1D modeling of long-term morphodynamics: Application to the Adige River, Italy

Michael Nones[1, 2]

1- Previously at Department of Civil, Architectural and Environmental Engineering, University of Padua, Via Marzolo 9, 35131, Padua, Italy.
2- Present address: gerstgraser - Ingenieurbüro für Renaturierung, An der Pastoa 13, 03042 Cottbus, Germany. Phone +493554838919

* Corresponding Author: nones@gerstgraser.de

Abstract

The morphological river evolution at long-time (centuries and even millennia) and large spatial scale (watersheds of several square kilometres) can be described by means of simplified 1D models, able to simulate the variation of bed elevation and grain size composition at non-detailed scales, involving a reduced computational effort. The erosion and deposition phenomena acting along rivers can be modeled by a simplified approach based on the Local Uniform Flow hypothesis and on the instantaneous propagation of the water flow. Such an approach computes the sediment yield of large watersheds at long-time scale relatively quickly, taking into account the non-sorted granulometry of river systems. In the paper, a 1D simplified model is described and applied to the Adige River (Italy), in order to study the morphological evolution of the watercourse after a redesign of some cross sections in its lowland part. Local variations of river altimetry propagate downstream and upstream, in relation to the Froude number and to the changes magnitude. The results highlight the reliability of the code to simulate the long-term effects of human works in rivers at non-detailed scale. In addition, the outcomes of 1D simulation can be used as input data for detailed models (2D or 3D) to study local changes at shorter time scale.

Keywords: 1D model; Adige River; Morphology; River long-term evolution; Sediment transport.

1- Introduction

The attempt to control and manage the evolution of rivers has been a focus of the human activity since the beginning of the civilization: irrigation, water supply, food, hydropower, transport, etc. are strongly related to river resources (Simonovic, 2000; Bernardi, 2015). Due to the fact that fluvial response to human interventions is faster and more intense than adaptation to natural forcing (Gregory, 2006; Scorpio *et al*., 2015), the evaluation of short- and long-term consequences of different but interrelated water resources uses represents a key aspect in planning engineering projects (Chang, 1988).

In recent years, the study of the river geomorphology has become a central focus of river management (Thorne *et al*., 1997; Simon and Rinaldi, 2006; Gurnell *et al*., 2015; Scorpio *et al*., 2015), because geomorphic processes can significantly affect the various environmental services that fluvial systems provide to society, ranging from flood mitigation to ecological aspects. The economical quantifications of these direct and indirect ecosystem services are difficult to estimate and a matter of recent studies (Gilvear *et al*., 2013), and their evaluation cannot be neglected during the planning of modern catchment management strategies (Bernardi, 2015).

The adoption of numerical models able to solve the equations governing the hydro-morphodynamics of rivers has established itself among the scientific and engineering communities. Such models span from 3D models used to describe local variations in a very detailed scale to 1D, and even 0D codes, necessary to evaluate the river evolution at watershed scale reducing the computational load (Nones, 2013). The choice of a numerical hydro-morphodynamics model in a river management problem is not only driven by the accuracy in the representation of physical processes, but also by morphological, hydrological, anthropogenic features of the river system that have to be considered, as well as spatial and temporal scales of the involved processes. Long-term modeling of river morphodynamics is a challenge involving complex phenomena in a non-static system subject to continuous and random changes. For these reasons, despite of the availability of many commercial and open-sources codes for 2D and 3D modeling, 1D codes are still widely used by river engineers and managers worldwide due to their simplicity and reliable outcomes, associated with a reduced computational effort, and are frequently used to support more detailed models (Coulthard and Van de Wiel, 2013; Guerrero *et al*., 2013). In this respect, interesting applications of such models to rivers span from the analysis of incised streams in northern Mississippi (Langendoen *et al*., 2009) to the investigation of the effects of large impoundments on the Lower Zambezi River (Nones *et al*., 2013), or the simulation of long-term estuary development in Papua New Guinea (Canestrelli *et al*., 2013), and the analysis of climate change impact on the Parana River (Guerrero *et al*., 2013).

The river hydro-morphodynamics can be studied by means of 1D mathematical models based on the De St. Venant equations, describing the hydrodynamics, and the Hirano and Exner equations, describing the sediment transport phase (Exner, 1920; Hirano, 1971). These equations can be treated in a rather simple way, with the involvement of a limited number of input data and, therefore, successfully applied to long-term studies of rivers evolution at large spatial scale. The main hypothesis introduced in this paper is the validity of the Local Uniform Flow (LUF) for relatively short river reaches, hereafter called “morphological boxes”, on the basis of the Froude number (Ronco, 2008; Fasolato *et al*., 2009; Nones, 2013). Over these boxes, the river characteristics (liquid and solid discharges, slope, width, grain size composition) are averaged. As verified in other studies (Ronco, 2008; Fasolato *et al*., 2011), the validity of such assumptions is related to the velocity of the current and, therefore, the model can be applied to mountain streams (Di Silvio and Peviani, 1991; Nones, 2007) as well as reaches with mild slope (Ronco, 2008; Nones *et al*., 2014), provided that the morphological boxes are sufficiently long (up to dozens of kilometres) and the involved adaptation processes result slow enough (Fasolato *et al*., 2011).

The present paper is structured as follows. The next section is focused on the mathematical background of the model, highlighting the introduced simplifications. In the third section, the study site is described, focusing on the high anthropogenic impact on the river, used for hydropower production in the upper basin and agricultural exploitation in the lower part. To show the reliability of the model, a brief description of the performed calibration is reported. In its lowland basin, the Adige River flows at a higher level than the surrounding floodplains, constrained by artificial levees. The water authority that manages the river will redesign the shape of some cross sections in this part, with the aim to facilitate the agricultural exploitation, improving the river depth. The long-term evolution of the watercourse after these works is herein studied and the results are reported and discussed. A final concluding section is necessary to point out the reliability of the present 1D approach in predicting the long-term evolution of watercourses despite the numerous simplifications adopted. To overcome some weaknesses of the model, future improvements of the code are also presented.

2- 1D MODEL

2.1- Liquid phase

The 1D model describes the hydraulics by means of the De St. Venant equations: the flow continuity is described by eq. 1:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0 \qquad (1)$$

where Q is the water discharge and A the wetted area, while x and t represent the longitudinal and temporal variables, respectively.

Assuming the coefficients that account for energy and momentum distribution over the cross sections (Coriolis forces) equal to one, the momentum equation can be written as:

$$\frac{\partial}{\partial x}\left(H+z+\frac{Q^2}{2\cdot g\cdot A^2}\right)=-\frac{1}{g}\cdot\frac{\partial U}{\partial x}-J \qquad (2)$$

where H is the water depth, z indicates the bottom level with respect to a reference position, U represents the flow velocity, J is the slope of the energy line and g indicates the gravity.

The continuity (1) and energy (2) equations may be subjected to a series of simplifications if the flow hydrograph is relatively flat compared with the energy slope J. This condition corresponds to use the expression:

$$\frac{\partial Q}{\partial x}=\frac{2}{3}\frac{1}{U}\frac{\partial Q}{\partial t} \qquad (3)$$

instead of eq. (1), assuming the kinematic wave hypothesis, and dropping the time-depending terms in eq. (2) under the hypothesis of quasi-steady water flow.

$$\frac{\partial}{\partial x}\left(H+Z+\frac{Q^2}{2gA^2}\right)=-j \qquad (4)$$

A strong simplification consists in the assumption of the instantaneous propagation of the liquid flow, valid for liquid waves that are longer than the distance between two consecutive tributaries (Fasolato *et al*., 2011).

$$\frac{\partial Q}{\partial x}=0 \qquad (5)$$

The momentum equation can be simplified assuming the validity of the Local Uniform Flow hypothesis: in other words, imposing that the variation of the energy line is directly proportional to the variation of the bottom profile:

$$J=-\frac{\partial z}{\partial x} \qquad (6)$$

The LUF hypothesis is applicable to mountain rivers (Di Silvio and Peviani, 1991; Nones, 2007) as well as watercourses with lower slope, since the analysed quantities are averaged over sufficiently long reaches (Fasolato *et al.*, 2011). In other words, this model can be suitably applied if one is interested in a watershed study rather than a more detailed analysis (Nones, 2007). In detail, the minimum length of the morphological box (i.e., the spatial scale) is related to the Froude number of the current (Ronco *et al.*, 2009; Fasolato *et al.*, 2011).

2.2- Solid phase

The solid phase is modelled using the Exner (7) and Hirano (8) equations.

$$\sum_{i=1}^{N}\frac{\partial P_i}{\partial x}=-B\cdot\frac{\partial z}{\partial t} \qquad (7)$$

where P_i is the sediment transport of the *i*-th class of sediment characterized by the diameter d_i, while B indicates the river width, assumed here constant.

$$\delta\cdot B\cdot\frac{\partial\beta_i}{\partial t}=-\frac{\partial P_i}{\partial x}-B\cdot\beta_i\cdot\frac{\partial z}{\partial t} \qquad (8)$$

where β_i represents the percentage of the *i*-th class of sediment.

To permit the application to a wide range of cases, the present model considers up to ten classes of sediments.

As shown in eqs. (7) and (8), the sediment balance is made for each granulometric class, taking into account two different layers: i) a transport layer, near the bottom, where all the particles transported in suspension and as bedload are located; ii) a mixing layer (Hirano, 1971), which considers the particles that are temporarily at rest, but can vertically move to the transport layer. In the upper layer the sediment continuity is assured, while in the mixing layer a vertical balance is imposed to consider the erosion and deposition phenomena.

The sediment transport is computed for each granulometric class by means of a monomial equation of the Engelund-Hansen type, which has to be calibrated for each river. The instantaneous solid discharge P_{si} of the i-th class results proportional to the percentage presence of each granulometry in the mobile bed and to the hiding-exposure coefficient ξ_i, as well as to the river geometry and the flow discharge (eq. 9).

The sediment transport P_s along the river is the sum of the transport related to each single class (eq. 10).

$$P_{si} = \alpha \cdot \left(\frac{Q^m \cdot I_f^n}{B^p \cdot d_i^q} \right) \beta_i \cdot \xi_i \qquad (9)$$

where d_i is the diameter of the i-th class, Q indicates the flow discharge and I is the bottom slope (equal to the energy slope J under the LUF hypothesis). The exponents m, n, p, q and the coefficient α need to be calibrated for each watercourse, in relation to the applied uniform flow formula (Di Silvio, 1996; Basile, 1994).

$$P_s = \sum_{i=1}^{N} P_{si} \qquad (10)$$

The hiding-exposure coefficient takes into account the intrinsic mobility of the particles: fine particles move less with respect to the coarser ones (Egiazaroff, 1965).

$$\xi_i = \frac{d_i^s}{\left[\sum_{i=1}^{N} \left(\beta_i \cdot d_i \right) \right]^s} \qquad (11)$$

At seasonal time-scale, the hydrology may be represented by a three-parameter flow duration curve for the hydrological year τ.

$$Q = \left[Q_{\max} - Q_{\min} \right] \cdot e^{-\gamma(\tau)\frac{t}{\tau}} + Q_{\min} \qquad (12)$$

where the variability coefficient γ is expressed as:

$$\gamma = \frac{Q_{\max} - Q_{\min}}{Q_{mean} - Q_{\min}} \qquad (13)$$

where Q_{max}, Q_{min} and Q_{mean} represent the maximum, minimum and mean flow discharges, respectively. Generally, these three quantities oscillate from year to year and may be subject to anthropogenic and natural long-term modifications.

Following Ronco (2008), the equivalent discharge is the water flow that conveys the long-term average sediment transport T_S, where P_S represents the instantaneous sediment discharge (eq. 10).

$$Q_{eq} = \left[\frac{{Q_0}^{m-1} \cdot \left(Q_{mean} - Q_{\min} \right)}{m} + {Q_{\min}}^m \right]^{\frac{1}{m}} \qquad (14)$$

and Q_0 is the difference between the maximum flow Q_{max} and the minimum flow Q_{min}.

Once the equivalent discharge is computed and assuming that, during the hydrological year τ, the granulometric composition β_i and the river slope I remain quite constant, the total sediment transport can be obtained integrating eq. (9).

$$T_S = \int_\tau P_s = \left(\sum_{i=1}^{N} \frac{\xi_i \cdot \beta_i}{d_i^q} \right) \cdot \left(\frac{I_f^n}{B^p} \right) \cdot \int_\tau Q^m \cdot e^{-\gamma \cdot \frac{m}{\tau} t} \qquad (15)$$

where the first term is the “sedimentological factor”, the second represents the "morphological factor" and the last one is the "hydrological factor" of the analysed river.

The precedent equations can be rearranged to estimate the equivalent diameter of the river, indicating a significative diameter of the particles transported by the equivalent discharge.

$$d_{eq} = \left[\frac{\left(\sum_{i=1}^{N} \beta_i \cdot d_i \right)^s}{\left(\sum_{i=1}^{N} \beta_i \cdot d_i^{s-q} \right)} \right]^{\frac{1}{q}} \quad (16)$$

3- Case study

3.1- Adige River

The Adige River has its source in the Alpine province of South Tyrol near the Italian border with Austria and Switzerland (Fig. 1). With a length of about 410 kilometres, it is the second longest river in Italy, after the Po River. Starting from a hydropower reservoir created in 1953 near the Reschen Pass, the Adige River flows eastbound through the Val Venosta to Merano, where it joins the Passirio River from the north. Downstream of Bolzano, the river is joined by the Isarco River and turns south through a valley which has always been one of the major routes through the Alps, connecting Italy and Austria. Near Trento, the Avisio, Noce and Fersina rivers join the Adige. The river crosses Trentino and later Veneto, flowing through the city of Verona and the north-eastern part of the Po Plain into the Adriatic Sea. The Adige and the Po run parallel in the river delta without properly joining. Along its course, the Adige River is connected through artificial underground canals to the Garda Lake for flood prevention.

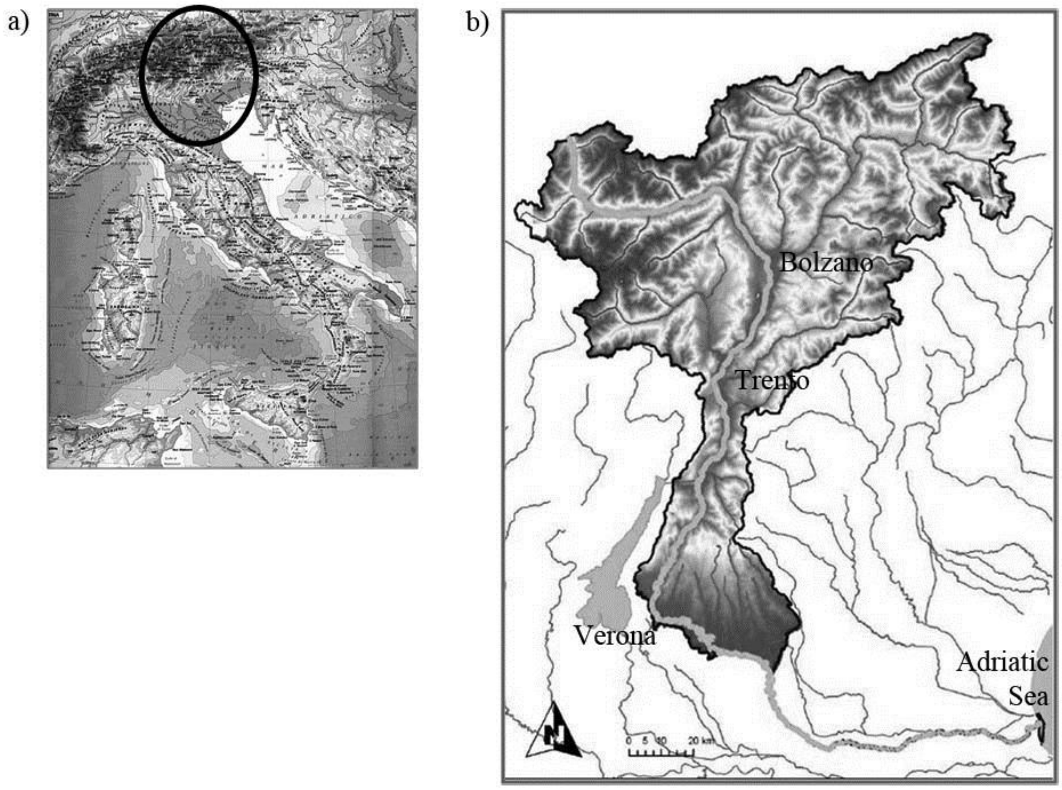

Figure 1a) Map of Italy; the Adige River watershed, with the principal cities.

From the ancient times, the Adige River was considered as a strategic resource for inner navigation and agriculture in the lowland basin, while production of hydropower energy becomes very important in the mountain part starting from the 1950s. For this reason, the actual watercourse is highly impacted by the human pressure: artificial levees all along the course, quite constant water flow and reduced sediment yield (consequences of numerous dams and weirs) have reduced the biological status of the river and threaten its habitat. To improve agricultural uses or the biodiversity of this heavily modified water body various actions were proposed in the last years, such as the redesign of the shape of some cross sections, especially in the lowland part downstream the city of Verona, for agricultural aims.

As visible in the equations reported in the previous section, the 1D model requires, as input data, equivalent flow discharge, sediments characteristics and river geometry (bottom slope and width). In the present application, the river width is assumed constant, because the river is embanked within levees for the entire lowland reach. In Table 1 the input data are summarized, indicating the location where they were measured and the relative references.

Table 1) Input data used by the 1D model, with the measuring method and the relative source.

quantity	*location*	*measuring method*	*reference*
hydrology	Verona	water stage	Nones, 2007
bed composition	Verona	bed samples	Brunelli, 1987
geometry	Verona	aerial images, DTM	Nones, 2007
sediment transport	Trento	turbidity	Ispra, 2015

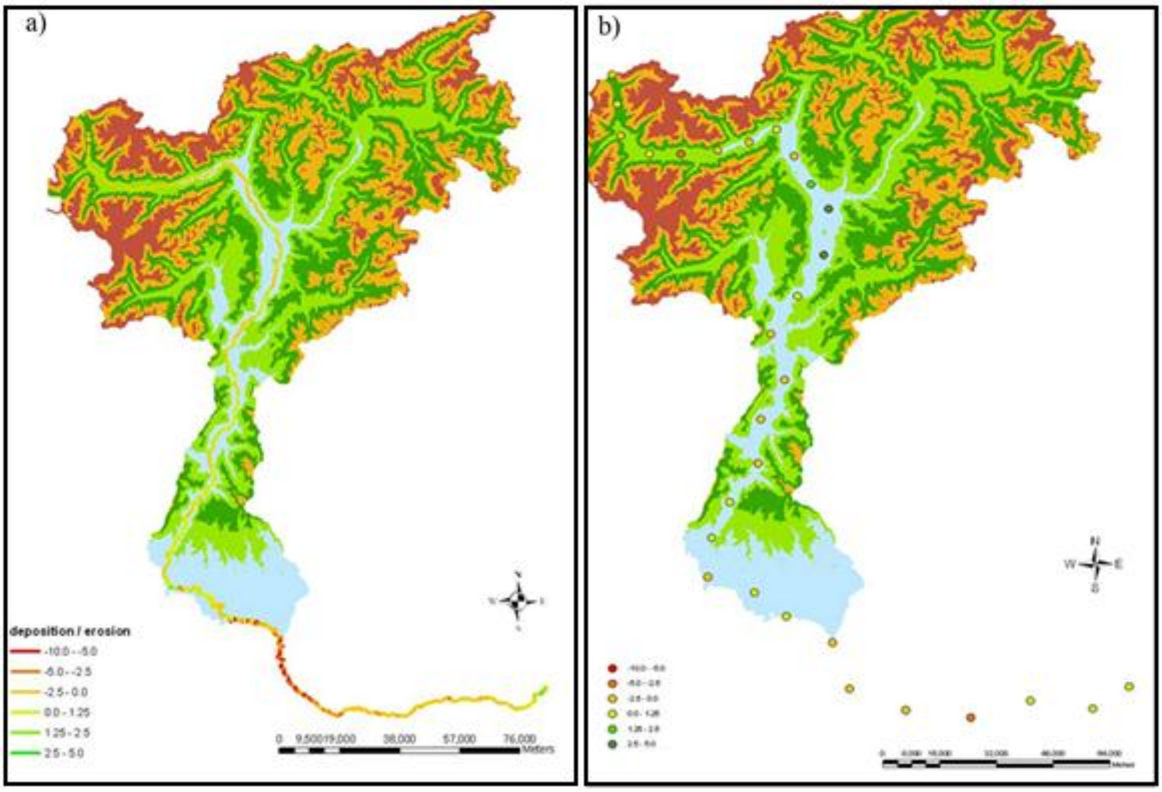

Figure 2) Evolution of the Adige River between 1954 and 1996: a) measured values, b) computed values.

Briefly, geometry was measured by means of a DTM representing the 1996 state and aerial images available for the entire course, while the water stage are derived from gauging stations installed along the river. The turbidity data are taken from historical measures made in Trento and Boara Pisani and extrapolated in the studied reach, while the bed samples were taken as a part of an MSc Thesis in 1987 and result the most updated values available in the analysed cross sections. More details about the measured quantities are reported in Nones, 2007.

3.2- Calibration of the model

The ID LUF model was calibrated using the data reported above, and comparing the outcomes with measured data in terms of variations of the bed elevation. The measured data were derived comparing two bathymetric surveys performed in 1954 and 1996 (Nones, 2007), while the computed ones come from a model simulation starting from the 1954 state.

As visible in Figure 2, the model simulates quite well the river behaviour at large scale. As reported above, the morphological boxes are function of the Froude number: namely, shorter boxes in the upper part of the basin and longer boxes in the lowland reach.

3.3- Proposed measures

In this paper, two similar works of bed excavation downstream of Verona are studied, following the works proposed by the local water authority. These works were simplified as local and instantaneous digs happened in 2010 (Nones *et al.*, 2010). To highlight the long-term impacts of these measures, for each location two distinct excavation volumes are imposed, corresponding to different depth of dredging, and the evolution of the near morphological boxes is analyzed.

The first cross section (Fig. 3a) is located nearby the town of S. Giovanni Lupatoto (Vr). In this section, the dredging operation is schematized as a local and instantaneous scour made in the year 2010, with different depths: i) 0.25 m, corresponding to a dig volume of about 0.8×10^6 m^3; ii) excavation of 2.5 m for a total volume of 8×10^6 m^3.

The second redesigned cross section (Fig. 3b) is located near Zevio (Vr). As the previous case, the scour made in 2010 is local and instantaneous, with different conditions: i) digging of 0.20 m, corresponding to a volume of about 0.7×10^6 m^3; ii) excavation of 2.0 m, for a volume of 7×10^6 m^3.

Figure 3) Excavated cross sections near a) S. Giovanni Lupatoto (Vr) and b) Zevio (Vr).

4- Results

4.1- S. Giovanni Lupatoto

To analyse the bed excavation effects, river evolutions in natural conditions (continuous line) and after the excavation (dashed line) are compared.

The excavation of 0.25 m causes a local alteration of the longitudinal profile with respect to the natural tendency (Fig. 4a), but only negligible variations of equivalent diameter (Fig. 4b) and sediment transport (Fig. 4c) were observed.

The deposition/erosion trend of the morphological boxes located upstream and downstream of the intervention remains the same during the analysed period, indicating that the involved sections are relatively resilient to small perturbations.

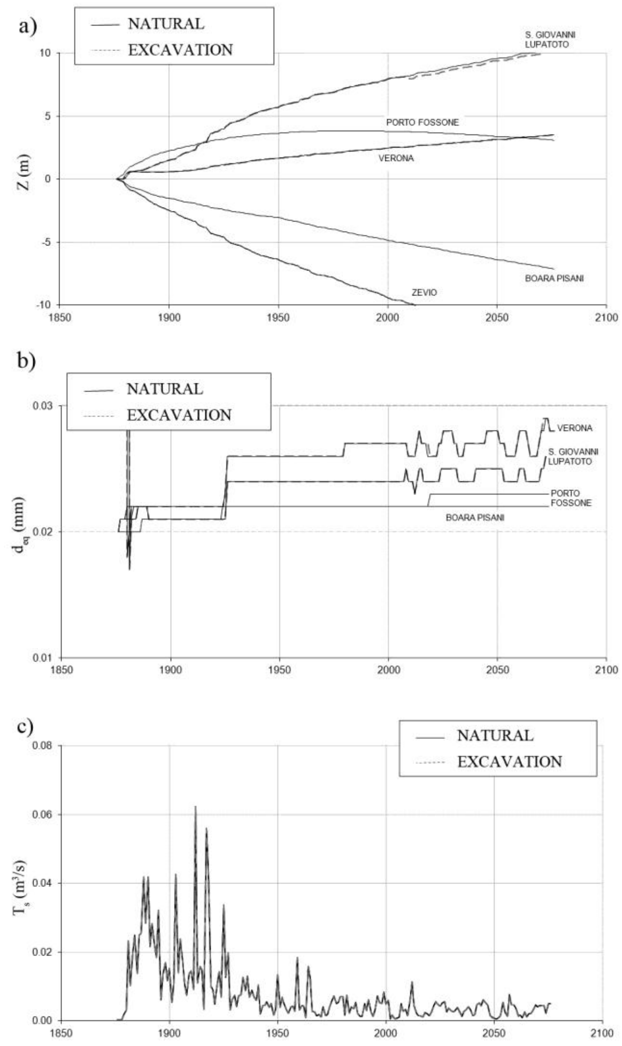

Figure 4) Evolution of the Adige River after the excavation of 0.25 m at S. Giovanni Lupatoto in terms of a) longitudinal profile, b) equivalent diameter and c) sediment transport.

With the aim to point out the reliability of the model in simulating long-term effects of river works, an instantaneous and local excavation of 2.5 m is imposed. As visible in Figure 5a, this large excavation causes an alteration of the morphological boxes located both upstream and downstream of S. Giovanni Lupatoto (namely, 10-20 kilometres), with a lower magnitude in the farer morphological boxes. In terms of equivalent diameter (Fig. 5b), one can observe that the variation of this parameter in the more distant boxes is delayed as a consequence of the low velocity of the morphological wave (small celerity). Regarding the sediment transport (Fig. 5c), it is evident that a local but significative excavation can slightly reduce the transport along the river, with a consequent alteration of the entire fluvial system.

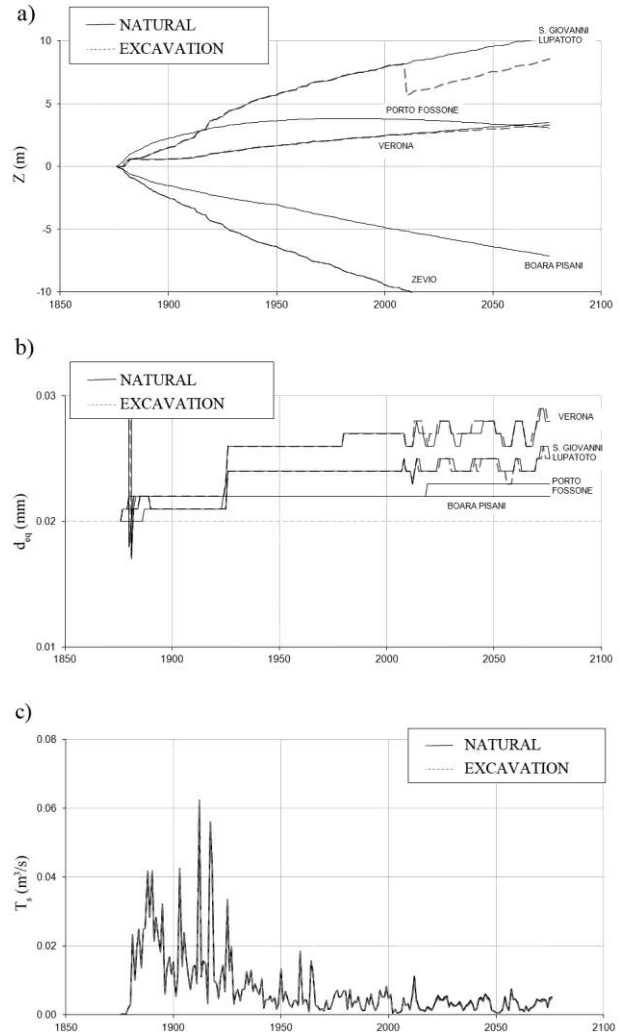

Figure 5) Evolution of the Adige River after the excavation of 2.5 m at S. Giovanni Lupatoto in terms of a) longitudinal profile, b) equivalent diameter and c) sediment transport.

4.2- Zevio

As reported in the previous case, a small and local excavation cannot induce relevant altimetric and granulometric modifications far from the involved cross sections (Fig. 6). Analyzing the equivalent diameter (Fig. 6b), it is possible to observe a slight variation of the grain size of the Zevio morphological box, where this quantity is subjected to an instantaneous change, but, after an adaptation period, it follows again its natural evolution.

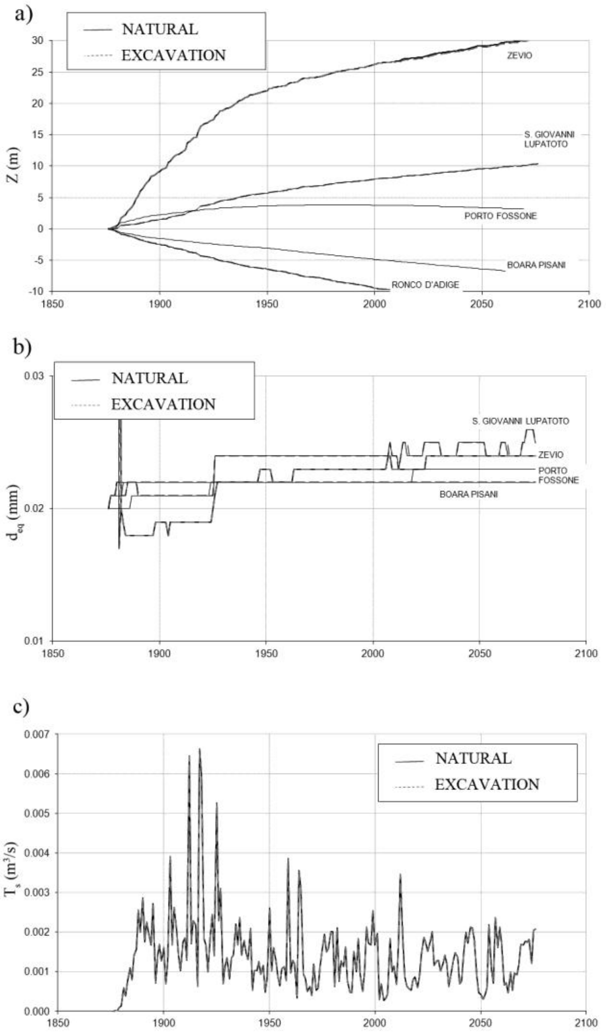

Figure 6) Evolution of the Adige River after the excavation of 0.20 m at Zevio in terms of a) longitudinal profile, b) equivalent diameter and c) sediment transport.

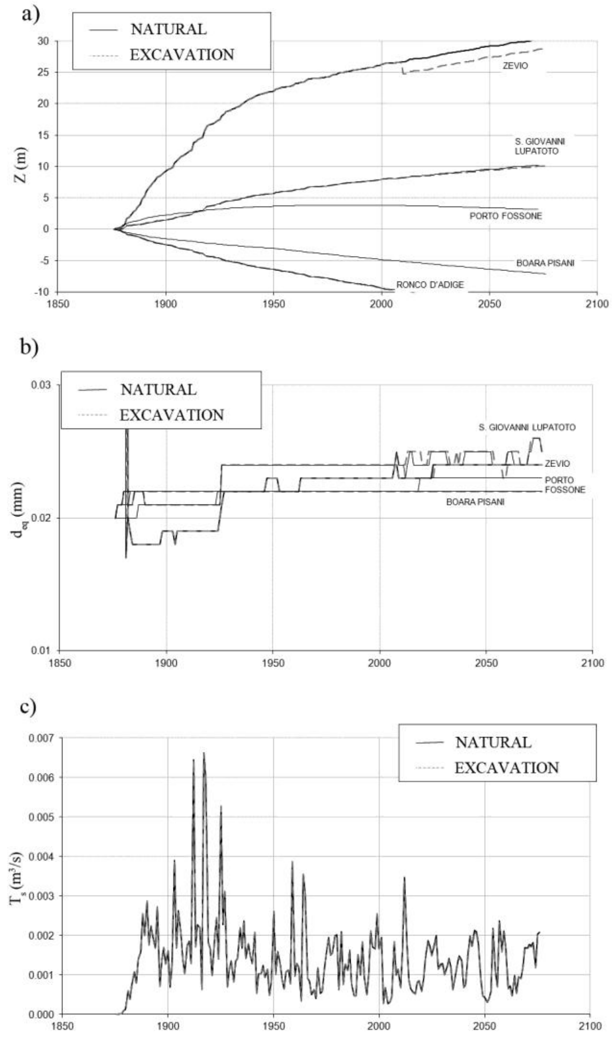

Figure 7) Evolution of the Adige River after the excavation of 2.0 m at Zevio in terms of a) longitudinal profile, b) equivalent diameter and c) sediment transport.

A more important excavation involves altimetric changes in the near morphological boxes, which propagate during time (Fig. 7a). Similarly to the previous case, also in this section a massive dig creates a variation of the grain size composition (Fig. 7b) of the involved section (Zevio) and the upstream one (S. Giovanni Lupatoto), while the downstream sections (Ronco d'Adige, Boara Pisani and Porto Fossone) are influenced in a negligible manner due to the small wave celerity. A slight decrease of the sediment transport is locally observed (Fig. 7c).

5- Discussion

Small works such as digs in the order of some centimetres cannot alter the bed morphology of the lowland part of the Adige River far from the works, not even at long time scale, due to its bed characteristics and flow velocity. With the aim to see significant modifications upstream and downstream of the digged sections, it is necessary to increase the excavated depth to at least a couple of meters. In this manner, the upstream sections are affected, pointing out an erosion that evolves during time, altering also the equivalent diameter that becomes slightly coarser. Local scours produce a reduction of sediment transport downstream of the involved sections, which is related to a coarsening of the grain size composition, while the other analysed quantities remain quite constant at long-term.

The propagation of the disturbances for some kilometres upstream and downstream of the excavation works is due to the small Froude number of the current (small slope and low flow velocity). In this respect, the present model is not able to catch possible variations near the involved sections, due to the spatial scale adopted (namely, morphological boxes on the order of tens kilometres).

The reported results highlight the importance of performing studies at large spatial and temporal scales for river restoration projects to have an idea of the long-term evolution and derive additional data for specific studies. Massive interventions of river re-sectioning can alter the watercourse very far from the works, and at long temporal scale. Obviously, due to its large representation scale, the 1D LUF model cannot forecast the local evolution of the watercourse, but can be successfully applied in combination with more detailed analyses.

6- Conclusions

The study of long-term evolution of rivers morphology in response to anthropogenic interventions can be made by means of non-detailed 1D models, if the distance between two consecutive cross sections (morphological box) is long enough with respect to the Froude number of the current. Namely, the lower is the Froude number, the larger results the morphological box. In this manner, the errors introduced by the LUF hypothesis can be limited under a reasonable threshold. Moreover, 1D models can be successfully applied to compute additional information necessary for studies at local scale, generally performed with more detailed (2D and even 3D) codes.

The long-term modeling of the cross section redesigned along the lowland part of the Adige River points out that the response of the river to small anthropic changes of the bed elevation is sufficient slow, in relation to the fine sediments and the slow slope of the studied reach. Indeed, only a massive excavation can alter sections upstream and downstream of the interventions, underlining that the river is quite resilient.

To improve the results of the present model, more detailed and up-to-date input data are necessary, in particular regarding the grain size composition of the river bed, as well as a better calibration of the sediment transport formula on the basis of historic and current data.

Notation

A = wetted area (m^2);

d_i = grain size composition of i-th class of sediments (m);

d_{eq} = equivalent diameter (m);

B = active river width (m);

g = standard gravity (m/s^2)

H = water depth (m);

I = average bottom slope (m/m);

J = average energy line slope (m/m);

m = exponent of the sediment transport formula (-);

n = exponent of the sediment transport formula (-);

P_{si} = instantaneous sediment discharge of the i-th class of sediments (m^3/s);

P_s = instantaneous sediment discharge (m^3/s);

p = exponent of the sediment transport formula (-);

Q = flow discharge (m^3/s);

Q_{max} = maximum river discharge (m^3/s);

Q_{min} = minimum river discharge (m^3/s);

Q_{mean} = mean river discharge (m^3/s);

Q_{eq} = equivalent river discharge (m^3/s);

Q_0 = maximum annual river discharge (m^3/s);

r = exponent of the sediment transport formula (-);

T_s = total sediment transport (m^3/s);

t/τ = statistical (seasonal) time-scale (s);

U = flow velocity (m/s);

Z = bottom elevation (m);

α = coefficient of the sediment transport formula (-);

β_i = percentage of the *i*-th class of sediments (%);

χ = Chézy coefficient ($m^{1/2}/s$);

ξ_i = hiding-exposure coefficient of the *i*-th class of sediments (-);

γ = variability coefficient of river discharge (-);

τ = multiannual time-scale (s);

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Dr. Miloš Gregor
Geological Institute of DionysStur, MlynskaDolina, Podjavorinskej 597/15 DubnicanadVahom, 01841, Slovak Republic
E–Mail: milos.gregor@hydrooffice.org

Dr. Alexander K. Stewart
Department of Geology, St. Lawrence University, Canton, NY, USA
E–mail: astewart@stlawu.edu

Dr. Cristina C. Bicalho
Environmental Geochemistry, Universidade Federal Fluminense – UFF, Niteroi–RJ, Brazil
E–mail: ccbicalho@gmail.com

Dr. Lenka Findoráková
Institute of Geotechnics, Slovak Academy of Sciences, Watsonova 45,043 53 Košice, Slovak Republic
E–Mail: findorakova@saske.sk

Dr. Mohamed Omran M. Khalifa
Geology Department, Faculty of Science, South Valley, Qena, 83523, Egypt
E–Mail: mokhalifa@svu.edu.eg

Prof. A. K. Sinha
D.Sc. (Moscow), FGS (London). B 602, VigyanVihar, Sector 56, GURGAON 122011, NCR DELHI, Haryana, India
E–Mail: anshuksinha@gmail.com