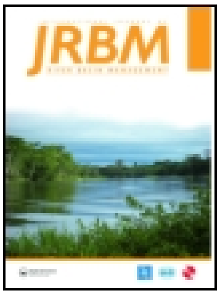

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What river morphology after restoration? The methodology VALURI

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Research paper

What river morphology after restoration? The methodology VALURI

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ABSTRACT
This paper proposes a tool which river managers may need to ascertain whether the key idea of River Restoration is valid, i.e. that rivers in more natural status are desirable not only for pure environmental reasons, but also to combat flood and geomorphic risk. The point addressed is how to predict the morphology and geometry that a river will assume after the application of a River Restoration project which foresees significant changes in the system of defence and exploitation works as well as morphological adjustments (e.g. reconnection of an incised main channel with the surrounding ex-floodplain). To this aim we developed a semi-quantitative methodology that integrates several differing criteria: from historical analysis of geomorphic evolution, expert-based mechanistic reasoning, checking with empirical qualitative formulas and analytical support from fluvial geomorphology and classic hydraulics. The development of the methodology has taken place on a case study along the 80 km of Chiese River, downstream of Idro lake, in northern Italy. Although the product to be considered is just a pilot one, we see it as a promising tool, which also opens several challenging questions suited for further fascinating research work.

Keywords: River management; river restoration; hydro-morphological risk assessment; environmental cost–benefit analysis; integrated evaluation; Po-River basin (Italy)

1 Introduction

All over the world, the measures to reduce hydro-morphological risk have so far been driven by the paradigm of ‘putting the territory in safe conditions’ which relies on getting rid as fast as possible of flood water to avoid overflows, and by fixing the river and mountain slopes. All this implies hard interventions, like canalization, levees, weirs, retention tanks connected by artificial input–output works. There is perhaps no need of references, as the world is full with this kind of interventions, most of which date back to the end of the nineteenth century, and much earlier in some countries (e.g. Italy, as shown in the case study below). On the other hand, damages are increasing (see, for example, Cellerino 2004, for the Italian situation), partly because land use is getting more and more urbanized, partly because hydrological events are getting perhaps harsher, and partly because interventions have too often negatively modified river behaviour.

A growing number of scientists and practitioners think that a different paradigm is needed, one which works with nature, rather than against it, and define it as River Restoration (RR; see for instance Bernhardt and Palmer 2007; Kondolf *et al.* 2007; Mika *et al.* 2010; or the web site of the European River Restoration Centre www.ecrr.org). One of the current key challenges of RR is to demonstrate that indeed more natural rivers are rewarding and socially desirable not only for purely environmental reasons, but also because they can reduce risk or, at least, the total cost of expected risk, including investment and maintenance of interventions.

This issue lies at the core of the possibility to successfully answer both the requirements introduced in Europe by the Water Framework Directive 2000/60/EC (WFD in what follows) – i.e. to achieve a good ecological status by 2015 – and those introduced by the Floods Directive 2007/60/EC, aiming at reducing flood risk and requiring risk mapping and identification of measures capable of controlling risk.

A broad-view RR project would consider the dismantling of levees, weirs and bank protection works; it would try to give space back to the river by purchasing land and/or by establishing working agreements with land owners/users, so that the environmental services they provide – such as the general reduction of

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flood damage by bearing locally part of the damage – could be recognized and remunerated.

In this context two issues need to be tackled. First, in order to perform a flood analysis, the future morphology of the river needs to be predicted, basically by trying to assess what will happen once new works were to be implemented or existing ones dismissed. Second, particularly in Mediterranean countries, it is necessary to consider, together with the flood problem, also the associated hydro-morphological risk represented by bank erosion and landslides problems, by identifying the river erosion/divagation corridor.

Any RR project that aims at contributing to risk management needs to undertake this exercise, a very 'challenging' one to both river geomorphologists and hydraulic engineers, but one which is often neglected.

What is needed is indeed an instrument that enables us to make predictions of river morphology, considering all relevant physical driving forces and constraints acting on the river in a particular *alternative river setting* under consideration. This includes the water management decisions, such as reservoirs and withdrawals management, the administration of land use and vegetation cover, as well as the setting of all defence works (like bank protections and levees), exploitation works (like weirs or navigation locks), and river interventions (like periodic sediment removal or cross-section reshaping).

The ideal tool would be a mechanistic physically based model. Several models belonging to this category do exist (Kovacs and Parker 1994; ASCE 1998; Menéndez *et al*. 2008). At the moment, however, none of them is at the same time really sufficiently versatile and viable, close enough to reality to include all main processes, and sufficiently economic in terms of needed data, to carry out reliable, medium–long-term simulations at the spatial scale of river corridors. The processes that should be captured develop over decades, even centuries, involve dozens of kilometres and include change of river type, as artificialization often drastically has modified the inner nature of the river, transforming wandering rivers into monocursal sinuous or rectified channels. Consequently, change of depth, width and slope has to be considered, together with riparian vegetation and river bed interaction with artificial structures and human interventions.

For meandering rivers, there exist models that, through a suitable description of the field of motion within the river bed, provide computationally tractable and sufficiently reliable solutions of planform evolution (Zolezzi and Seminara 2001; Frascati and Lanzoni 2009). However, only very experienced staff can operate them, and some weaknesses in their applicability are present. For instance, they are very sensitive to the assumptions introduced, among others, to model bank erosion, a process very site specific, nonuniform, intrinsically intermittent and quite complex (Darby and Thorne 1996; Darby 1998; Darby *et al.* 2002). Then, they generally require an extensive *in situ* information on river characteristics, definitely far from applicable to most planning purpose cases (Kean 2003; Constantine *et al.* 2009), although perhaps the use of historical maps to calibrate the speed of meanders displacement could partially overcome such a difficulty. More in general, most mechanistic models would not be able to treat the rather frequent situation of rivers suffering from incision because of rectification and canalization, for which a structural restoration action would definitely see a significant change in river bed width and depth. Besides, simplified hypothesis on hydrologic regime, considering constant bankfull or average flow, embedded in such models do not allow us to consider how a change in water regime, typically affected by reservoir management, but also by significant water withdrawals, will influence the future morphology.

Some software, like for instance the well-known HEC RAS (USACE 2010) can perform to some extent simulations of channel evolution, but the morphological prediction is limited to the definition of the scour or deposition tendency over moderate time periods. Therefore, HEC RAS is generally used to verify hydraulic conditions and sediment transport potential after some changes have occurred in the river geometry (MacWilliams *et al*. 2010; Sholtes and Doyle 2011), but not to predict the new river geometry itself and particularly the change of fluvial typology or variations in length, etc.

Another class of river geo-morphological models is denominated as 'cellular models', like CAESAR (Coulthard *et al*. 2008), in which the river spatial domain is represented by means of single cells, and the morphological evolution is governed by deposition/erosion processes within each cell, and by the interaction with adjacent cells (Murray and Paola 1994; Nicholas 2005). Initially, CAESAR drew considerable interest as it was the first model able to describe a shift in fluvial typology from meandering to braided. However, the model can reproduce similar types of behaviours only if the user voluntarily specifies suitable characteristics of the cells where a change is thought to occur (e.g. the cells along the external boundary of a bend, when a meander shift is 'expected'). In some senses, CAESAR is a tool that 'does what the user tells it to do' and hence to get meaningful results, one needs to already know…the correct answer. This fact, together with the oversimplification of the hydraulic behaviour, makes us conclude that such type of models currently does not offer the concrete ability to provide reliable and practical answers to RR questions, although they are stimulating tools for investigating the inner nature of river dynamics.

More in general, all models need a quantification of all variables involved, including in particular the water and solid flows incoming into the studied river head section, a key information affected by very high uncertainty. A semi-qualitative methodology, like the one proposed here, is somehow free from this binding requirement, because prediction relies rather on a logical thinking and on the comparison of basic differences in behaviour between a given solution of river setting (set of works and initial morphology) and current configuration, once historical behaviour and current trends are understood.

In the future, thanks to progress in scientific research in river behaviour as well as in monitoring and remote sensing data acquisition, in parallel with computers power, mechanistic and/or cellular models will probably offer the sought solution. For the moment, however, we can say that this is not yet the case.

An alternative approach is that followed by fluvial geomorphologists and relies on basic laws of hydraulics and solid transport, together with accurate observation and measurements of real cases and statistical analysis. Among the most known, we can find Lane's (1955) theoretical relationship, obtained from the equations of fluvial hydraulics, or Schumm's (1977) relationships which include river cross-section geometry. These latter can support a qualitative prediction of morphological changes particularly when a change in the control variables water (Q) and solid (Q_S) flows is foreseen, as shown by the following equations (↑: increase; ↓: decrease):

$$Q \uparrow \rightarrow w \uparrow, d_{50} \uparrow, \lambda \uparrow, S \downarrow \tag{1}$$

$$Q_S \uparrow \rightarrow w \uparrow, d_{50} \downarrow, \lambda \uparrow, S \uparrow, p \downarrow \tag{2}$$

where d_{50} is the 50th percentile of sediments diameters, S the slope, w the bankfull width, l the meanders wavelength and p the sinuosity index.

More recently, other authors provided further insight and strength in this type of relationships, like in particular Kellerhals and Church (1989) and others.

These qualitative tools are seen here, however, as a valuable support within an articulate procedure, rather than the ultimate resource for prediction. Indeed, RR mainly concerns the response of artificialized river systems after (part of the) works are removed, which means that each case is a very special case, in general definitely far from available data sets, and which requires an *ad hoc* reasoning. This is why we developed a methodology which integrates a number of different criteria, so taking advantage of different types of knowledge and wisdom, starting from historical analysis, an idea – this latter – that has already been applied by others, like for instance by Ashmore and Church (2001), for Canada's rivers, and by Chin (2006), in her interesting world review of urban catchments.

On the other hand, historical behaviour is not considered at all by the methodology FISRWG (1998), which is – as far as we could investigate – the one closest to our proposal.[1]

In this paper an application to Chiese River, in northern Italy, is shown. It has to be considered as a pilot case study, since our methodology was conceived and developed during this application. Nevertheless, we believe that the methodology developed for Chiese River is of quite general validity and offers a path for similar applications to a wide class of water streams.

2 Approach and methodology

2.1 *Problem definition*

We consider a river at the corridor scale, with its current morphology, planform pattern, longitudinal profile, bankfull depth and width, cross-section shape and type of substrate, water regime and riparian vegetation, together with all the anthropogenic actions acting on it in terms of works aiming at flood protection or exploitation/regulation, channel maintenance (e.g. sediment periodic abstraction, section reshaping) and current management of water withdrawals. This set of elements will be referred to as 'the river setting'. The water and sediment flow inputs from the upstream catchments are considered given and not varying among the alternatives unless they affect the upstream catchment (see also the Limitations section); it rather conforms a *scenario* under which the prediction is being performed.

The VALURI methodology starts considering a set of *alternative river settings* (simply 'alternatives' in what follows). For each of them, a new set of flood defences and exploitation works is defined together with a possibly modified initial morphology (as a consequence, for instance, of removing weirs, dismantling levees, or renewing the connection between channel and previous floodplain through excavation of what is currently a new terrace).

In correspondence with each *alternative*, a new dynamic equilibrium is assumed to establish, soon or later, where 'dynamic' means that changes in shape and position will continue to occur, but in statistical terms its own characteristics (morphotype, sinuosity, slope, bankfull depth and width, sediments size, etc.) will remain the same, if seen at a management time scale of tens of years.

The problem posed is hence to predict the future equilibrium morphology for each *alternative*.

2.2 *The proposed approach to geomorphic prediction*

In essence, the approach we propose is based on the historical geomorphologic evolution, current equilibrium analysis, together with mechanistic expert-based reasoning, supported by some analytical hydraulics.

2.2.1 *Geomorphological analysis*

The historical geomorphologic analysis (*river history*) together with the assessment of current equilibrium state, leads to a (sometimes very simple) *interpretative theory* that tries to capture and explain how river did behave and why. The hypothesis is then introduced that the river tries in essence to follow its own *river style* (Brierley and Fryirs 2005), except when an irreversible change has occurred (as when, for instance, the incision completely consumed the alluvial mattress). Following its own *river style* does not imply re-taking the same setting, but possibly just a similar morphology and behaviour; e.g. after removing rectification, it can return to be meandering, but perhaps all translated at a lower level within the floodplain, because of irreversible incision. In any case, the most important point is the assumption that understanding from *river history* how the river responded in the past (interpretation theory) is a key support to infer how it will likely respond in the future to current and new interventions. This is the scope of the *interpretation theory.*

2.2.2 *Mechanistic expert-based reasoning*

The mechanistic, morphological-engineering reasoning (in line with what Degoutte 2006 presents in his illuminating book), together with qualitative relationships from fluvial geomorphology (Lane 1955; Schumm 1977; Kellerhals and Church 1989), provides a guide to infer what changes are likely to occur. A key consideration concerns solid transport capacity: *the river will evolve seeking a new morphology consistent with the transport capacity needed to cope with the* (*possibly modified*) *solid and water inputs, given the* (*modified*) *physical constraints* (*works, topography, substrate, banks sediments type, etc.*). An example of such a reasoning is as follows: for a river reach with meandering nature and current state 'stable moribund', i.e. blocked by longitudinal defences and incised: if such defences are removed, but a downstream weir is kept, banks are progressively de-stabilized; as a consequence, local solid input from banks increases, while river's inner nature 'wakes up' and it starts meandering; furthermore, if it were originally wider, and incision narrowed it down, most probably it will widen. River path gets longer because of meandering thereby reducing slope, but in order to keep a suitable (increased) solid transport capacity, it has to increase its slope; hence the longitudinal profile will rise pivoting around the downstream weir. This kind of reasoning has to be done for every river reach.

2.2.3 *Analytical support from fluvial hydraulics and fluvial geomorphology*

From the above steps, a very wide range of arbitrariness still remains. This additional criterion provides a quantitative constraint among the several unknowns to reduce such arbitrariness. The main hypothesis introduced here is that, in fully alluvial stretches, the bankfull discharge Q_{B} coincides with the effective flow Q_{E}, i.e. the flow that maximizes the expected solid transport, because it is this relatively high, but quite frequent flow, which in the average determines the shape of the active river bed. This is definitely not true for some categories of river stretches (e.g. fixed bed, arid water regime, highly artificialized, etc.), but can be considered a working hypothesis to be applied with expert knowledge (Williams 1978; Crescimanno *et al.* 1989; Petit and Pauquet 1997).

This step consists in practice of an iterative search of the channel morphology that produces a bankfull flow Q_{B} (approximately) equal to the effective flow Q_{E} defined as follows:

$$\begin{gathered} Q_{\mathrm{E}} = \arg\left[Q_{\mathrm{S}}(Q) \cdot \Delta P(Q) = \max\right] \\ Q \in (Q_1, Q_2, \ \ldots\ Q_n), \end{gathered} \tag{3}$$

where $\Delta P(Q)$ denotes the probability that the flow Q falls within the discrete interval of flow values $[Q_i, Q_{i+1}]$, and can be expressed in terms of recurrence time T_{R} of such flows

$$\Delta P(Q_i) = \left[1 - \frac{1}{T_{\mathrm{R}}(Q_{i+1})}\right] - \left[1 - \frac{1}{T_{\mathrm{R}}(Q_i)}\right] \tag{4}$$

assuming that for Q_n, $T_{\mathrm{R}}(x_{n+1}) = \infty$.

Notice that this implies, for each river stretch, a nontrivial procedure at each return time T_{R}: in fact, a corresponding flow-rate $Q(T_{\mathrm{R}})$ is determined hydrologically for that stretch (typically by a hydrological model); then, for each trial value of slope (assuming a cross-section shape class and roughness coefficient) the corresponding water height (and width, etc.) is determined so that its associated flow-rate $Q_{\mathrm{H}}(T_{\mathrm{R}})$, determined by classic hydraulic relationships (Chèzy or Manning, steady state), coincides with the hydrological value $Q(T_{\mathrm{R}})$. This last step usually requires solving an implicit equation which has no closed-form analytical solution (unless when the cross-section shape is trivially simple). The corresponding geometry is then used to determine the solid flow $Q_{\mathrm{S}}(Q(T_{\mathrm{R}}))$.

An additional support is offered by empirical relationships derived from fluvial geomorphology which can be used as a test to check whether the inferred future typology is consistent with some of the variables considered (e.g. given flow and slope, the typology should be 'sinuous'; see case study for details).

2.2.4 *Consistency*

The predicted river morphology must be both coherent with the surrounding topography and intimately coherent among reaches. In particular, the bankfull water elevation of the river cannot exceed bank-edge elevation; if this occurs, it means that the foreseen morphology is not physically feasible and needs to be modified accordingly. The opposite case, however, is possible, because incised rivers, when restored, tend to re-create a smaller floodplain at a lower level than the original one (Rosgen 1997).

Besides, all the reasoning and predictions developed for each reach should be considered all together to ascertain that there is mutual consistency. As an example, if it is predicted that a reach aggrades its bed around a downstream pivot (weir or rock formation), the upper edge of its bed will raise to a higher elevation which will also characterise the end of the upper reach; or, if there is a diminution of solid transport capacity, a sedimentation tendency with reduction of sediment flow downstream should have been envisaged, and so on with similar reasoning. From a practical point of view, however, this is exactly the kind of relationships that only a mathematical (or physical) model can really respect; manually, we can only approach some of them.

The historical analysis is, in our opinion, fundamental, particularly in rivers that have experienced heavy anthropogenic alterations. It provides a comprehension of the type of river and its behaviour and reaction to several possible causes of alteration. In essence, the idea is that, by knowing how the river reacted in the past to given interventions or modifications of the control variables, one has a strong basis to infer what it will do in the future, also as a consequence of new interventions.

2.3 *The prediction methodology in practice*

Once relevant *alternatives* have been defined, the above criteria are implemented following a number of steps. First of all geomorphic homogeneous river stretches have to be identified. The River Styles methodology proposed by Brierley and Fryirs (2005) is particularly suitable and can be used. Then, for each stretch (which does not exclude looking at the river as whole), one has to:

(a) develop the river history and interpretative theory;
(b) assess current equilibrium state (by comparison of recent aerial photographs with 10 – 20 years interval, analysis of differential transport capacity of stretches, field observations, etc.);
(c) identify 'fixed points' (e.g. weirs, rock formations, rigid longitudinal defence, etc.) that are assumed to be present in the alternative considered and that fix to a certain extent the river bed in some points,
(d) infer, from the interpretative theory and the response of equilibrium assessment, how will the river stretch respond to the considered alternative, in qualitative terms;
(e) speculate, as a first trial, which will be the corresponding new equilibrium bankfull geometry (slope, length or sinuosity, width and depth), by applying mechanistic-engineering reasoning and qualitative relationships;
(f) (for fully alluvial stretches) modify the guessed geometry until, by trial and error, the corresponding bankfull flow Q_B acceptably equals the efficient flow Q_E and check, with empirical relationships, whether the identified features are consistent with empirical evidence. In our case study, we assumed a steady state, uniform motion relationship between flow rate and hydraulic variables (wet area, hydraulic radius, etc.), obtained from classic hydraulics (water profiles);
(g) for the whole river corridor, possibly iterate on the assumed geometry of all stretches until topographic and system consistency is found.

Finally, for the river corridor, geometry has to be translated into planform by respecting the predicted typology and length and by considering geomorphic evidence and the fact that river evolution will somehow be controlled by avoiding, as far as possible, to touch urban settlements (through pointwise, bio-engineering interventions). This is the weakest point and is discussed further below.

It is perhaps useful to stress that our methodology relies in summary very scarcely on equations, while its basis lies in the historical investigation and in the knowledge of engineering-mechanistic rivers behaviour. Equations are adopted only afterwards in two different and complementary ways:

(1) where meaningful (i.e. for alluvial stretches), we assume that $Q_B = Q_E$ as a support to reduce indetermination of the unknowns; to apply this criterion operationally, a specific equation has to be utilized for solid transport and hydraulic profile to determine both elements and then, by trial and error, find the appropriate geometry that fulfils such a condition; but the choice of which equation to use is totally open and depends on the context;
(2) on the other hand, and in parallel, empirical equations are used just as a check to guide the prediction (only for those stretches where the validity of the formula can be reasonably assumed): if the predicted geometry is consistent with what the formula indicates, prediction if considered definitely more reliable than in the opposite case; and in this latter, possibly further search of a consistent geometry is undertaken.

3 Case study

The methodology was developed and applied to the whole stretch of Chiese River, downstream of Lake Idro – one of the piedmont post-glacial natural, but regulated lakes of northern Italy – until the confluence with river Oglio (Figure 1). Some significant data are reported in Table 1. Most of the river runs in a semirural area, touching several small towns and rural settlements. Almost its entire course is highly artificialized with several big size weirs and semi-continuous longitudinal defences, and big, sometimes multiple, levees. Some examples of this works and some representative cross-sections belonging to the stretch between Montichiari and Acquafredda (about 15 km long) are illustrated in Figure 2.

For this river, the River Po Basin Authority (AdBPo 2004) had developed a feasibility study (SdF in what follows) to define the proper hydraulic setting to combat flood risk; the proposal from SdF included some interventions of partial restoration, mainly afforestation of river corridor and removal of obsolete defences, but also several new defences or adjustments of existing ones.

We wanted to investigate whether a different solution, with much 'less concrete in the river', could imply significant economical savings in terms of works not implemented and/or OMR (Operation, Maintenance and Replacement) costs avoided, while the risk increase could be kept sufficiently low, and the ecological status improved.

To this aim a number of *alternatives* have been defined.

3.1 *Considered* alternatives

We defined a number of different *alternatives* all based on the existing setting and the setting foreseen according to SdF. In the end, owing to the heavy burden of elaborations required

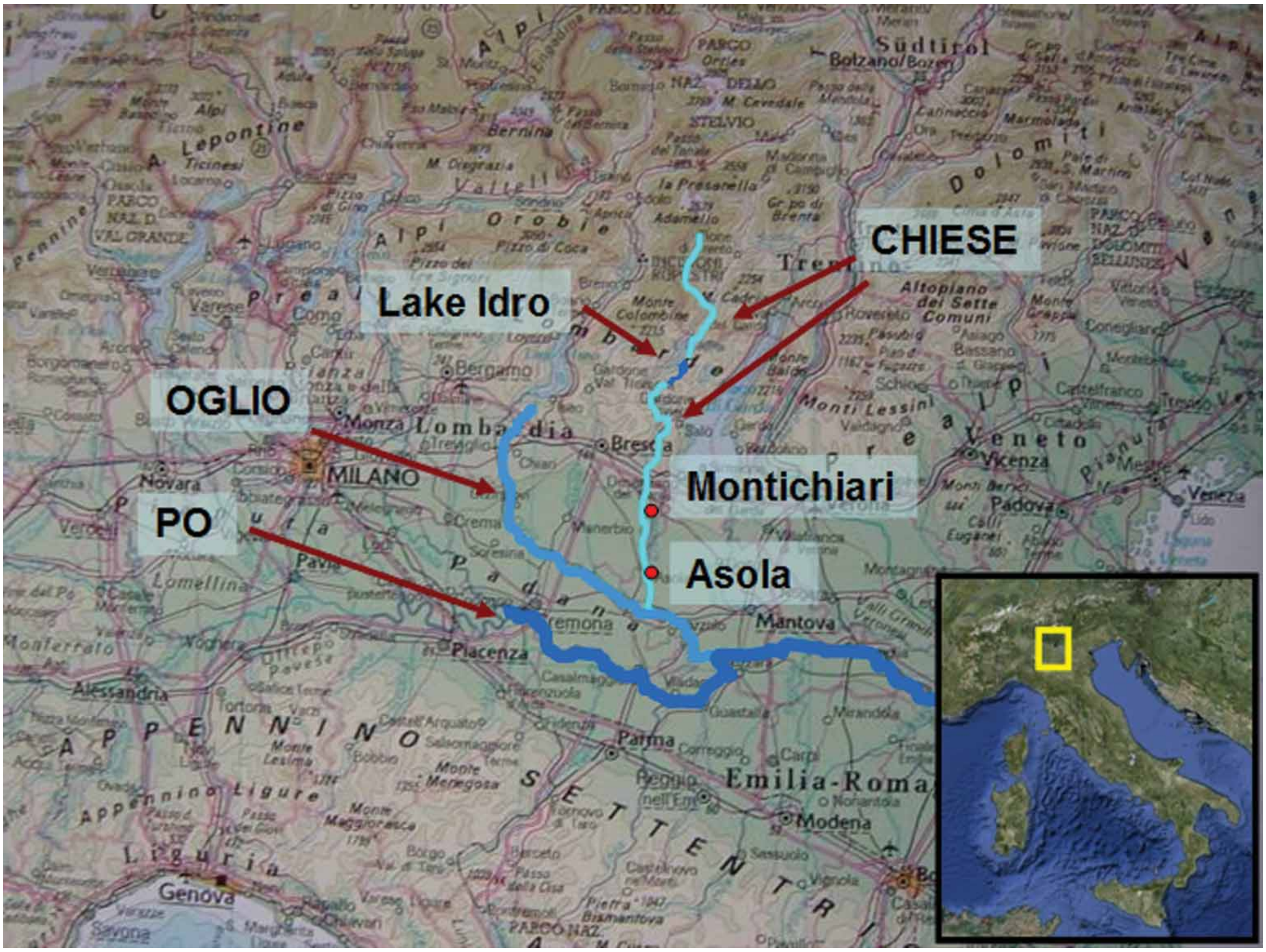

Figure 1 Chiese River case study location. The yellow square indicates the river position in northern Italy. Montichiari and Asola are two of the most important towns touched by our river

for the whole analysis, only three of the *alternatives* were fully analysed:

- ALT_0: the ‘quasi business-as-usual’ *alternative*, which implies high OMR costs for keeping the current defence and exploitation works system and some pointwise, urgent interventions that were considered mandatory by River Po Basin Authority.
- ALT_SdF: this represents the solution proposed by AdBPo (2004) which basically espouses the criterion of putting the river corridor in safe conditions – where land use is other than just unexploited natural areas – with respect to the 200 years recurrence time T_R flood.
- ALT_Base: this is a first step of restoration which implements the criterion of eliminating as much as possible concrete works, while keeping the impact on the anthropogenic system as low as possible. Let us say that it implements a ‘prudent’ strategy, because it makes a step forward for improving the ecological status, but without much glamour, while raising the flag of a search for increased efficiency through savings.

Table 1 River Chiese main features.

Catchment area	1400 km^2
River length	180 km
Studied stretch	80 km
Average flow	33 m^3/s
Maximum flow (T_R= 200 years)	750 m^3/s
Idro Lake volume	747 Mm^3
Idro Lake regulation volume	75.5 Mm^3

The definition of an *alternative* is an iterative process; indeed, after a preliminary definition is specified and geomorphic prediction and flood behaviour analysis are carried out, meaningful or necessary modifications can often be easily identified in order to achieve a more efficient performance. For instance, flood analysis may reveal that without a certain levee (that RR approach would have initially eliminated) a too large/sensitive area would be affected by flooding; hence, that levee (or a modified, more environmentally friendly version) should be re-introduced,

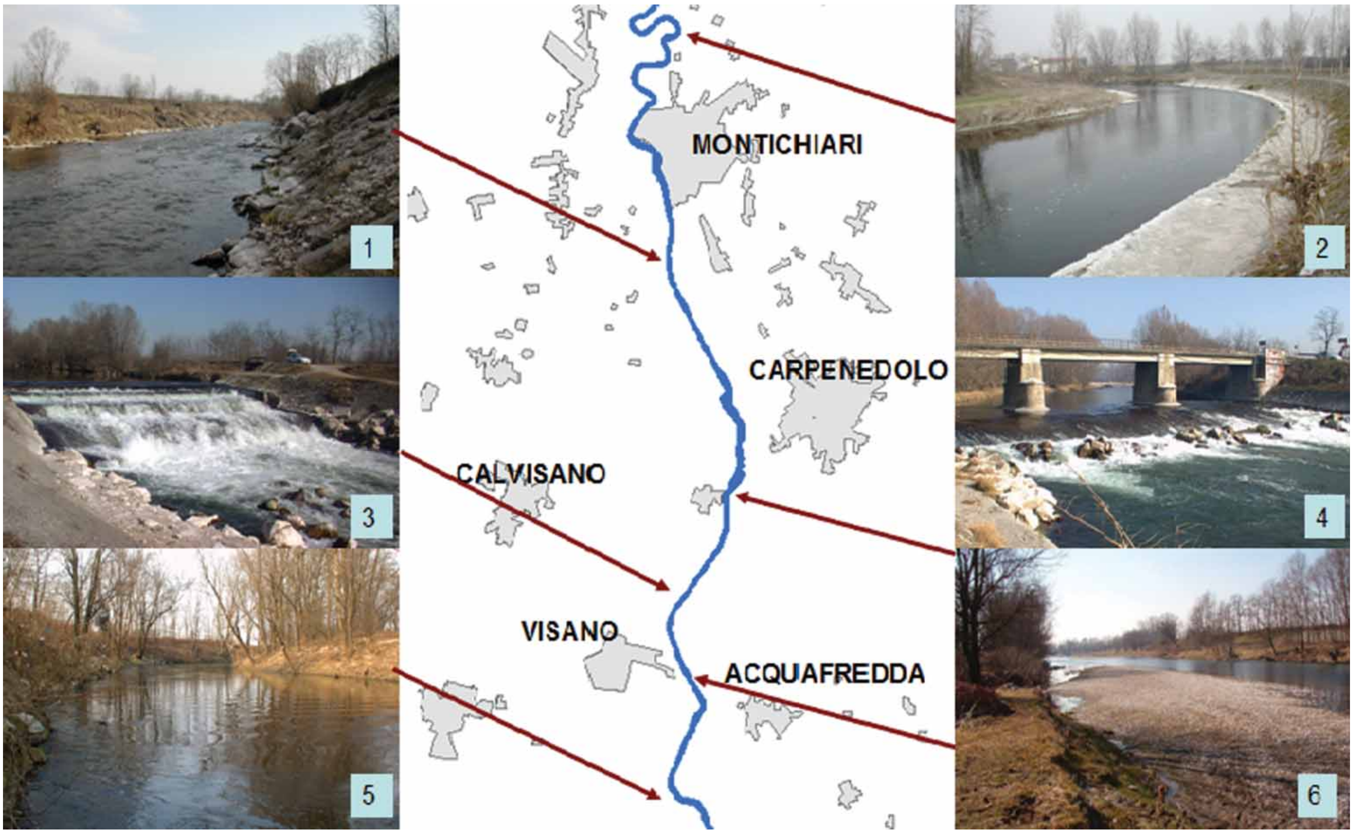

Figure 2 Examples of engineering structures along river Chiese. (1) Rectified reach, now sensibly incised downstream Montichiari, characterized by high levees and extensive bank protection; (2) concrete bank protection in a meander bend upstream Montichiari; (3) one of numerous barrages for irrigation purposes; (4) bridge downstream Carpenedolo protected from erosion by a rocky bed sill; (5) and (6) quasi-natural cross-sections near Acquafredda

hence in fact modifying the original alternative; therefore, a new prediction exercise has to be carried out and so on. Expertise and common sense drive this process and set its sensible end. Our ALT_Base eventually evaluated is indeed a modification of the one originally defined.

It has to be noted that currently more than 200 engineering structures (works) exist on our river and several others are planned in the SdF, so that defining an *alternative* is a challenging and lengthy work that implies a preliminary assessment and a decision for each work and the compilation of a thorough description. Figure 3 gives two examples of the engineering works setting corresponding to the three *alternatives* defined.

3.2 *River history*

A preliminary step is the identification of homogeneous geomorphological stretches, which has been carried out according to the river style methodology of Brierley and Fryirs (2005) slightly adapted to take into account the presence of works. The following attributes were considered and evaluated (see Figure 4 and the column 'Morphological characterization' of following Table 2):

- *confinement degree* imposed by the valley: topography, landscape units, valley width and slope,
- *planform*: morphological type, river bed sinuosity,
- *artificiality*: presence of works that impact lateral (longitudinal defences or levees) or longitudinal continuity (weirs or jumps),
- *set of geomorphic units in the corridor floodplain*: terraces, paleo-courses, sediments bags, morainic deposits, related wetlands,
- *set of geomorphic units within the river bed*: bars, islands, pools, natural levees,
- *river cross-sections*: shape type, aspect ratio, symmetry, size, presence of banks/ledges,
- *sediments*: type of material composing the river bed; type of supposed transport (suspended, bed-load, mixed).

To investigate the historical behaviour of the river, several official sources have been consulted. The search started from official State Archives of Milano, Mantova, Brescia and Venezia, and continued through the documents of River Po Basin Authority, of local irrigation associations and AIPO (Po Interregional Agency), which is the main hydraulic works implementing agency.

The most interesting pieces of information were the ancient maps (an example can be seen in Figure 5), dating from the early 1900s, back to about 1400, and the writings among engineers, stakeholders and administrators of those times who were repeatedly discussing the most appropriate interventions to be executed. Amazingly, in some cases, the same problem and the

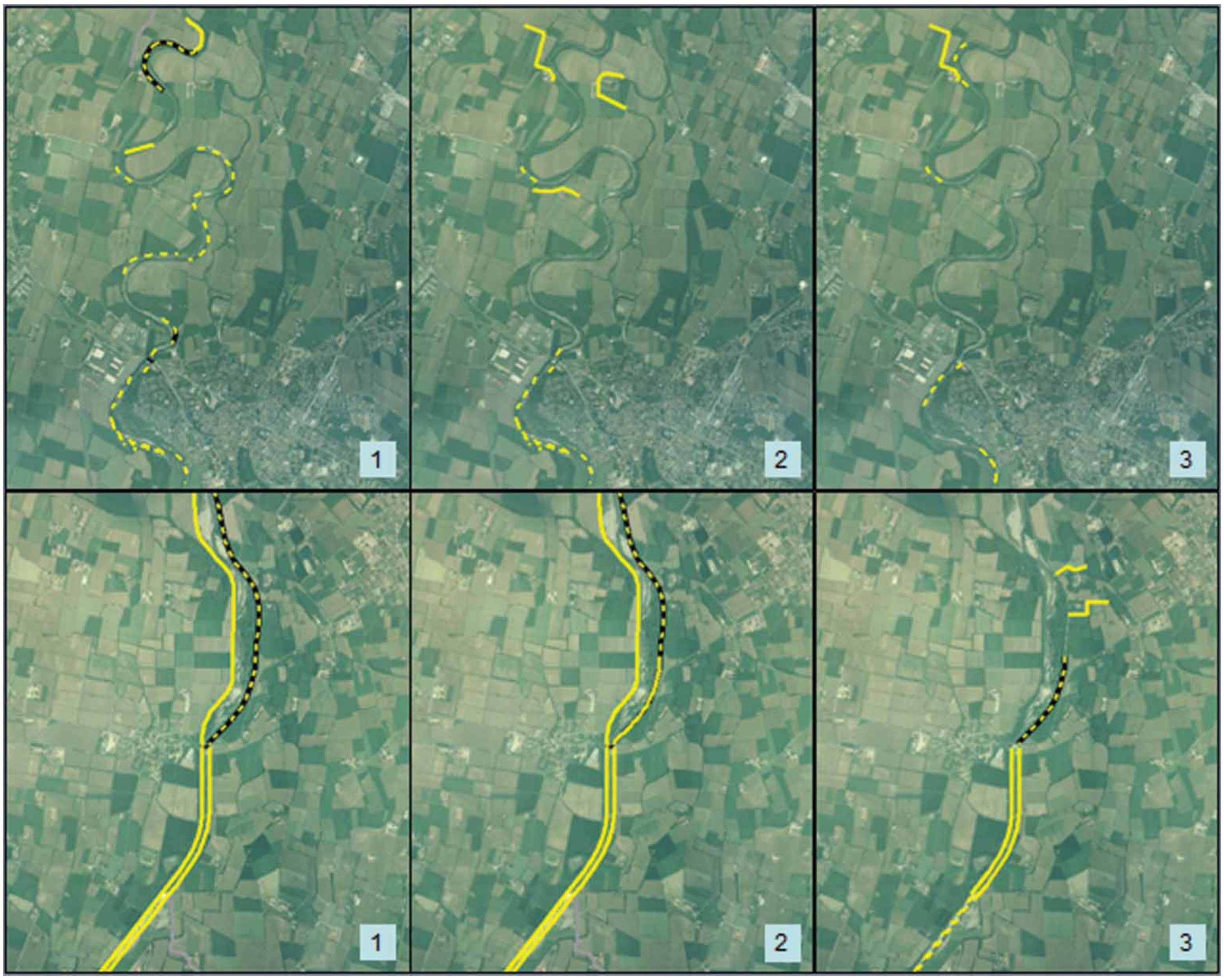

Figure 3 Two stretches of the river Chiese represented for ALT_0 (1), ALT_SdF (2) and ALT_Base (3). The first sequence of pictures refers to the meandering stretch just upstream of Montichiari (homogeneous stretch 20); the second sequence refers to the stretch just downstream of Carpenedolo (homogeneous stretch 23). One can clearly notice the difference in terms of works presence, which distinguishes the *alternatives* and which makes necessary the morphologic evaluation. Legend: covered levees, levees, bank protections

same solution (e.g. a bank protection) were re-proposed and re-implemented literally for centuries. For example, in the reach just downstream of Asola, stakeholders were fiercely debating, since at least 1428, the upstream flooding impact of an irrigation withdrawal weir. Recently, during the first days of November 2010, a damaging flood has occurred once again in the same area!

Based on such evidence, a *river history* has been built for each geomorphic homogeneous river stretch, as the example in Figure 6 shows. This information led us to set up a very simple *interpretation theory*, as represented in Figure 7.

This very simple theory was accompanied with the findings of the analysis of current equilibrium (not reported here, but foreseen in the steps of our methodology, as stated in Par.2.3 which showed that some reaches have not yet found their new artificialized equilibrium and indeed are still incising, which implies continuous and high OMR costs.

3.3 *Prediction of morphological changes*

3.3.1 *Prediction*

For each of such stretches, a new bankfull channel configuration has been predicted according to existing works removal or new works implementation, as explained above. To perform in particular the computations required to apply the fluvial geomorphology analytical criterion (Step f) an articulated computational sheet was compiled. This tool allows us to compute the uniform-flow discharge for any guessed geometry, through Manning's classic formula:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}. \tag{5}$$

The tool also determines the effective solid flow on a discrete basis as explained above, with respect to the flow-rates of recurrence times $T_R = 1, 2, 5, 10, 20, 50, 100, 200, 500$, and by

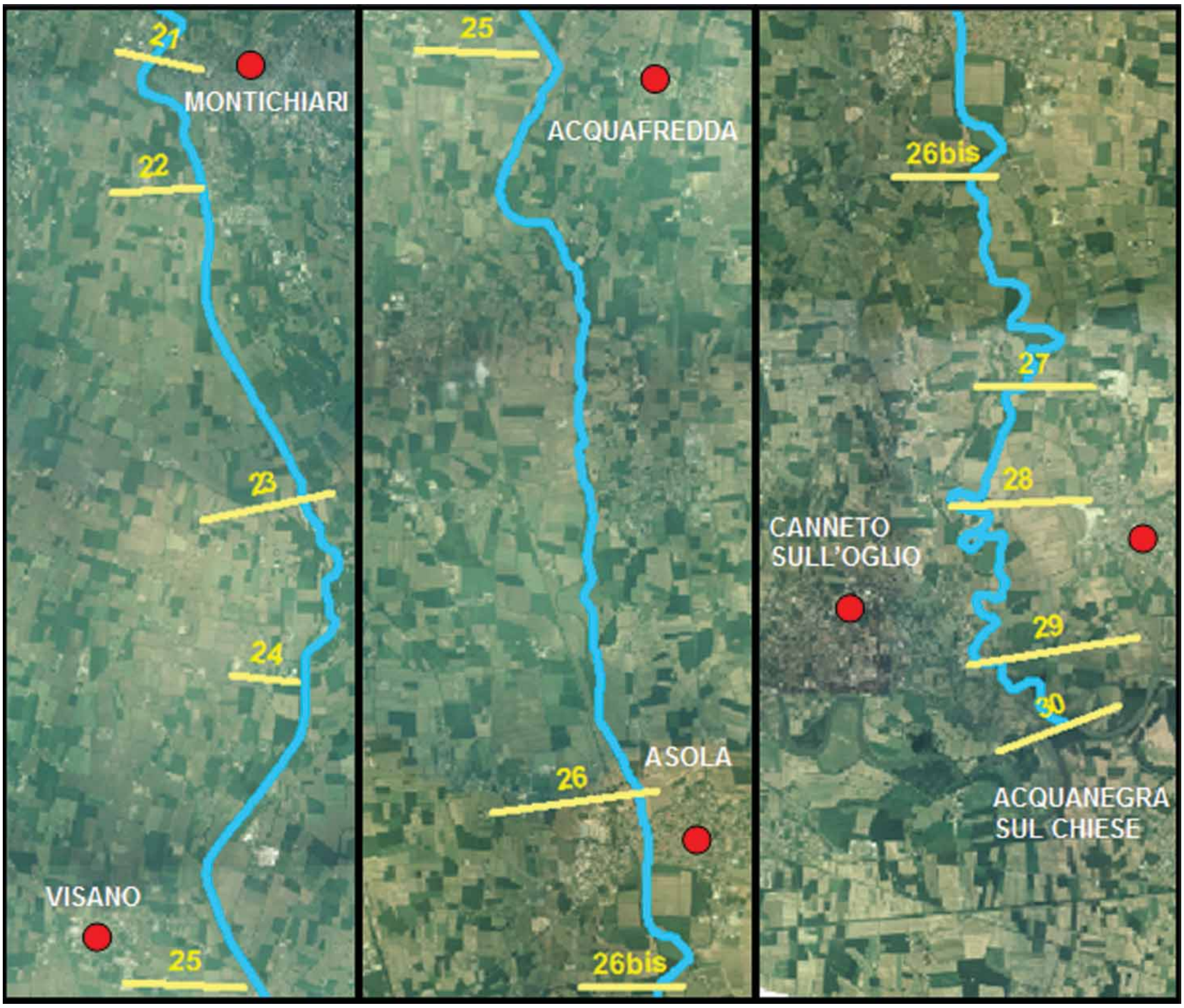

Figure 4 Identification of geomorphic homogeneous river stretches of lower Chiese River (left: upstream; right: downstream). The identifier of a Stretch is located at its head (the last one represents downstream boundary conditions)

determining the corresponding solid transport through a modification (Ramez 1995) of the classic Meyer-Peter and Muller (1948) formula :

$$q_S = 32(\tau * - \tau_S)^{3/2} d_{50}^{3/2}, \tag{6}$$

with

$$\tau * = \frac{R \cdot S}{[(\gamma_S/\gamma_W - 1)d_{50}]}, \tag{7}$$

where Q (m^3/s) is the water discharge, n (s/m$^{1/3}$) is the Manning coefficient, A (m^2) is the cross-section wetted area, q_S (m^3/s) is the dry solid transport capacity per unit of river width, γ_S and γ_W (N/m^3) are the specific weights of solids and water, respectively, S is the slope of the reach, R (m) is the hydraulic radius of the reach representative cross-section, τ^* is the nondimensional shear stress and d_{50} (m) is the 50th percentile of the granulometric curve of the bulk sediments. The nondimensional Shields' parameter t_s is the threshold under which there is no solid transport; according to Degoutte (2006), for uniform grain size (between 0.4 and 30 mm) it can be assumed equal to 0.047, while for non-uniform, armoured beds can be around 0.138, but in this case d_{50} refers to the bulk sediments including the armoured surface layer (see also Ramez 1995; Wong and Parker 2006).

In the case study we adopted a double rectangle for the cross-section geometry class (Figure 8).

3.3.2 *Check with empirical formulas*

To support the consistency of the qualitative conclusions on the morpho-type, the Leopold and Wolman (1957) empirical formula, as cited in Lebreton (1974), can be adopted. It gives the threshold slope $S_{\lim}$ beyond which the morpho-type is likely to be wandering or braided:

$$S_{\lim} = 0.013\ Q^{-0.44}. \tag{8}$$

Table 2 Synthesis of key results obtained from the prediction step for the alternative ALT_Base.

		Current							River story	Planning	Future						Applic.	FUTURE		CHECK
ID	Morphological characterization	d_{50} (m)	S (‰)	w_B (m)	h_B (m)	ΔH_T (m)	L (m)	Equilibrium status	Conclusions from River story	Works synthesis for ALT_Base	Engineering-mechanistic prediction reasoning	S (‰)	w_B (m)	h_B (m)	ΔH_T (m)	L (m)	FULLY ALLUV	Q_B (m^3/s)	Q_E (m^3/s)	Morpho type
21	Moraine piedmont, semi-confined, sinuous, gravel-cobbles, much defended with some vertical control	0.032	2.92	59.0	2.50	1.20	2113	Signs of local widening in the last decades	Suffered interventions to significantly limit its wandering character, probably only after 1976 (and not before of 1954). Works aiming at recovering floodplain on right bank, but do not seem ancient (possibly 1954). In the meantime, it incised (those same works appear too high on current bankfull and just between 1972 and 2002 it lost 1 m of elevation). Witnessing of destroyed works in 1976	Dismission of almost all defence works on the right bank; keep in place weir downstream	Will not change much, recovers its wandering nature and hence widens significantly; will tend to recover from incision and will simultaneously rise its elevation to keep sufficient slope to maintain and increase transport capacity, currently a bit too low. Consequently, current artificial total jump present will diminish and even reversed	3.07	150.0	1.30	−0.21	2113	YES-V	459	468	WANDER
22	Moraine piedmont, unconfined, rectified, gravel, much defended	0.049	2.84	35.8	3.23	0.30	4381	Incising at least in the upstream reach, while downstream is sedimenting and widening probably owing to a weir presence	Naturally wandering until the end of 1800; from at least 1954 defences and levees started: currently fully artificialized. Between 1885 and 1954 a progressive narrowing, simplification and incision were started (just between 1972 and 2002 lost 2.2 m) which is still undergoing. Downstream elevation has been artificially kept by the bridge weir. No witnesses of damages	Longitudinal defences and levees will be dismissed; downstream weir will stay in place (Reach 24)	Current residual excess of transport capacity provokes banks erosion ®–> it will widen and re-take its wandering nature (although less than before because, being incised, any unit widening moves a lot of material from banks). To carry the solid flow – increased because of renewed bank erosion – will probably increase a bit its slope, increasing elevation upstream; as previous one, current artificial jump will be buried	2.99	150.0	1.55	−0.55	4381	YES	564	551	WANDER
23	Moraine piedmont, unconfined, wandering, gravel	0.020	2.52	82.0	1.32	0.00	2456	Clear aggradation caused by a downstream weir	Partially defended and with levees since at least 1954, but definitely less than others: this is the wandering reach with more available space today. Anyway it suffered from narrowing and simplification from 1954 to nowadays. It has got a weir downstream which limited incision and, on the contrary, imposed an increment of elevation: between 1972 and 2002 it rose 1.2 m while diminishing slope. There are no important damages	ALT_Base will eliminate defences and levees exception made for levee CHAR1691b on left bank which revealed to be a key to protect from too frequent overflows. Downstream weir is kept in place (Reach 24)	Analogous to previous reach, but less evident as granulometry is finer and hence roughness is lower and the same flow passes with a smaller section	2.64	114.8	1.07	−0.35	2456	YES	253	257	WANDER
24	Medium plain, unconfined, sinuous-rectified, gravel, many defences, some vertical controls	0.015	1.12	34.6	2.12	7.50	4399	Clear tendency to incision with slight bank erosion	Wandering, then heavily artificialized with levees since 1885 and vertically fixed by weirs to allow for water withdrawal. Since 1885 it quickly narrowed down, simplified, shortened and incised. In 1807: upstream this zone the bed was similar to the one of the end of 1800, very dynamic (significant variations of the planform can be identified in few years), probably with a lower number of channels. However, at that time it already	Levees are eliminated (today they are inactive as the Q200 stays fully wihin the bankfull) and current longitudinal defences are substituted with bio-engineering ones. The weir at sect. 040.01S is lowered of the new bankfull height, otherwise would create a hanging bed.The rest is kept as it is	Nothing changes, but the width of 'lit majeur', as levees are dismissed (but defences stay), and the total artificial jump available is reduced because a weir within this reach is lowered in ALT_Base to reduce overflows (a problem old dating) (rigorously speaking some change should occur because of the increased solid input from upstream)	1.12	34.6	2.12	−0.04	4399	NO			SINUOUS

									passed through the site of current bridge. Incision went on until recent years: between 1972 and 2002 it lost 1.9 m. Destruction of some works and flooding occurred in 1966 and 1997											
25	Plain, semiconfined, sinuous, gravel, some vertical controls	0.011	1.37	39.7	3.34	5.87	10,504	Seems now close to stability with incipient bars forming, but still some signs of incision present (riparian trees and defences excavated) –>® can be defined 'stable moribound' with still an excess of transport capacity	It was meandering; then, several straightening interventions occurred (ex. meander cutoff in 1814, since end of 1800 banks are protected completely by levees); then a series of weirs followed which provoke, today, a large artificial jump. The elevation dropped, but less than one would expect because some weirs were built on purpose; anyway incision upstream occurred to reduce slope and, so, transport capacity (a fact that provoked a large artificial jump) and is currently still going on although a new equilibrium is closer (between 1972 and 1902 an average of 30 cm has been lost). Unexpectedly the length has a bit increased since 1885. In the lower reach, although not visible, straightening are very likely. Witnesses of several damaging events: (1951, 1966, 1976, 1993, 1997) with disruption of works and flooding	All defences and levees are eliminated, but weirs downstream the reach are kept in place as the withdrawal at section 034M, and so elevations are kept. A local protection with bio-engineering is implemented on the bend upstream the weir	Current residual excess of transport capacity will provoke incision, then banks erosion and then collapse –>® it will widen and re-take its meandering nature (although less than original setting because, being incised, any unit widening moves a lot of material from banks). The slope will progressively drop to reduce the transport capacity, now in excess because of rectification, to values close to natural ones (although a bit increased due to the increased availability of solid inputs from eroding banks, at least during transition). At the same time, it will get longer as sinuosity will increase, as well as elevation as previous reaches	0.96	50.0	2.20	−0.10	14,706	YES-O	232	259	SINUOUS
26	Plain, semiconfined, sinuous, gravel, some vertical controls	0.011	0.18	35.5	2.69	0.00	2737	As previous reach	Area prone to flooding and meandering. Various defences implemented since 1500 or before; since 1800, 80% with levees, which limited meanderization. A weir existing since 1800 – or much before (1400) with several adjustments – served Acquanegra agriculturers – requiring water withdrawal – by limiting incision, but provoked several conflicts with Asola town, flooded. Anyway, elevation dropped 50 cm between 1972 and 2002, but influence of downstream Oglio river, definitely incised, was blocked by the weir. After the 1976 flood suddenly widened and some islands temporarily appeared (now disappeared). Witnessing of damages to houses and agricultural areas and works in events of 1951, 1976 and 1993	Left and right protection levees of Asola are kept and reinforced, as well as along the whole reach –>® there is no fully alluviality (even because of weir control at sect.018S)	Assumption of no changes, in agreement with SdF	0.18	35.5	2.69	0.00	2737	NO			SINUOUS
26 bis	Plain, unconfined, meanders, sand	0.004	0.84	26.5	4.65	3.72	4350	Seems closer to a new equilibrium (several	Various protections existing since beginning of 1800 and	Levees dismissed almost	With no longer defences, will go back to its meandering nature; hence	0.34	50.0	3.00	2.82	13,050	YES	268	262	SINUOUS

(*Continued*)

Table 2. Continued

								Current	River story	Planning	Future						Applic.	FUTURE		CHECK
								riparian trees hanging, but quite old which speaks of previous incision now stopped; portions of plain sometimes flooded, contrary to upstream reaches; sporadic appearance of bars; signs of widening)	straightenings (designed in 1777 and implemented before 1831) which reduced meandering. It incised, as reminded by a huge weir with high jump at the beginning of reach, and between 1972 and 2002 lost 20 cm, while narrowed and simplified. To note that based on natural valley topography, this was the reach with maximum slope reduction, marking the beginning of plain; on the contrary, now it has a slope much higher than neighbouring reaches, while previous one has got a slope lower than its previous one and than valley. Witnessed serious damages in events of 1951, 1976 and 1993	completely –>® fully alluviality	will significantly increase length, and significantly reduce slope to get closer to a long profile consistent with the natural valley topography; will anyway rise a bit elevation because of a significant length increase. Furthermore, will widen trying to recover from incision and narrowing that had occurred									
27	Plain, semi-confined, meanders, fine sand, some vertical controls	0.003	0.19	27.7	4.62	0.00	1697	As previous one, but still some signs of incision	Several defences built during years; it was straightened between 1852 and 1862, previously followed path of right levee (present since the end of 1800); little free space left. Not much sensitive to Oglio incision because of weir in sect. 09.01 present since at least 1954, but still incised a lot (approx. 4 m) between 1972 and 2002, possibly because of progressive erosion from upstream and increase of transport capacity, now almost over; it also narrowed a bit and simplified. Slope more similar to original one than for other reaches downstream. Witnessing of damages in events of 1976 and 1993	Existing levees at Acquanegra are kept as well as the withdrawal weir downstream, but several defences are dismissed almost reaching fully alluviality	Will tend to its meandering nature hence increasing a bit its length, but not as much as previous one because significant incision occurred, any planform change implies huge volumes of sediments moved; accordingly, as solid input from banks increases (more initially and less in the long run), will need a slope possibly even (slightly) higher than current one to sustain transport capacity. Will also widen a bit to get closer to its previous status	0.21	50.0	3.20	0.00	2376	YES	244	263	SINUOUS
28	Plain, semi-confined, meanders, fine sand	0.003	0.50	27.4	4.89	0.30	4363	As previous one, but still some signs of incision	Few data available for this reach. Important straightening anyway occurred, but probably concentrated in a big meander. Slope is significantly higher than next reach slope (not fixed by weirs): natural valley topography presents almost the same pattern, but much less marked. Probably, it was significantly more meandering and longer (no previous elevation data available)	Existing levees at Acquanegra kept and foreseen (by SdF) levees at Bizzolano implemented. However, several levees on left bank are eliminated reaching almost fully alluviality	Thanks to newly obtained freedom, will go back to its meandering nature increasing hence length while reducing slope and the residual excess of transport capacity and to recover natural topographic setting, but only partially because solid input from usptream increases a bit and requires a bit higher slope. Furthermore, it widens a bit	0.33	45.0	3.00	0.00	6981	YES-O	251	263	SINUOUS
29	Plain, unconfined, meanders, fine sand	0.002	0.27	31.4	4.49	0.00	1780	As previous one, but still some signs of incision	Various defences occurred during years (continuous levees since 1800), but still a bit of freedom space as levees are never on the bank edge. River Oglio (downstream receptor) lowered by incision probably around 1950 – 1970 and even after, dropping also Chiese river	No works dismissed or built (in particular master levees are kept otherwise large floodplain would be often flooded)	Current slight bank erosion will lead to some widening and according bankfull height diminishing (probably more structural changes will take place anyway, affecting slope and length, but to maintain consistency with the SdF study no modification is assumed)	0.27	40.0	3.50	0.00	1780	YES-O	275	264	SINUOUS

elevation (between 1972 and 2002 1.35 m lost). Chiese narrowed and has got today a river bed with $Q_B > Q_E$, and perhaps still a residual excess of transport capacity (meandering was obstacled by defences, but not to at very high extent), although close to a new equilibrium. Witnessing of damages to settlements and works in events of 1933 and 1976

Note: In the columns heading: d_{50} is the mean sediment diameter, S is the bottom slope, w_B is the bankfull width, h_B is the bankfull depth, ΔH_T is the artificial total jump, L is the reach length. The applicability of empiric formulas is assessed by column 'Fully Alluvial', in which suffixes 'V' and 'H' beside 'YES' means, respectively, 'Fully alluvial with vertical or horizontal constraints'.

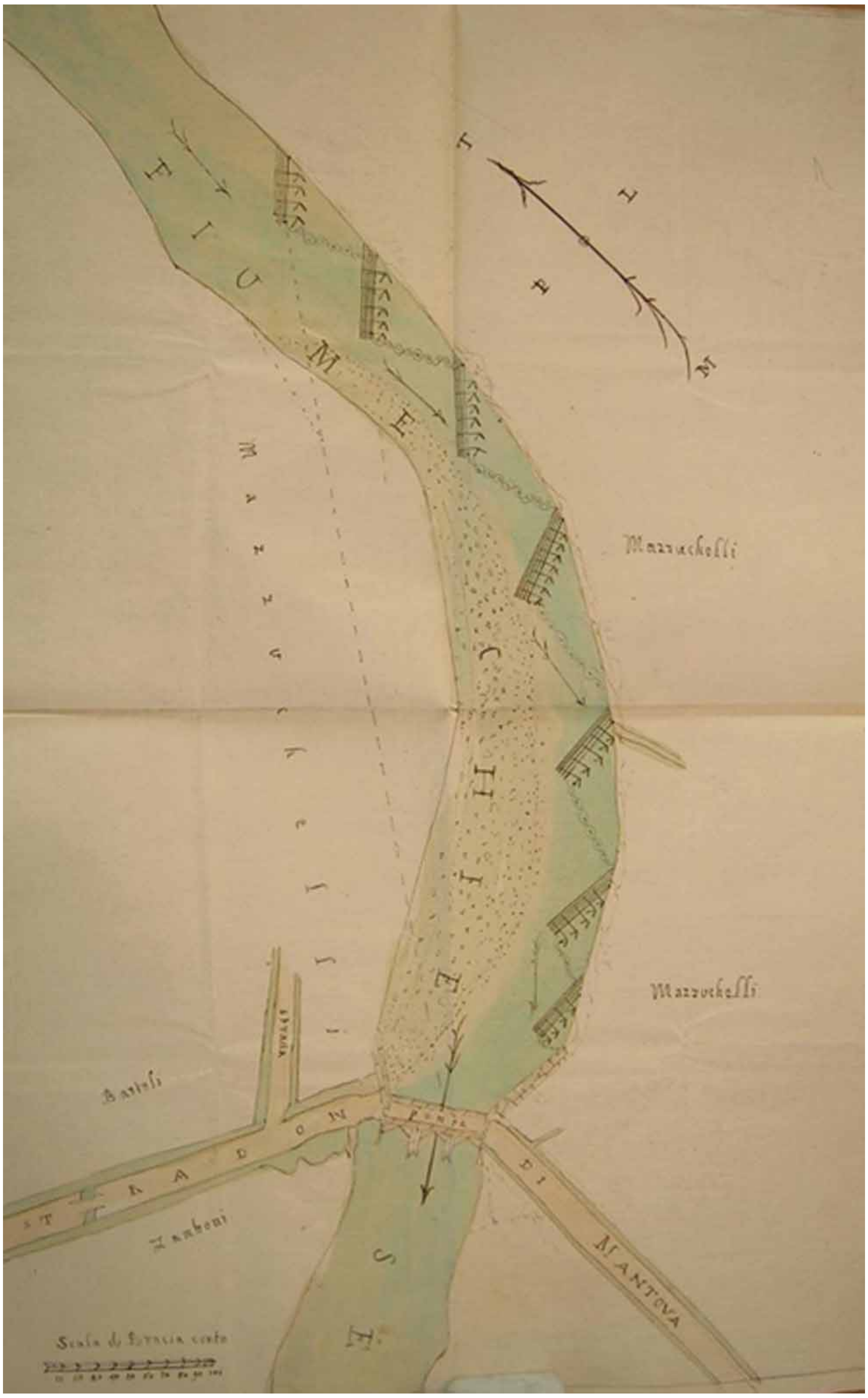

Figure 5 Milano's State Archive (I) – Folder of Genio Civile no. 483 (with permission of State Archive)

Another similar formula is the one proposed by Henderson (1966) (d in (m) and Q in (m^3/s) in both formulas):

$$S_{\text{lim}} = 0.5d^{1.14}\,Q^{-0.44}. \tag{9}$$

We adopted both formulas to compare results and obtained the same results, although both hold, strictly speaking, it hold only for river stretches in equilibrium. Of course, this particular choice of formulas is inherent in the specific case study and in general any other formula more suited to the case at hand can be used without altering the overall methodology.

3.3.3 *Results obtained*

Table 2 summarizes for ALT_Base only (because of lack of space) the key results obtained in the prediction exercise carried out for the three alternatives:

We report here only part of the prediction table in a very synthetic (and incomplete) form for reasons of space, by basically skipping the upstream, mountain portion of the river where

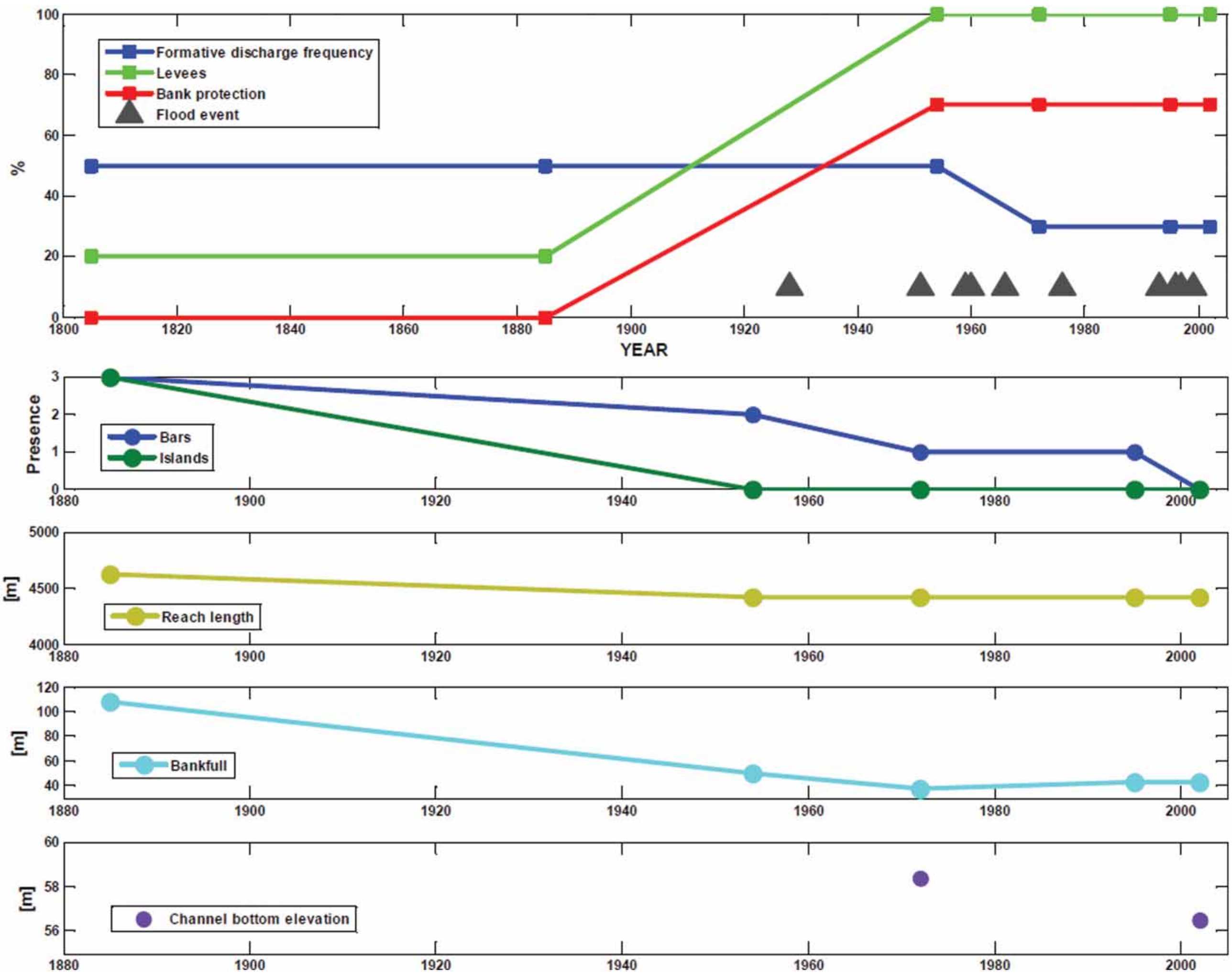

Figure 6 Example of *River history* for stretch 24 (shown in Figure 4). Top: the likely causes of morphological modifications: big floods (as recorded by historical documents), longitudinal defences and levees (the indicator is the *% total length of both banks protected*). The likelihood of formative discharge is reported contextually, through a qualitative indicator, reflecting the implementation of regulation works on the natural Lake Idro. Following below, some state variables are shown, reflecting the effects: number of bars and islands (progressively disappearing), width and length of stretch (narrowing and shortening) and river bottom elevation (incising). Major damages (not shown in this sketch, but investigated) are associated with more recent flood events, most probably because of the growth of urban centres and land use change

few variations of current setting are foreseen in our alternatives (and so substantially no morpho changes are foreseen) and, in general, stretches are not fully alluvial so that analytical conditions could not be applied, as occuring in particular for stretch 24 (grey cells). Furthermore, SdF study assumed no morphological changes for reaches heavily modified by works; as we wanted to produce results consistent with SdF results, we kept this assumption to ensure a fair comparison of risk assessment. The interpretation theory assumed is substantially the one already illustrated before (Figure 7). The increase in solid input in some reaches has a marginal effect on downstream reaches when a withdrawal weir is present because its periodic 'cleaning' still is common practice. Notice that prediction takes place from downstream towards upstream, but in the text we refer to 'previous' when mentioning upstream reaches.

Given a geometry, a corresponding plausible planform has then been identified according to the criteria already presented

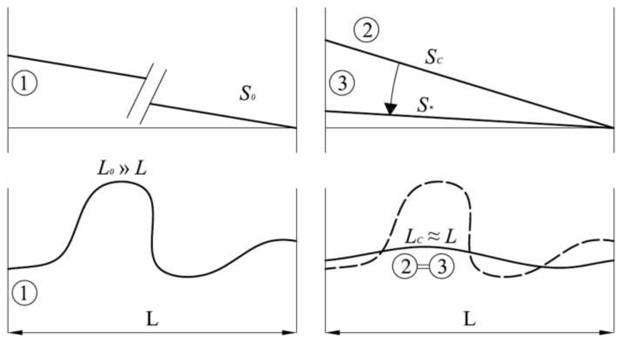

Figure 7 *River interpretative theory for Stretch* 24 (and many other), corresponding to the *River history.* (1) Original situation: meandering stretch of length L_0 with low slope S_0; (2) right after rectification: the stretch is shorter, $L_C \ll L_0 L_C \ll L_0$, and with higher slope $S_C \gg S_0 S_C \gg S_0$; (3) new equilibrium, assuming that upstream control variables Q and Q_S did not change: it has incised upstream, when downstream a weir stays in place (built and re-built several times), in order to reduce the excess of transport capacity until a slope similar to the original is reached

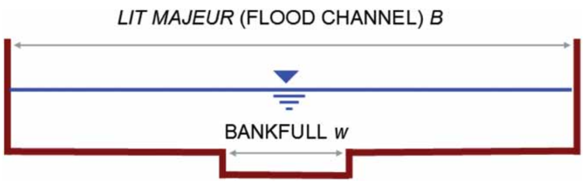

Figure 8 Cross-section schematization as a double rectangle

(Figure 9). We are well aware that the obtained planform is not univocal, but it has to be noted that to this work's aim, the exact location of the channel in the future possible configuration has a marginal importance. The key point of interest is the hydraulic behaviour, and the associated flood risk, corresponding to the new geometry. Of course, flooding depends also on the river position, but much more on vertical bed position and slope, than on exact planform position. On the other hand, we were concerned also with geomorphic risk from river bed divagation; to this aim, we traced a divagation corridor as the envelope of the historical and predicted bankfull positions.

3.4 *Geometry for hydraulic simulations*

A sub-problem encountered was how to translate the new morphology into new river cross-sections to feed a mathematical hydraulic simulation model.

First, as the planform is modified, a criterion is needed to establish the correspondence between new and old cross-sections ('homologous sections'), in order to carry out a somehow fair comparison. The answer is neither trivial nor univocal because both river length and position are modified. We decided to consider homologous cross-sections, i.e. those falling along the same crossing line of the original river bankfull. This is justified by the fact that – since we are concerned with hydraulic simulations to evaluate flood stage – what matters is the hydraulic functionality of cross-sections, determined by geometric variables and slope, in a certain physical zone of the territory, rather than their exact plan position. As an example, the red segment of cross-section 008.01 in Figure 9 identifies the corresponding cross-sections of both the current and predicted bankfulls. Notice that the stretch length between two homologous sections varies.

Then, we explored a number of options to translate geometry. The two most favourable options were:

(I) find a schematic geometry hydraulically equivalent to the current actual geometry and then just scale it with a scaling factor, in order to minimize arbitrariness,
(II) scale all current bankfull cross-sections according to the predicted variation of the corresponding stretch, since geomorphic prediction is carried out only for stretches, but several cross-sections are defined in each stretch. The adopted rule can be summarized in this way: if current

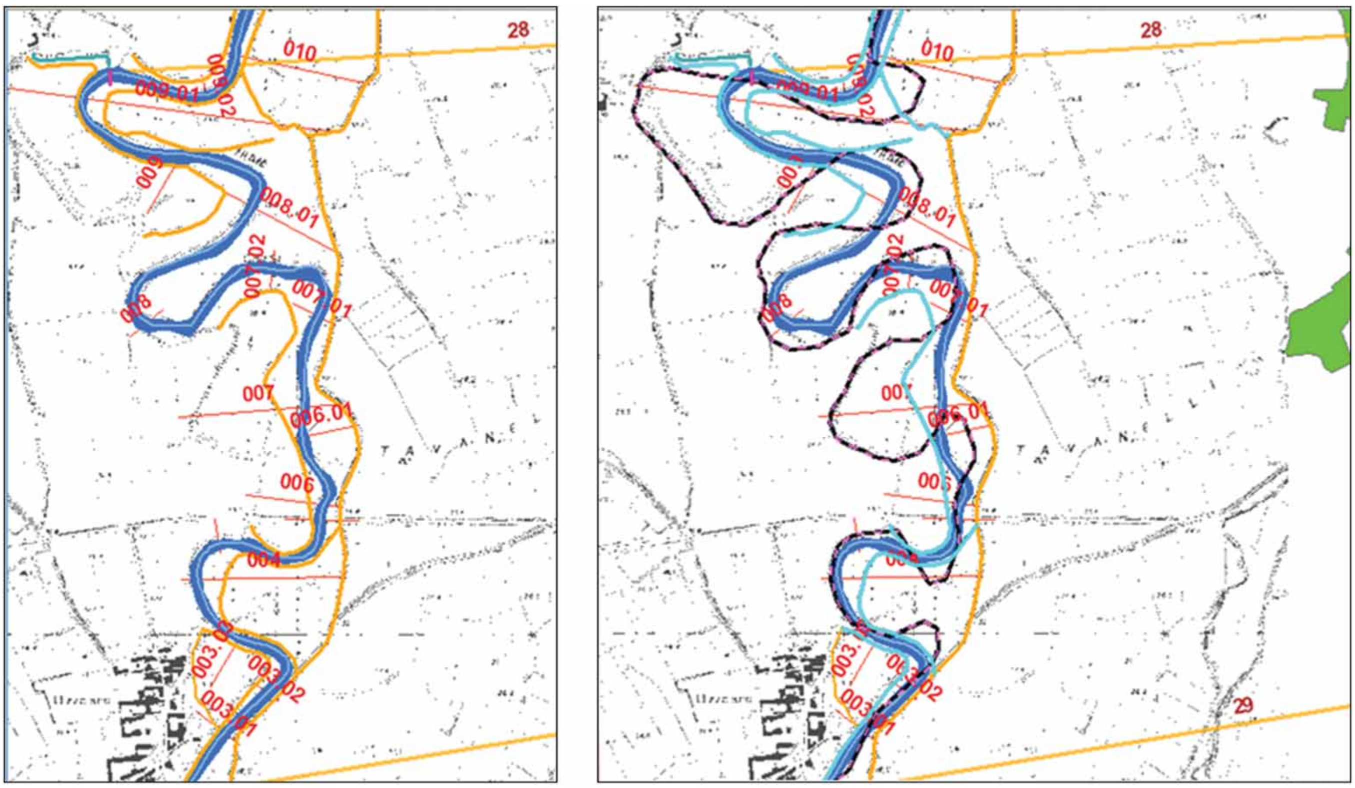

Figure 9 Example of planform prediction (ALT_Base, stretch 28; see Figure 8 to locate it). In this figure, the light brown lines along the river indicate works that exist and will stay in the considered *alternative* ALT_Base, while the light blue ones indicate works to be dismissed. The new planform is the dashed violet-black, thick meandering line (on the right)

average stretch bankfull width is W^*, and the predicted width is W^{**}, the predicted cross-section width w^{**} in each section s would be: $w^{**}(s) = w^*(s)\ W^{**}/\ W^*$, where $w^*(s)$ is the current actual width of section s; a similar procedure has been applied to bankfull depth. The bottom elevation of the bankfull is instead determined by summing to current cross-section elevation the cumulative elevation increment corresponding to the predicted slope times the new stretch length from a reference section.

After few attempts, we discarded approach (I) because it was basically impossible to apply due to the numerous artificial discontinuities present in the river and we could not find a univocal criterion to establish equivalence. We hence relied on approach (II).

Another aspect is how to deal with existing works which are kept in the *alternative* considered; take for instance a weir: we assumed that if the bottom elevation of the downstream bankfull rises so much to bury it, the weir just disappears; while, if the increment produces an elevation lower than the weir threshold, the weir remains in place with a reduced jump.

4 Conclusions

The methodology developed has a significant strength: it allows room for quite different criteria to be integrated, merging qualitative and quantitative information in an overall framework for long-term (decades), wide-space (river segment scale) morphological prediction. Although quite cumbersome, it is applicable, as our case study can witness.

The results obtained so far provide seemingly meaningful answers; indeed:

- the fulfilment of the condition $Q_B = Q_E$ led us to define morphology in agreement with what was expected from the qualitative prediction based on the river history and engineering-mechanistic reasoning; furthermore, it was generally straightforward and robust for the fully alluvial stretches, i.e. the only ones for which it can strictly be assumed to hold;
- the predicted morphotype was almost always in full agreement with the response from the empirical formulas described above and, again, the more so for fully alluvial stretches;
- the obtained morphology appeared generally sensible, from the point of view of overall consistency, as the result shows a kind of river continuum, intuitively consistent with the valley topography; and only in the segment that historically was naturally wandering, the predicted geometry showed, consistently, sudden changes.

However, several weaknesses can immediately be identified:

- *technical assumptions*: one embedded hypothesis is that the granulometry of each river stretch does not vary in the homologous stretch after morphological adjustment, which is of course not true as the modified transport capacity and bank erosion process are likely to modify also the spatial pattern of sediments granulometry; similarly, we did not consider the effect that a different riparian vegetation, associated with renaturation, would induce, although this could be attempted based on expert judgment. The way the predicted morphology is translated into cross-sections geometry leaves room for some arbitrariness. The calculations of bankfull flows and solid transport are all carried out assuming steady, uniform flow, which is of course far from reality.
- *non fully alluvial stretches*: in such stretches, the analytical condition introduced to support the indetermination of geometry cannot be applied. Analogously, the empirical formulas should not be considered because they are meaningful for fully alluvial stretches only, furthermore their utilization in rivers with high artificialization can be questioned, and in any case they just provide a check *a posteriori*.
- *variations of control variables water (Q) and solid (Q_S) input flows*: the methodology here presented was born from our case study in which Q and Q_S are very likely not to change (and hence to be the same for all the considered *alternatives*). In more general cases, with possible changes of Q and Q_S, the general framework proposed is still valid, but definitely prediction is more difficult and less reliable because there are ambiguous cases (e.g. channel gradient and depth could either increase or decrease in response to an increase in both Q and Q_S), as also indicated in Schumm (1977).
- *planform arbitrariness*: definitely, the weakest step in the above methodology is the planform prediction, as the same morphotype, length, sinuosity can occur with infinite planforms. Indeed, the meaningful result one can obtain is, strictly speaking, just the width of the river corridor that will be periodically swept by the river divagation. If a reliable prediction of the actual bankfull position matters in order, in particular, to associate a flood model with overflows to estimate flooding risk, one could rather develop a Monte Carlo approach by predicting a large number of planforms and hence develop the following analysis in a statistical sense. Practically speaking, however, this can be carried out only through a dedicated modelling support system, as the number of calculations involved is very large and the procedure quite cumbersome.
- *transition process*: the methodology developed completely disregards what happens from the moment when the interventions are made until the new equilibrium is (supposedly) reached. But when will it be reached? Chin (2006), in her world review of urban streams alterations, concluded that this new equilibrium does exist in most of the cases, provided that the forcing variables are set at a steady state, but the process duration is extremely variable and can last indeed decades. In the meantime, higher risk situations can occur.
- *historical information*: is not always available or obtainable.

Definitely, we would like to assess how reliable is the proposed methodology. Unfortunately, if our analysis on existing mechanistic modelling tools is correct (see the Introduction), then …there simply is no model, at our knowledge, against which to test the validity of our methodology. The direct way would be to wait for some decades – after a RR project is implemented and the resulting morphology change predicted – to check what happened in reality. A more useful method would be an ex-post simulation, i.e. to undertake the prediction exercise referring to a time instant of the past for which sufficient historical information is available, but still sufficient time for 'future' evolution is left. This is indeed the type of verification we are planning to carry out.

Still, one has to choose whether to go on with very complex hydraulic simulations where key assumptions may be very arbitrary and hidden, or rather comply with the essentially qualitative, expert-based, but explicit character of the methodology presented here. In any case, ignoring the need for geomorphic prediction is certainly not a feasible choice.

For sure, a lot of research can be carried out to ascertain how reliable the corresponding prediction is and to definitely improve the methodology.

Acknowledgements

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Note

1. Another difference is that FISRWG (1998) assumes the existence of a unique relationship between river bed slope S, valley slope S_V and river sinuosity p ($S = S_V/p$), while the presence of artificial jumps, very frequent in anthropogenically impacted rivers – for instance, because of weirs for irrigation withdrawal – significantly modifies this relationship. Moreover, it does not utilize the analytical support from fluvial hydraulics described later on in this paper.

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