, 2003; Zeng and Beck,

2003; Shih et al., 2008). However, many key factors related to physical phenomena such as no uniformity of sediment and simulating techniques, still need further survey and research. According to Wang and Traore (2009), the hydrological characteristics of the Laonong River such as sediments concentration, change temporally and spatially and therefore are difficult to estimate.

To ensure flood safety goal, generally, dredging method is used to increase the flow section area and for reducing flood level. However, it would be possible to

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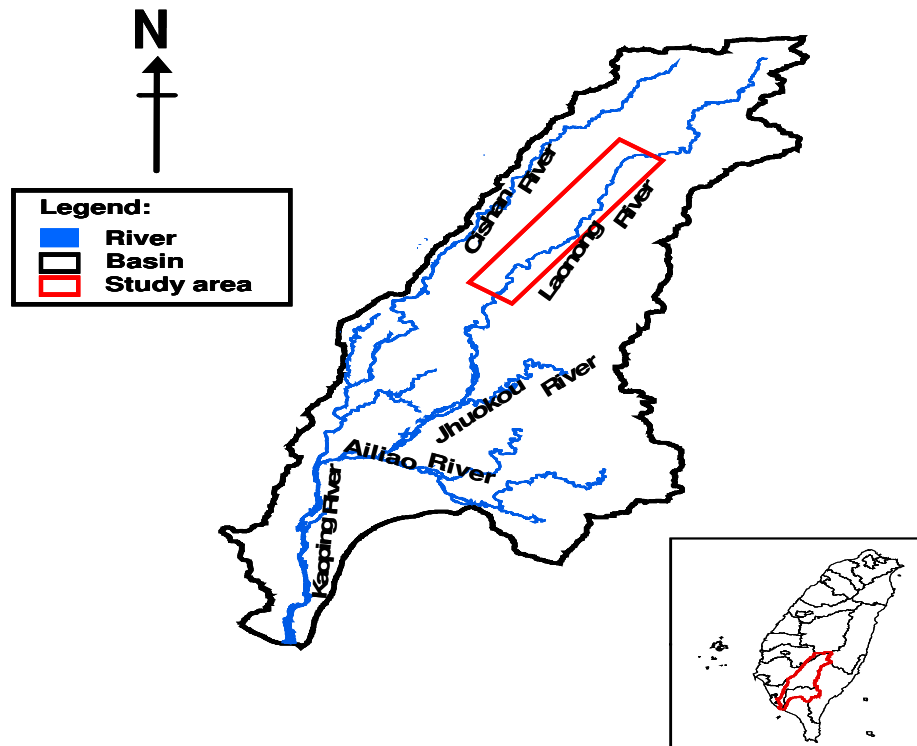
Figure 1. Location map for Laonong River.

make the original balance of the river erosion and deposition future, change after dredging. When dredging proceeds in the lower reaches of the river, it results in excessive deposition due to relying on the upper reaches of the sand volume increases. On the contrary, dredging in the upper reaches of the river, promotes the sediment transport capability due to the increasing flow section area and faster flow velocity on the lower reaches. Therefore, dredging of the river after the impact to explore the river bed, in terms of stability, is an important issue. The most recent example, the rainfall of typhoon Morakot, has reached 2,000 mm which caused serious disaster including instantaneous rainfall overflow, debris flow and bloated stream in this research region on August 8, 2009.

A quasi-two-dimensional hydrodynamic and sediment transport model in alluvial channels was adapted and applied to the Laonong River system in southern Taiwan, while the numerical model was calibrated and verified with the observed water level and bed elevation. The paper presents the model application with emphasis on the management scenarios for deposition variation, under numerous hydraulic conditions.

Study site

The Laonong River is one of the three major tributaries of the Kaoping River (Figure 1) and has a continuous flow year-round. The Kaoping River is the largest and most intensively used river basin in Taiwan. The drainage area of the entire Kaoping River basin is about 3,625 km^2 and has a total channel length of 171 km. It consists of three major tributaries: the Cishan River, Laonong River and Ailiao River.

The Laonong River has a drainage area of 1,372 km^2 and a total length of 136 km. The annual mean rainfall is 2550 mm, 90% of which is concentrated in the months of May to September. It primarily supplies irrigation water demand and serves as water supply for Kaohsiung metropolitan (the second largest city in Taiwan). The bed gradient ranges from 0.0016 to 0.022, due to relatively steep slope in the upstream and midstream reaches of the Laonong River watershed. Therefore, the river flows fast and with a relatively strong sediment transport. As such, it is referred to as a rapid flow river type.

Model description

A quasi-two-dimensional numerical model (Network of Stream Tube Model for Alluvial River Simulation, NETSTARS) was developed by Lee et al. (1997). NETSTARS is an uncoupled sediment routing model and it consists of a hydraulic routing section and a sediment routing section. Suspended load and bed load are treated separately in sediment routing.

However, a network algorithm was proposed to solve the nodal point problem. As such, the flow discharge at the nodal point has to satisfy the continuity equation, that is, the summation of the inflow and outflow discharges from all the tributaries at a nodal point must

be zero or there is no storage at the nodal point.

Hydraulic equations

The de Saint Venant equations are used in the unsteady flow calculation, including a continuity equation and a one-dimensional momentum equation. The governing equations are expressed as:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\alpha \frac{Q^2}{A}\right) + gA\frac{\partial y}{\partial x} + gAS_f - \frac{Q}{A}q = 0 \tag{2}$$

Where A = channel cross-sectional area, Q = flow discharge, t = time, x = coordinate in the river direction, q = lateral inflow/outflow discharge per unit length, α = momentum correction coefficient, g = gravitational acceleration, y = water surface elevation, Sf = friction slope, K = channel conveyance, n = roughness coefficient of Manning's formula and R = hydraulic radius.

Sediment transport equation

Most of the sediment routing models, adopt the total load equations to calculate the sediment transport capacity and thus can only be applied to the equilibrium conditions. To reveal the deposition characteristics of the suspended sediment in a non-equilibrium flow condition, separate treatment of the suspended load and bed load is necessary.

In the NETSTARS model, the governing equations for sediment routing consist of a sediment continuity equation, a sediment concentration convection-dispersion equation and a bed load equation. The sediment continuity equation is shown as:

$$(1-p)\frac{\partial A_{dt}}{\partial t} + \frac{\partial}{\partial x}\sum_{k=1}^{N_{size}}(q_t C_k) + \frac{\partial Q_b}{\partial x} = 0 \tag{3}$$

Where:

Qb = bed load transport rate, qt = flow discharge, Ck = depth-averaged concentration of the suspended sediment of size fraction k, Adt = amount of sediment scouring/deposition per unit length and p = channel bed porosity. The concentration, Ck is calculated using the convection-diffusion equation which is expressed as:

$$\frac{\partial(C_k A_t)}{\partial t} + \frac{\partial}{\partial x}(C_k q_t) = \frac{\partial}{\partial x}\left(A k_x \frac{\partial C_k}{\partial x}\right) + S_k + \left(h k_z \frac{\partial C_k}{\partial z}\right)\Big|_r^t \tag{4}$$

Where:

kx and kz = longitudinal and transverse dispersion coefficients, At = area across stream tube, h = flow depth and Sk = source term of the suspended sediment of size fraction k.

Hydrologic data collection

Sources for the field hydrological data gathered include, channel geometric cross-section, inflow discharge, upstream inflow suspended sediment concentration and rainfall of watershed, providing data for NETSTARS model input.

For this study, the channel geometric cross-section data collected for the Laonong River was collected by Taiwan WRAMEA (Water Resources Agency, Ministry of Economic Affairs) in 2002 and 2007. Inflow discharge data were collected from the Sinfa bridge station while rainfall of watershed data, was collected mainly by Taiwan CWB (Central Weather Bureau). Due to lack of field data, the upstream inflow suspended sediment concentration versus the inflow discharge rating curve was obtained from the Sinfa bridge station. Figure 2 shows the rating curve of the flow and suspended sediment at the Sinfa bridge station from June, 1965 to December, 2005. The regression equation of the rating curve is Qs = 1.338Q1.930, and is used for the upstream boundary condition. Qs is the suspended sediment concentration (ton/day), while Q is the inflow rate (m³/s). In addition, delivering field sampling at the Sinfa bridge station upstream, there is an awareness of the in-site Manning's coefficient of the Laonong River.

The Strickler, Meyer-Peter and Muller, Keulegam, Einstein, Lane and Carlson's empirical formula were used to calculate the Manning's coefficient (Meyer-Peter and Muller, 1948; Yang, 1996). According to grain size analysis results, the maximum sediment size distribution range is from 75 to 365 mm and the Manning's friction coefficients were from 0.026 (by Einstein equation) to 0.032 (by Lane and Carlson's equation). However, the n = 0.032 was used to simulate the hydrodynamic and suspended sediment in this study.

RESULTS AND ANALYSES

Water level calibration and sediment transport equation

The hydrodynamic model was calibrated from 2 July to 5 2004 and the data were surveyed for 96 h (that is, mindulle typhoon) and as such, n = 0.032. The Manning's coefficient is a key parameter in the hydrodynamic calculation, characterizing the bottom friction in the channel that affects the calculated water level. The measured water level data from the gauging station at Sinfa Bridge were used to calibrate the Manning's coefficient value of this model.

The water level model results and field observation at Sinfa Bridge station is shown in Figure 3. In addition, n = 0.045 can also be used to simulate water level, in that the n value came from the research report at the Laonong River of Taiwan WRAMEA in 2001. The model results and field observation of the water level are also shown in Figure 3. In general, the model results are in reasonable agreement with the measured temporal distribution of the water level.

A qualitative evaluation of the model calibration can be made by the statistical errors and the coefficient (r2) of the least-square method is selected to quantify the results. The coefficients of the differences between model results and field measurements are 1.25 and 1.23 m for n = 0.032 and n = 0.045, respectively. Therefore, the Manning's coefficient is calibrated to be 0.045, due to less r2 in the study. In addition, the Yang's sediment transport equation (Yang, 1973) is utilized to simulate the deposition of bed elevation and as such, the stream tube is set to 3 and the scour depth is set to 0.4 m for the
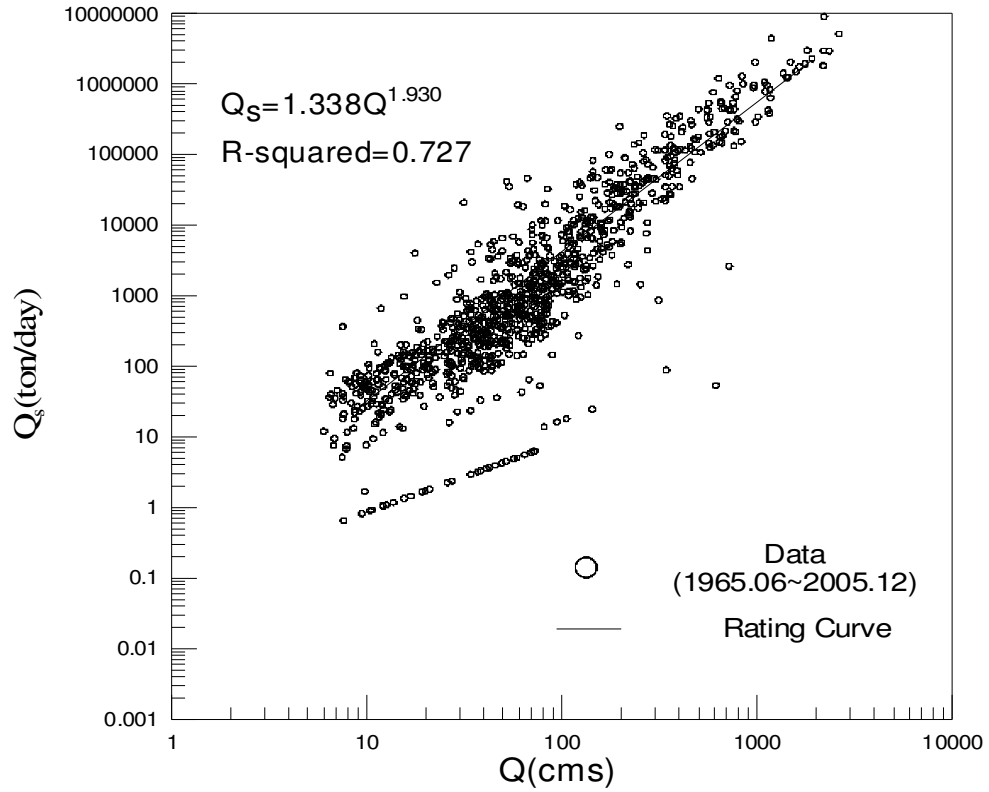
Figure 2. Rating curve of the flow and suspended sediment at Sinfa Bridge for the Laonong River.
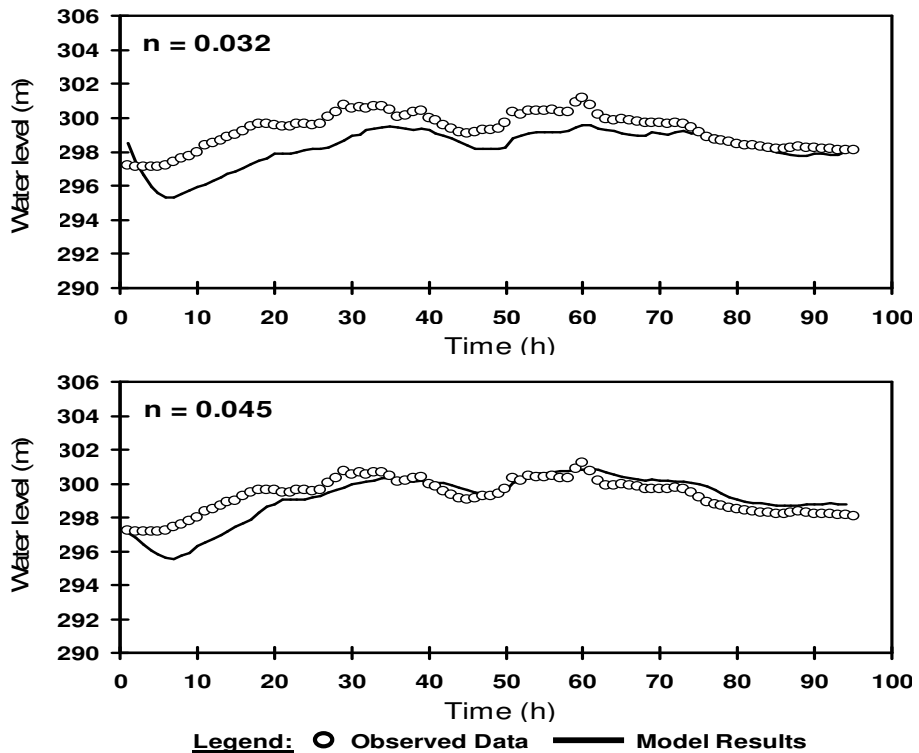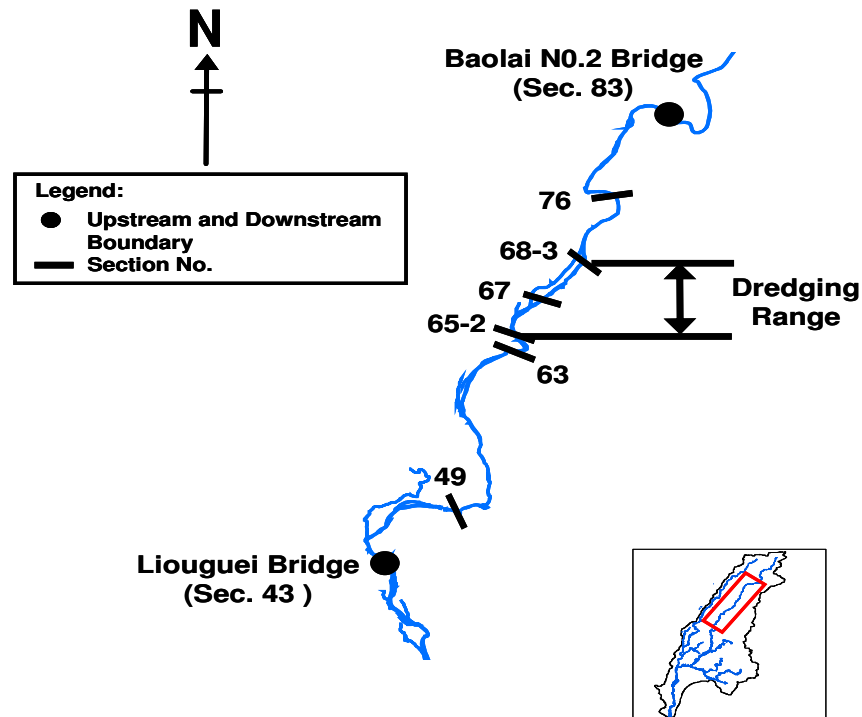

Figure 3. Hydrodynamic model results for water level at Sinfa Bridge for Laonong River.

Figure 4. Model domain of hydrology and sediment transport simulation, as well as dredging location for Laonong River.

suspended sediment model.

Upstream and downstream boundary

The hydrodynamic and suspended sediment simulation domain is presented in Figure 4. The upstream and downstream boundary is at Baolai No. 2 Bridge (Section 83) and Liouguei Bridge (Section 43), respectively. As such, the channel length is about 18.6 km from the upstream to downstream boundary.

The driving force of this model includes the flow and water level for upstream and downstream boundary conditions, respectively. In this study, upstream boundary flow was derived from the Sinfa Bridge gauging station. The peak discharge is 5,431, 6,238, 7,189 and 7,842 m³/s for 10, 20, 50 and 100 year return period storm, that occurred respectively, supporting the input flow for upstream boundary condition. The downstream boundary condition is obtained from the recorded real-time elevations at Liouguei Bridge gauging station, and as such, the water level are 238.87, 239.38, 240.01 and 240.45 m for 10, 20, 50 and 100 year return period.

Deposition verification

This scouring did not occur when the flow was less than 100 m³/s in this study. Figure 5 shows the depositing verification results of bed elevation at Sinfa Bridge upstream for the Laonong River in 2007. The model results are in reasonable agreement with the measured spatial distribution of the bed elevation's deposition. The accuracy of the model is considered acceptable, for the model projection analysis and evaluation of future deposition potential management strategies.

Model projection

The calibrated and verified model was used to perform the simulation of hydrodynamic and bed sedimentation, under various hydrological conditions. It would also be used to predict hydraulic pattern and scouring change, after different dredging depth and length condition in the future. Table 1 shows the nine projection scenarios, while the dredging area location at section 65.2 to 68.3 and length of 1.6 km are also provided in Figure 4.

When the dredging depth changes for sections 65.2 to 68.3, 65.2 to 67 and 67 to 68.3, the water level and Froude number remains relatively constant at the dredging section upstream (that is, at section 68.3 to 83). However, the water level reveals that dredging was slightly raised and Froude number remains relatively constant at dredging section downstream (that is, at section 68.3 to 43). At the dredging section, the water
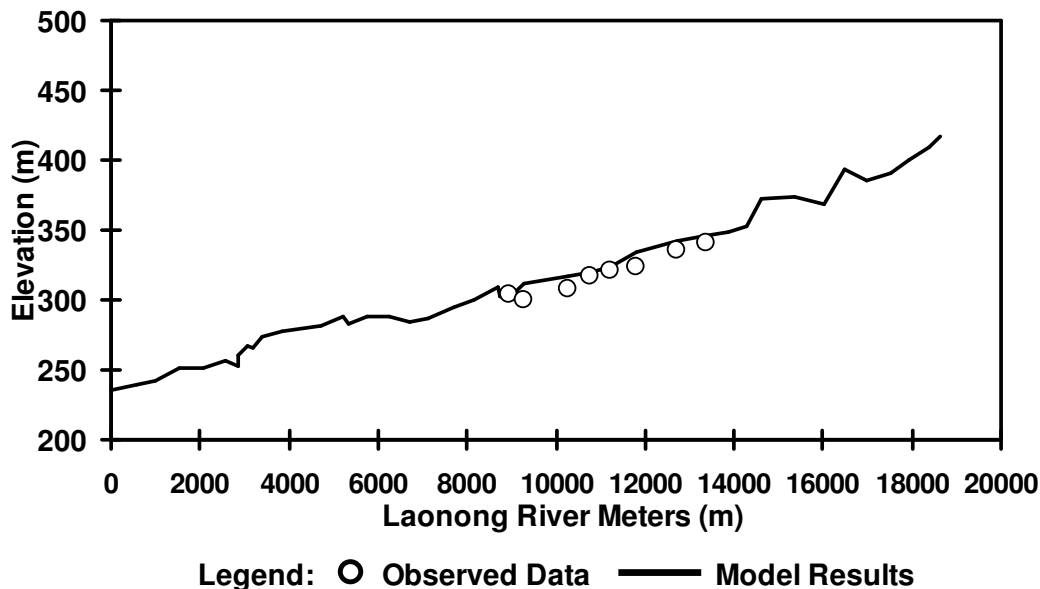
Figure 5. Simulated results of bed elevation for Laonong River.

Table 1. Scenarios of hydrodynamic and sediment transport simulation for Laonong River.

Scenarios	Dredging length (km)	Dredging depth (m)	Dredging average width (m)	Dredging section
1	1.6	1.5		65.2-68.3
2	1.6	2		65.2-68.3
3	1.6	2.5	240	65.2-68.3
4	0.8	1.5		65.2-67
5	0.8	2		65.2-67
6	0.8	2.5	266	65.2-67
7	0.8	1.5		67-68.3
8	0.8	2		67-68.3
9	0.8	2.5	214	67-68.3

level and Froude number were decreased with dredging depth. Nonetheless, the low Froude number is relative to the flood level and as a consequence, it reduced the flow velocity. Model results of water level and Froude number due to dredging depth variable for the Laonong River are shown in Figure 6.

When the dredging length changes for section 65.2 to 68.3, 65.2 to 67 and 67 to 68.3, the water level and Froude number still remains relatively constant at dredging section upstream. At the same time, the water level shows that dredging is slightly raised for scenario 7 and slightly decreased for scenarios 1 and 4 at dredging section downstream. In addition, the Froude number remains relatively constant. At the dredging section, the water level decreased with dredging length and the Froude number fluctuated for three scenarios. Figure 7 shows the model results of water level and Froude number due to dredging length variable for the Laonong River.

According to sediment transport prediction results, the deposition amount variables of the Laonong River are summarized in Table 2. In general, deposition amount increases with the dredging depth of 2 m and decreases with the dredging depth of 1.5 m. As such, the total deposition amount is about 2.4×106 m^3. In the up-mid reach, it accounted for 77% and about 1.85×106 m^3 of the total deposition amount.

SUMMARY AND CONCLUSIONS

A quasi-two-dimensional hydrodynamic and sediment transport model (NETSTARS) is applied to study the fluvial processes of Laonong River, Taiwan. However, a
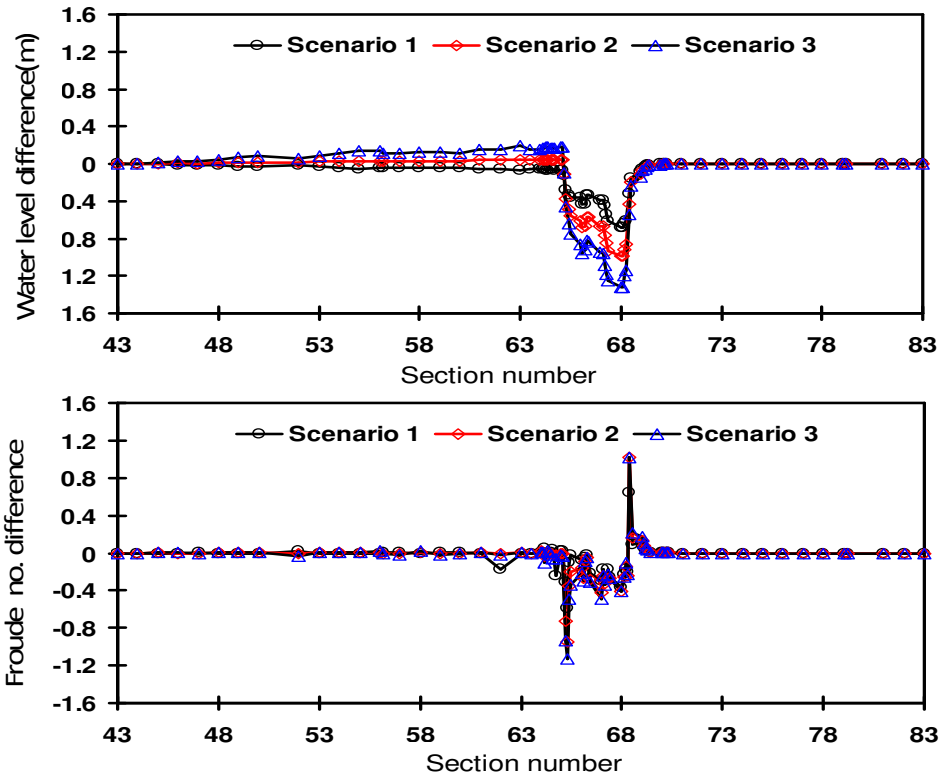
Figure 6. Model results of water level and Froude number due to dredging depth variable for Laonong River.
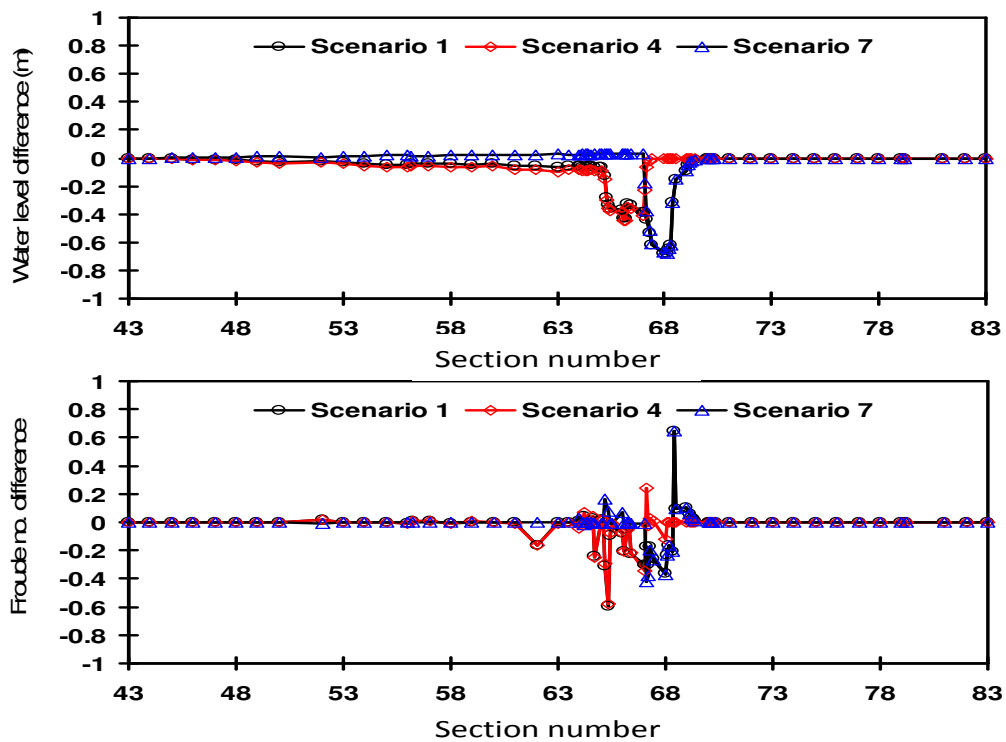

Figure 7. Model results of water level and Froude number due to dredging length variable for Laonong River.

Table 2. Results of deposition amount variables of sediment transport simulation for Laonong River.

Scenarios	Deposition amount (m^3)	Dredging length (km)	Dredging depth (m)	Dredging section
0	2,399,805	-	-	-
1	1,852,295	1.6	1.5	65.2—68.3
2	2,244,110	1.6	2.0	65.2—68.3
3	2,595,561	1.6	2.5	65.2—68.3
4	1,490,703	0.8	1.5	65.2—67
5	3,033,766	0.8	2.0	65.2—67
6	2,725,844	0.8	2.5	65.2—67
7	1,026,949	0.8	1.5	67—68.3
8	2,416,740	0.8	2.0	67—68.3
9	2,335,226	0.8	2.5	67—68.3

set of calibration and verification procedures of water level and suspended sediment is presented and as such, satisfactory model results were obtained. It is proven that the model is capable of predicting sediment transport, scour and deposition behaviors under different hydraulic conditions.

Scenarios of dredging at different areas of Laonong River are analyzed. From the results, it reveals that the river studied will continuously remain as sediment deposition status while the river management remains the same as present. And, the main deposition area will be at the upper stream which is about 77% of the total deposition amount. The study also shows that the change of sediment deposition due to dredging is more stable in upper stream than middle and down stream of the dredging area. Besides, applying dredging, it is found the Forude value decreases to lower than 1 in most of the sections. Thus, one can conclude that dredging is an effective method for lowering velocity and water level in the practice of river management. As a result, the model suggests dredging at the lower reach is the most effective method than dredging at different areas of the river.

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