Accounting for river morphology in the management of Red River (VietNam): a numerical modeling approach

CONFERENCE PAPER · APRIL 2014

ACCOUNTING FOR RIVER MORPHOLOGY IN THE MANAGEMENT OF RED RIVER (VIETNAM): A NUMERICAL MODELING APPROACH

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Abstract

During last 15 years, the Red River in northern VietNam has experienced severe river bed degradation along its lower course. The continued decrease of the minimum water levels aggravated water scarcity for agriculture. These outcomes can be attributed to strong in stream sediment mining, major upstream impoundments, climatic and land use changes. The aim of this work is to provide a valuable tool to assess the effects of different reservoir water releases and sediment mining policies on river reach morphology. A 1D mobile bed finite volume numerical model has been set up and preliminary results on the recent 2000-2009 period are presented and discussed. The model features facilitate its integration in optimization algorithms devoted to water management strategies.

Keywords: river morphology; mobile-bed numerical modelling; river basin management.

1. Introduction

Red River (*Song Hong*) rises in Yunnan province (China) and flows south-east towards VietNam and the Tonkin Gulf. Its total length is 1140 km and the total basin area is 157,000 km^2. Red River is actually named *Thao* up to the confluence with Da and Lo tributaries, located close to Viet Tri. Immediately upstream the VietNam capital, HaNoi, a large bifurcation with Duong River partially diverts the flow towards the city of Pha Lai. The lower course ends in a wide delta and is surrounded by many large and populated agricultural districts. Our study area is a 82 km long reach of the Red River, from the gauging station of Son Tay to the village of Phu Minh, located approximately 40 km downstream HaNoi (Figure 1)

The management of Red River basin has to take into account a large number of conflicting socio-economic issues. Instream sand mining is deeply affecting river morphology enhancing the bed incision process. Water releases from big reservoirs in the upstream catchments (*Thac Ba* on Lo river and *Hoa Binh* on Da river) are planned to maximize the hydroelectricity production, but still trying to reach the minimum water levels required for rice production in the low-lying delta area.

The reservoirs also act as flood control structures, and significantly alter sediment supply downstream and consequently river equilibrium (Kondolf, 1997; Dang *et al.*, 2010). At the gauging stations of Son Tay and HaNoi a strong decrease of the minimum water levels has been recorded from 2000 on. The noticeable acceleration in bed degradation is a danger for agriculture water supply as well as for infrastructure stability.

This paper deals with a physically based hydrodynamic-sediment transport numerical model capable of considering natural channel geometry, suitable for the integration of the understanding of river morphology evolution in the river management decisions planning (Bernardi *et al.*, 2013). Such attempts seem still rare in the literature, (see Nicklow and Mays, 2000) probably due to the high computational costs and limitations of physically based models. This work is propedeutical to the integration of the proposed model in an optimization framework.

First, the main features of the numerical model are described. Afterwards, a validation of the model taking advantage of the data series and topographical surveys available for the period 2000-2009 is carried on. In parallel, a sensitivity analysis of both main anthropogenic factors on river morphology, reservoir releases and sediment mining, is performed. Results of these early-stage simulations are then discussed and further developments of the research are listed.

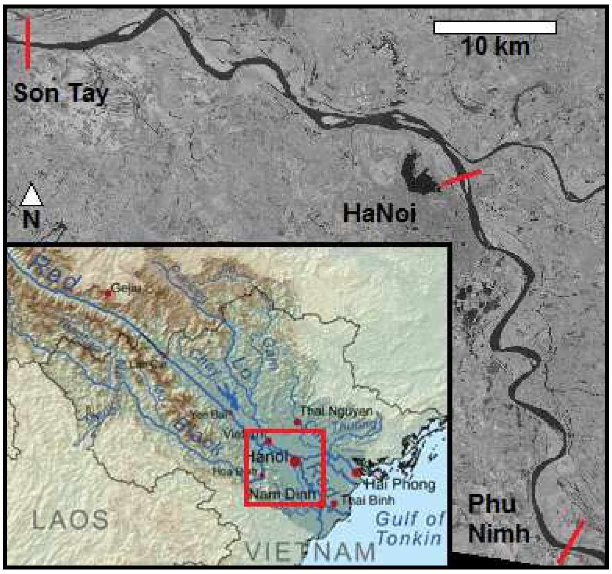

Figure 1. Lower course of Red River.

2. The mathematical model and the numerical scheme

Looking forward to integrate the hydro-morphological modeling tool into a resources management framework, the choice of a one-dimensional model is suitable to represent correctly the morphological processes without an excessive computational burden.

2.1 Governing Equations

The model is based on the system of three differential equations stating mass and momentum conservation for the liquid phase plus the Exner equation (Eq. [3]) stating mass conservation for the sediment phase. The system has the form

$$\mathbf{U}_t + \mathbf{F}(U)_x = \mathbf{S}(U) \quad [1]$$

where

$$U = \begin{bmatrix} A \\ Q \\ A_b \end{bmatrix} \quad F = \begin{bmatrix} Q \\ \frac{Q^2}{A} + gI_1 \\ \frac{1}{1-p} Q_s \end{bmatrix} \quad S = \begin{bmatrix} q \\ g \left.\frac{dI_1}{dx}\right|_{zw=const} - gAS_f \\ q_s \end{bmatrix} \quad [2]$$

In the system of Eqns. [1], x is the longitudinal river coordinate, t is time, **U** is the vector of state variables, **F** is the vector of fluxes and **S** contains source terms. In Eqn. [2], A is the cross-section wetted area, Q is the liquid discharge, g is the gravity acceleration, I_1 is the static moment of A with respect to the water surface, S_f is the friction slope, A_b is the sediment volume per unit length of the stream subject to erosion or deposition ("sediment area"), Q_s is the solid discharge in volume, p is the bed porosity, q and q_s are the liquid and solid lateral inflows (or outflows) per unit length, respectively.

The traditional form of the source term in momentum conservation law is slightly changed in order to avoid the explicit reference to a value of local bottom slope, which in non-prismatic natural rivers with abrupt changes in slope is undesirable. To evaluate pressure contributions due to the non-prismaticity of the channel, local bottom slope is replaced by a term estimating the static moment (I_1) variation between adjacent cross sections, with constant water level zw: see first term of the second element in vector S (Eqn. [2]: see Schippa and Pavan, 2008 for details). As closure equation for slope friction, the Manning formula is used after calculating an equivalent resistance coefficient over the cross section, to include the effect of roughness change between main channel and overbanks. To calculate sediment discharge Q_s, we chose the Engelund-Hansen formula (Engelund and Hansen, 1967)

$$Q_s = 0.05 \cdot \rho_s g U^2 B \sqrt{\frac{d_s}{g(s-1)}} \left(\frac{\tau_0}{\rho g (s-1)} \right)^{3/2} \quad [3]$$

where Q_s is the sediment discharge, B is the channel width, ρ and ρ_s are the densities of water and sediments, respectively; s is the relative density ρ_s/ρ; d_s is the sediment representative diameter; U is the water average velocity; τ_0 is the bed shear stress. Eqn. [3] application has been tested and some insights are reported in section 3.3

2.2 The bed evolution model

Solving Eqns. [1] means to update the value of A_b at every time step along the reach. A conversion into a bed elevation variation Δs, for every point of the cross sections, is needed. We assume that this variation is proportional to bottom shear stress, in turn linearly related to the local water depth h via a constant k ($\Delta s = kh$). The variation of A_b is given by integrating Δs along the wetted perimeter P.

$$\int_P \Delta s dp = \Delta A_b \quad [4]$$

Applying the same integral to *kh* leads to the integral of water depth along the wetted perimeter, which is the wetted area A, and consequently Eqn. [5] follows. The local bed elevation change can be calculated directly by *Δs*= *kh*.

$$k = \frac{\Delta A_b}{A} \qquad [5]$$

2.3 The numerical scheme

A Godunov-type finite volume scheme has been adopted to integrate Eqns. [1], first-order accurate both in space and time. A two-step splitting form of the scheme has been implemented, first solving the homogeneous part of the system and obtaining an intermediate step solution $U^{n+1/2}$, then integrating the ODEs involving source terms by the Euler method to obtain the solution U at the time step n+1:

$$\begin{aligned} U^n{}_t + F\left(U^n\right)_x &= 0 \rightarrow U^{n+1/2} \\ U^{n+1} &= U^{n+1/2} + \Delta t \cdot S\left(U^{n+1/2}\right) \end{aligned} \qquad [6]$$

To obtain the fluxes F in order to solve the homogeneous system in the finite volume framework, the Riemann problem formed at every time step by discontinuities in state variables at cell interfaces has to be solved. Among the large number of approximate Riemann solvers available in the literature, we followed the HLLC-type approach (Harten *et al*., 1983; Toro *et al*. 1994) presented in the work by Goutière et al. (2008) where the speeds of the waves originating at cell boundaries and delimitating the intermediate constant states are estimated by an eigenvalue analysis of the system matrix. These authors propose an estimation of the wave speeds $\lambda_{1,2,3}$ (in decreasing order) involving a nondimensional factor X related to sediment discharge.

$$\begin{aligned} \frac{\lambda_1}{u} &\cong \left(1 + \frac{1}{Fr}\right) \\ \frac{\lambda_{2,3}}{u} &\cong \frac{1}{2}\left[\left(1 - \frac{1}{Fr}\right) \pm \sqrt{\left(1 - \frac{1}{Fr}\right)^2 - \frac{4}{\left(Fr^2 + Fr\right)}\chi}\,\right] \\ \chi &= \frac{1}{(1-p)u}\frac{\partial q_s}{\partial h} \end{aligned} \qquad [7]$$

A unit-width rectangular channel is considered in their analysis: *u* is mean water velocity, *Fr* is the Froude number, *h* is water depth, *p* is bed porosity, q_s is the solid discharge in volume per unit width. To extend this approach to natural channel geometry and to adapt it to the governing equations Eqn. [1]-[2], we substituted the last expression in Eqn. [6] with

$$\chi = \frac{1}{(1-p)u}\frac{\partial Q_s}{\partial A} \qquad [8]$$

where *Qs* is the total solid discharge and A is the wetted area. The analytical expression for the derivative of *Qs* respect to *A* is easy to obtain for Engelund-Hansen sediment transport formula.

Herein, only minimum and maximum speeds (λ_1, λ_3) are needed to solve water continuity equation and momentum balance equation with a traditional HLL scheme (only two waves and one intermediate state); there are two intermediate states (HLLC-type) instead in the solution of sediment continuity equation and the sought intercell flux depends on λ_2, λ_3 (Goutière *et al*., 2008).

3. Application of the model to the case study and planning of simulation runs

The geometry of the Red River reach is available from topographical surveys carried out in 2000 and 2009. On every cross section, the boundaries of the overbanks and the thalweg are identified, then to improve spatial accuracy an interpolation between surveyed cross section is made, up to an interval of 330m (250 cross sections on the entire reach). Boundary conditions of the model are the rating curve at the downstream cross section (which is not significantly affected by incision process) and incoming hydrograph at the upstream gauging station of Son Tay. A database of daily water level, discharge and daily suspended solids concentration recorded by MONRE (Ministry of Natural Resources and Environment) is available at both Son Tay and Hanoi gauging stations.

The discharge Q_{DU} flowing towards Duong River is ruled by conveyance and friction slope ratios with the main branch, calculated by

$$Q_{DU} = \frac{K_{DU} \cdot \sqrt{Sf_{DU}}}{K_{DU} \cdot \sqrt{Sf_{DU}} + K_{HO} \cdot \sqrt{Sf_{HO}}} \qquad [9]$$

subscripts DU and HO indicate Duong River and Hong River respectively, whereas K_{DU}, K_{HO} are the conveyances (known if cross section geometry at bifurcation and water level are known) and Sf_{DU}, Sf_{HO} are the friction slopes. Bifurcation treatment is relevant for the validation of the model: we forced the lowering of the Duong bed level at the bifurcation during the simulation period, in order to change conveyance ratio with time and improve matching with the recorded data. Sediment distribution is assumed proportional to discharge distribution.

3.1 Sediment transport formula

A preliminary test on Engelund-Hansen transport formula has been carried on. Daily suspended solids (SS) concentration data (g/m^3) available from MONRE recordings include washload, which is ineffective in terms of morphological evolution, whereas bedload is neglected. However, considering the strong prominence of suspended load in a large sandy river as Red River (above 85%, Uyen, 2011), and taking into account the uncertainty that affects measurements, a first attempt to realise if Engelund-Hansen formula is representative of the sediment movement in Red River has been made. A daily value of total suspended discharge Qs has been derived from SS concentration and discharge time series at the cross section of Son Tay, and then compared with simulated values obtained from a representative run of the model (year 2000 only). The daily values of Q_s have been divided in Nc classes (0.01 m^3/s wide). Extreme values larger than 2 m^3/s are part of a single last class. For each class, the relative frequency RF(i) has been calculated. As reported in Figure 2, results can be considered satisfactory. The statistical expected values J_{Qs} for the recorded and simulated Qs differ by less than 10%.

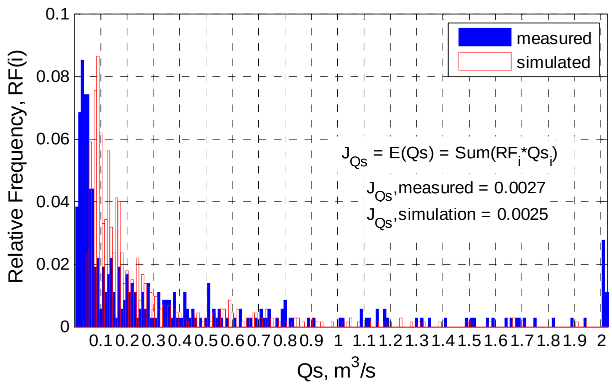

Figure 2. Test of sediment transport formula.

3.2 Planning of simulation runs

There are two main purposes at this stage of model set-up: the validation, taking advantage of the available flow and topographical data (2000-2009), and a preliminary analysis of the effect of sand mining and flow control through reservoirs on river reach morphology.

Validation of the model is performed taking as initial conditions the cross section surveyed in 2000, and running 10-year long simulations with the recorded discharge series in Son Tay (2000-2009) as upstream boundary condition. Bifurcation behavior is adjusted during this process, testing different bed lowering trends of Duong river initial cross section, to calibrate conveyance ratio and flow distribution between the two branches (see Eqn. [9]). Lowering trends are inferred from recorded minimum water levels at the Thuong Cat cross section on Duong River, just downstream the bifurcation. Bed roughness in the reach is assumed as invariant. The results of these runs (referred to with codes VD1 and VD2, see Table 1) are compared with recorded time series of discharge at Duong bifurcation, and water level in HaNoi.

As for the influence of anthropogenic activities, a reference simulation is run for the period 2000-2009 with the recorded upstream incoming discharge as input, in the hypotesis of no sand mining along the river (code REF). Then, two different scenarios of sand mining (code SM1, SM2) are analyzed: a starting value (sm_0) of sediment mining rate is provided in the report by MARD (2011): sm_0 = 6.6 Mm^3 /year in the reach Son Tay - Hanoi and sm_0 = 2.3 Mm^3/year downstream Hanoi. This has been increased by 50% to run SM2. In addition, a steady low-discharge simulation (1100 m^3/s) has been run accounting for the bed configuration resulting from the 10-year simulations and for the cross sections surveyed in 2000 and 2009; resulting water surface profiles have been compared to assess the reliability of the model.

The morphological effects of flow control through reservoirs are estimated substituting the recorded input hydrograph with a reconstructed "natural" flow hydrograph (Figure 5, code NAT) provided by previous studies at Hanoi IWRP (Institute of Water Resources Planning), supposing the absence of large impoundments upstream and consequently increasing peak flows. In this run series, both roughness and bifurcation behavior are always kept constant.

Table 1. Simulation runs plan.

CODE	INPUT HYDROGRAPH	SAND MINING RATE	DUONG RIVER BED LOWERING
VD1	Recorded	sm_0	Power-law decrease
VD2	Recorded	sm_0	S-shape decrease
REF	Recorded	0.0	No
SM1	Recorded	sm_0	No
SM2	Recorded	sm_0+50%	No
NAT	Reconstructed	0.0	No

4. Results

4.1 Simulations VD1 and VD2

The agreement between simulated and recorded data series in 2000-2009 is analyzed. Concerning bifurcation, flow in Duong distributary is slightly overestimated during dry season (Figure 3). In VD1, the Duong bed lowering follows a power-law decrease, with faster lowering at the beginning of the run, while in VD2 the lowering follows a S-shape curve, with faster lowering in the middle years. The total decrease is 2 m for both simulation runs. Moreover, we tried to calibrate a distinct friction slope ratio (see Eqn. [9]) for dry and wet seasons, following once again the observed data. On the other hand, peak flow in the Duong is slightly underestimated by the model. The overestimation of flow in the distributary leads to an underestimation of water level in Hanoi (Figure 4) during the first three-four years. Maximum levels provided by the model are in excellent agreement with recorded data.

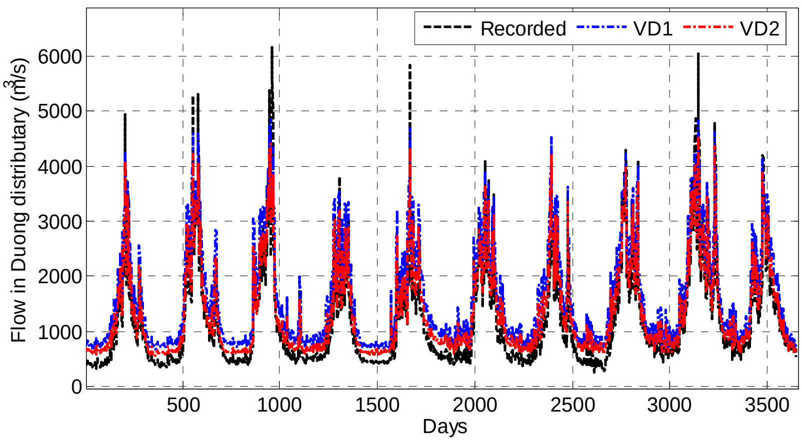

Figure 3. Discharge in Duong distributary, simulation runs VD1 and VD2.

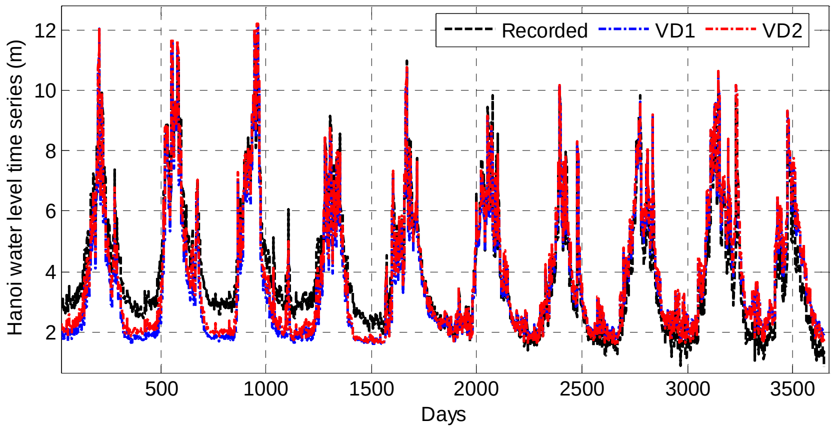

Figure 4. Water level in Hanoi, simulation runs VD1 and VD2.

4.2 Scenarios for sand mining and flow controls: simulations REF, SM1, SM2, NAT

An indicator J_{inc} to measure the river bed incision process has been defined (Eqn. [10]). We monitored the evolution of 5 representative points of the main channel bed (the thalweg, two left and two right) for every cross section. The level difference δ_i of these points between final and initial state is averaged to obtain a single value per cross section δ_{XS}, and then the value δ_{XS} is averaged over a reach to obtain J_{inc}. Starting value is zero: negative values mean that the river is undergoing incision in that reach. We analyzed 4 reaches of equal length (20 km each, numbered from upstream).

Figure 6 compares the evolution of J_{inc} in time for simulation REF, SM1, SM2; in Figure 7, the same evolution for simulation runs REF and NAT is compared. The influence of sand mining is clearly larger if compared to the reservoir presence. The water surface profile comparison for a steady, low flow simulation (Figure 8) shows that both SM1 and SM2 still underestimate the effect of sand mining on the water surface lowering.

$$\delta_{XS} = \frac{1}{5}\sum_{i=1}^{5}\delta_i ; J_{inc} = avg(\delta_{XS})\big|_{reach} \qquad [10]$$

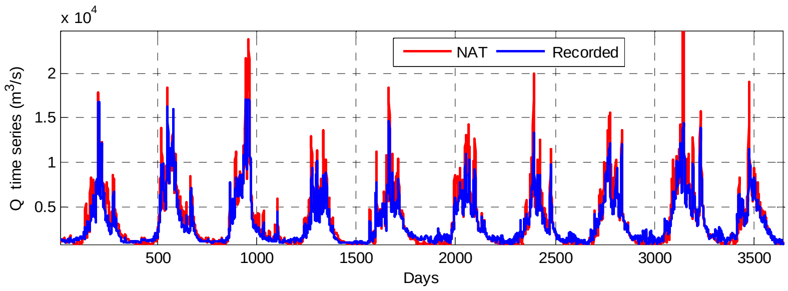

Figure 5. Recorded and reconstructed hydrograph in Son Tay.

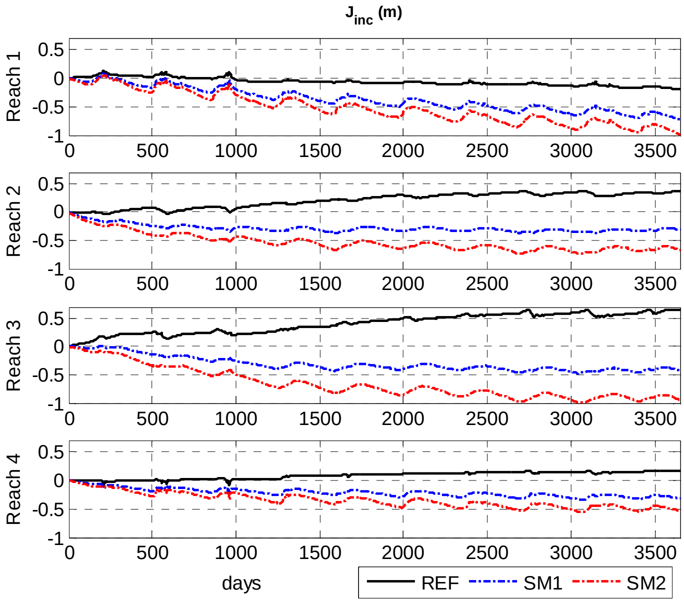

Figure 6. Incision indicator J_{inc} in time for different sand mining rates.

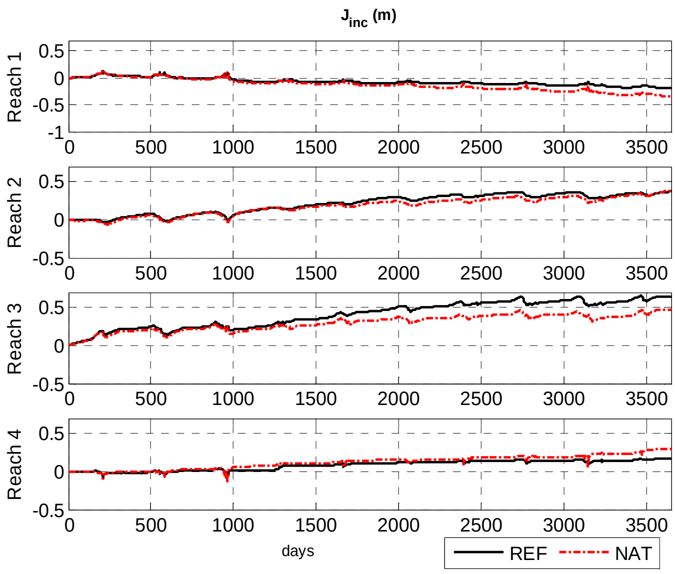

Figure 7. Incision indicator J_{inc} in time for simulations REF and NAT.

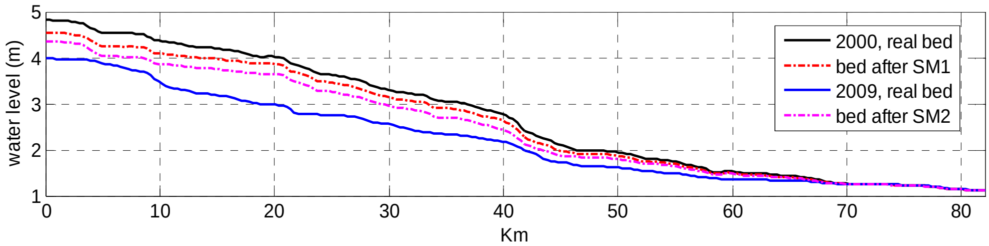

Figure 8. Water surface profiles comparison for steady, low flow simulations (1100 m3/s).

5. Conclusions

A finite-volume numerical model for analysis of morphological evolution of the lower course of Red River has been presented. A first validation in the period 2000-2009, still to improve, has been carried on. Sediment distribution at the bifurcation, an accurate roughness coefficients calibration, a development of the proposed numerical scheme are future issues to address to.

As for the simulation runs concerning sand mining and flow control, it is interesting to notice that in the REF simulation, the tendency to river bed degradation is visible only in the first reach. A natural process of slope decrease would probably occur, with deposition starting from the second reach analyzed. Sand mining instead, as expected (simulations SM1 and SM2, Figure 6), accelerates incision in first reach and reverses the trend in the following three reaches. Stopping or decreasing sand mining would probably start a restoring process. The flow profile comparison (see par. 3.2 and Figure 8) shows that the incision process in reality has progressed faster than in simulation runs performed so far: sediment mining rates could be larger than estimated by MARD (Uyen, 2011).

The flow control, conversely, appears to affect much less the morphological processes (Figure 7). The reconstructed hydrograph (Figure 5) is supposed to remove any effect of the impoundments upstream, in presence of the same precipitation pattern. Every release policy would result in inflows discharges between the recorded and "natural" one. The results indicate that the effect of flood control alone on morphology is very limited in the studied stretch, in comparison to sand mining.

Further developments of the research will focus on the improvement of the numerical model performance, on its application to other reaches of Red River (for instance closer to big reservoirs), on prediction of future scenarios, and on the integration of the model in a framework of optimal policies design. The integration of river bed evolution understanding in the basin-scale plans for optimal water resources management (e.g. optimization of water releases, quantification of sand mining benefits and environmental costs) is becoming worldwide necessary.

Acknowledgements

Data for this research were kindly provided by Vietnamese Institute for Water Resources Planning (IWRP), Ministry for Agriculture and Rural Development (MARD), Ministry of Natural Resources and Environment (MoNRE).

The authors thank Quang Dinh (Politecnico di Milano) for his help. The work was conducted as part of and receiving support from IMRR (Integrated Management of Red River Basin) project, between the Electronic, Information and Bioengineering Department of Politecnico di Milano, the Italian Ministry of Foreign Affairs and the Vietnamese authorities.

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