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CHANNEL ADJUSTMENTS AND IMPLICATIONS FOR RIVER MANAGEMENT AND RESTORATION

ABSTRACT: SURIAN N., RINALDI M. & PELLEGRINI L., *Channel adjustments and implications for river management and restoration*. (IT ISSN 0391-9838, 2011).

Most Italian rivers have experienced widespread channel adjustments over the last 100 years, mainly in response to a range of human activities. The aim of this paper is to show how knowledge of channel adjustment and reconstruction of evolutionary trajectory are or can be used in river management and restoration. The first part of the paper deals with channel adjustments and summarizes the results of recent studies carried out on twelve rivers in northern and central Italy. The second part illustrates three examples of application.

The selected rivers have undergone almost the same processes in terms of temporal trends. Initially, river channels underwent a long phase of narrowing (up to 80%) and incision (up to 8-10 m), which started at the end of the 19th century and was very intense from the 1950s to the 1980s. Then, over the last 15-20 years, channel widening and sedimentation, or bed-level stabilization, have become the dominant processes in most of the rivers, though channel narrowing is still ongoing in some reaches. Channel adjustments were mainly driven by human actions, but the role of large floods was also notable in some cases. Different human interventions have been identified as the causes of channel adjustments (sediment mining, channelization, dams, reforestation and torrent control works). Such interventions have caused a dramatic alteration of the sediment regime, whereas effects on channel-forming discharges have seldom been observed.

The first example of application concerns a new methodology designed for assessing the hydromorphological condition of Italian rivers and for monitoring their condition through time. This methodology is required in the context of the Water Framework Directive (2000/60/EC) which aims to assess the ecological status of rivers not only using biological and chemical elements, but also hydromorphological elements. The second example illustrates the potential of channel recovery in five gravel-bed rivers of north-eastern Italy. After defining four categories of channel taking into account recent evolution, it was analysed how different sediment management strategies could affect future channel dynamics. We concluded that even though both reach and basin-scale interventions may be carried out, it is likely that channels will not recover to the morphology they exhibited in the first half of the 20th century, since sediment yield and connectivity will remain less than during the 19th century and the first half of the 20th century. The last example deals with solutions for promoting future sustainable management of sediment and channel processes in the Magra River catchment. Knowledge of channel evolution and its causes was used as a basis for defining channel and sediment management strategies, coupled with quantification of bedload transport and bed sediment budget, and the identification of areas most suitable for potential sediment recharge.

KEY WORDS: Hydromorphology, Channel recovery, Italian rivers.

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INTRODUCTION

River management and restoration are complex activities which have to take into account different aspects, such as human safety from floods, economic interests, existing and potential ecological values and benefits. In this context it is increasingly recognized that a range of approaches (e.g. hydrology, ecology, geomorphology) have to be used if sound management strategies are desired. The role of geomorphology has been stressed by several studies (e.g. Downs & Gregory, 2004; Brierley & Fryirs, 2005; Habersack & Piegay, 2008) but also recognized by recent legislation (European Commission, 2000). Long-term channel evolution and sediment dynamics at basin and reach scale are key geomorphological issues for river management and restoration. Reconstruction of channel changes over the last 100-200 years allows to relate the present river state with its temporal trajectory of geomorphological evolution (e.g. Brierley & *alii*, 2008). In rivers affected by remarkable changes temporal trajectory of evolution can be used to assess river alteration respect to more natural conditions and the potential, or limitations, for channel recovery. The recognition of the key role of sediments in river restoration, e.g. in most Alpine rivers (Habersack & Piegay, 2008), stimulated investigation and application of new sediment management strategies such as the erodible corridor concept and promotion of sediment input from hillslopes and tributaries (Piegay & *alii*, 2005; Liebault & *alii*, 2008).

This paper deals with alluvial channels in Italy which have experienced, in most of the cases, widespread adjustments over the last 100-200 years (Surian & Rinaldi, 2003; Surian & *alii*, 2009a). Our aim is to show how knowledge of channel adjustment and reconstruction of evolutionary trajectory are or can be used in river management and restoration. The paper relies on some works published recently, or works in press. The aim is to summarize these recent studies, showing present understanding of channel adjustments in Italian rivers and different implications of knowledge of channel adjustments in river management. The first part of the paper deals with channel adjustments and summarizes the results of studies carried out in twelve rivers in northern and central Italy. The second part illustrates three examples of application: the first example is about a new methodology developed for the hydromorphological classification of Italian rivers, which is required by the European Water Framework Directive 2000/60/EC; the second example describes an approach to assess the potentials and limitations for channel recovery in some alpine rivers in north-eastern Italy; the last example deals with solutions for promoting future sustainable management of sediment and channel processes in the Magra River catchment.

CHANNEL ADJUSTMENTS IN ITALIAN RIVERS

Alluvial channels in Italy, as in many other areas worldwide (e.g. Williams & Wolman, 1984; Wyzga, 1993; Kondolf, 1997; Winterbottom, 2000; Liebault & Piegay, 2001; Marston & *alii*, 2003; Lu & *alii*, 2007; Hoyle & *alii*, 2008), have experienced notable adjustments in recent decades, in particular incision, narrowing and configuration changes, e.g. from braided to a wandering or single-thread morphology. Such adjustments have been studied since the 1960s (e.g. Roveri, 1965; Pellegrini & Rossi, 1967; Castiglioni & Pellegrini, 1981; Gentili & Pambianchi, 1987; Dutto & Maraga, 1994; Rinaldi & Rodolfi, 1995) and, more recently, conceptual models of channel evolution have been proposed (Rinaldi, 2003; Surian & Rinaldi, 2003; Surian & Rinaldi, 2004). Our recent research has focused on twelve rivers (Pellegrini & *alii*, 2008; Rinaldi & *alii*, 2008; Surian & *alii*, 2008; Surian & *alii*, 2009a; Surian & *alii*, 2009c) aiming to (i) reconstruction of evolutionary trends (e.g. changes of channel width, bed elevation, braiding intensity, sinuosity), (ii) understanding the causes of channel adjustments, (iii) re-examination of existing channel evolution models.

The twelve rivers are in northern and central Italy (fig. 1): seven drain from the Alps (Stura di Lanzo, Orco, Brenta, Piave, Cellina, Tagliamento, and Torre) and five from the Apennines (Trebbia, Panaro, Magra, Vara, and Cecina). The drainage basin areas range from 446 to 3899 km^2 and the river length from 53 to 222 km. In the study reaches, which range in length from 10 km to 49 km, the river channels are generally very wide (up to several hundred metres) and not confined, or slightly confined. River beds are mainly composed of gravels and banks are non-cohesive or composite. Channel changes were studied using various sources and methods (i.e. historical maps, aerial and satellite images, topographic surveys, and geomorphological surveys).

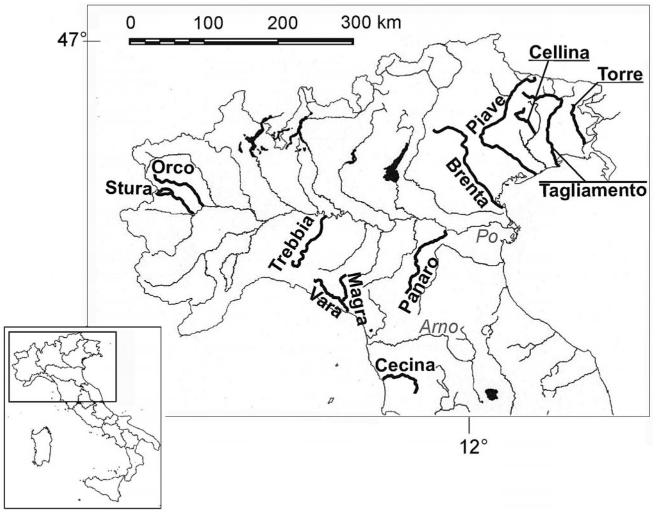

FIG. 1 - General setting of the study rivers.

The selected rivers have undergone almost the same processes in terms of temporal trends (Surian & *alii*, 2009a; Surian & *alii*, 2009c). Initially, river channels underwent a long phase of narrowing (up to 80%) and incision (up to 8-10 m), which started at the end of the 19^{th} century and was over in the 1980s or early 1990s. Then, over the last 15-20 years, channel widening and sedimentation, or bed-level stabilization, have become the dominant processes in most of the rivers. Channel width rates of change suggest that two main phases of narrowing occurred (fig. 2). In fact, during the first part of the narrowing phase, that is up to the 1950s («Phase I» in fig. 2), rates of width change were up to –0.7%/year (changes were calculated referring to the original channel width in the 19^{th} century), while rates were commonly higher, up to –2.3%/year, from the 1950s to the 1980s/1990s («Phase II»). Data on bed-level changes (derived from topographic and geomorphological surveys) confirmed the occurrence of those two phases, with slight incision and moderate or intense incision associated to the first and second phase respectively. Over the last 15-20 years («Phase III» in fig. 2),

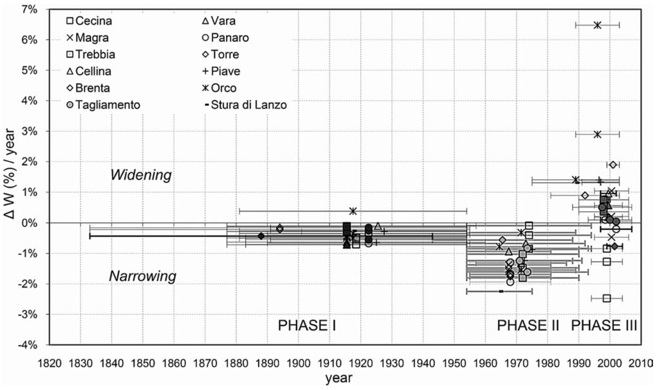

FIG. 2 - Channel width changes (calculated referring to the original width in the 19th century); narrowing is the dominant process in the first two phases, but higher rates of change characterize the second phase (1950s-1980s/1990s); widening is dominant in the third phase, though narrowing is still ongoing in some reaches.

channel widening has become the dominant process in most of the study reaches (rates of width change were commonly lower than +2.0%/year, but in one case up to +6.5%/year), though channel narrowing is still ongoing in 6 reaches out of 27. Widening is associated with aggradation in some reaches, but the relation between width and bed-level changes is not so strong as during the previous phases of narrowing (Surian & *alii*, 2009a). In fact, channel widening has taken placed without significant bed-level variations in some reaches (Surian & Cisotto, 2007; Comiti & *alii*, 2011). As for the last 15-20 years we suggest that a new phase of channel adjustment could be ongoing in some reaches («Phase III» in fig. 2), while other reaches could be already in a quasi-equilibrium condition (i.e. without going through a significant phase of channel widening and aggradation).

Channel adjustments were mainly driven by human actions, but the role of large floods was also notable in some cases (Surian & *alii*, 2009a, Comiti & *alii*, 2011). Different human interventions have been identified as the causes of channel adjustments (sediment mining, channelization, dams, reforestation and torrent control works). Such interventions have caused a dramatic alteration of the sediment regime, whereas effects on channel-forming discharges have seldom been observed (Surian & Cisotto, 2007; Surian & *alii*, 2009a). Alteration of sediment regime, especially due to gravel mining from the 1950s to the 1990s (this activity has ceased or significantly reduced in the last years), can be identified as the key driving factor of channel adjustments (Surian & *alii*, 2009a) (fig. 3). This alteration explains the phases of narrowing and incision, while recent channel evolution appears to be strongly controlled also by flood magnitude and frequency (Turitto & *alii*, 2010).

IMPLICATIONS FOR RIVER MANAGEMENT AND RESTORATION

Definition and monitoring of hydromorphological status of rivers

A new methodology designed for assessing the hydromorphological condition of Italian rivers and for monitoring their condition through time has been recently developed (Rinaldi & *alii*, 2010). This methodology is required in the context of the Water Framework Directive (2000/60/EC) which aims to assess the ecological status of rivers

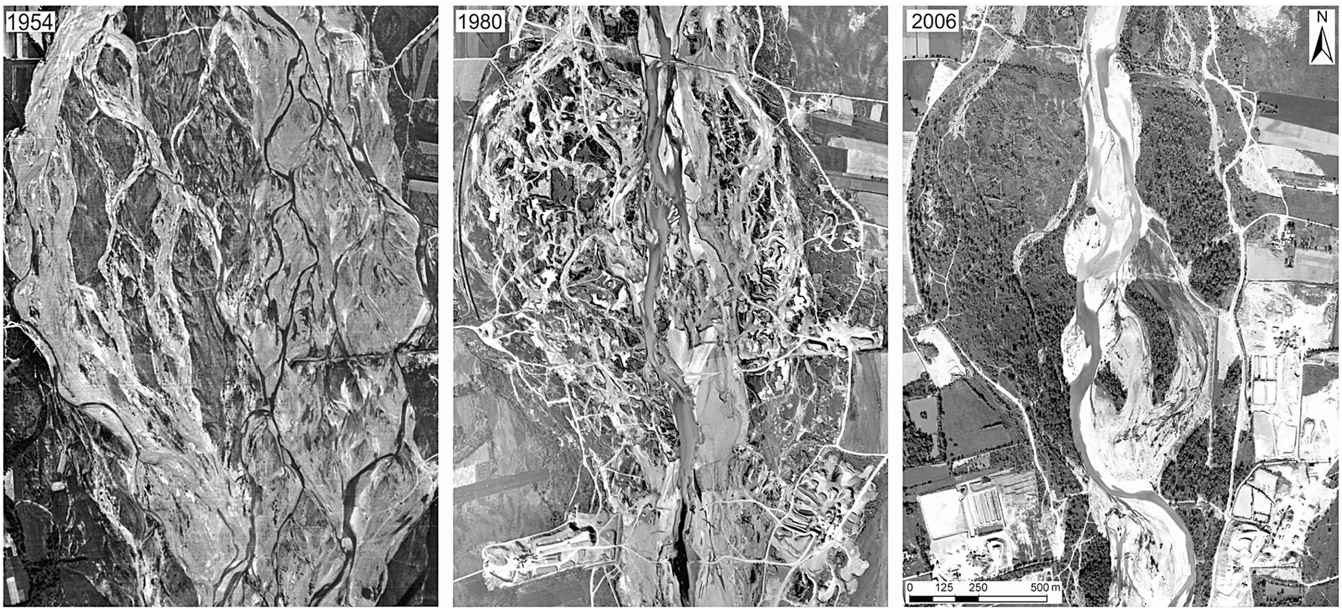

FIG. 3 - Gravel mining was very intense in most of the rivers between the 1950s and the 1980s. Aerial photos of the Trebbia River document river morphology before major channel changes (1954), when mining was widespread within the channel (1980), and after major adjustments (2006).

not only using biological and chemical elements, but also hydromorphological elements. Analysis of river processes and channel changes are crucial in this methodology, implying substantial differences from «form-based» classifications or approaches (e.g. Rosgen, 1994; Raven & *alii*, 1998) and affinities with recent approaches taking into account river processes (e.g. Ollero & *alii*, 2007; Chandesris & *alii*, 2008).

The methodology (Rinaldi & *alii*, 2010) is made up of three main phases (fig. 4):

1) Initial setting and subdivision in river reaches: the main physical aspects of the fluvial system (i.e. drainage basin and river channels) are identified, e.g. channel confinement and configuration, and river reaches, that is the morphological units used in the following phases, are defined.
2) Evaluation of the present morphological condition: the morphological state of the river reaches is assessed in terms of geomorphological functionality, artificiality, and recent channel changes.
3) Monitoring: several parameters are measured to evaluate if the morphological quality of the stream remains unaltered or is changing.

For the assessment of present morphological state, coherently with the requirements of the Water Framework Directive, the following aspects are considered (fig. 4): (a) longitudinal and lateral continuity; (b) channel pattern; (c) cross-section configuration; (d) bed structure and substrate; (e) vegetation in the riparian corridor. Then, a «Morphological Quality Index» (IQM, «Indice di Qualità Morfologica») is determined focusing the morphological analysis on:

(1) Geomorphological functionality: this implies observation of forms and processes in the present condition, and their comparison with forms and processes expected for that river typology (e.g. sinuous, wandering, braided);
(2) Artificial elements: presence, frequency and continuity of artificial structures and interventions in river channels and drainage basins are evaluated;
(3) Channel changes: recent morphological variations are assessed, specifically over the last 50-60 years, in order to verify if the river has undergone physical alterations (e.g. incision and narrowing).

According to this approach the reference conditions for a river reach can be identified with the following conditions: (a) functionality of the processes, corresponding to dynamic equilibrium conditions; (b) absence of artificiality; (c) absence of significant adjustments of form, size and bed elevation over the last decades. The latter condition is restricted to alluvial mobile channels, therefore it does not apply to most mountain streams which commonly have a fixed planimetric position (confined reaches).

Analysis of channel changes contributes to define the «Morphological Quality Index», that is the present morphological state, but the analysis that is required is relatively simple implying an overall evaluation of changes. Magnitude of changes in channel width and bed elevation are assessed (e.g. from two different sets of aerial photographs), while a detailed reconstruction of channel evolution (i.e. trajectories of evolution) is not required in this phase of the methodology. Channel changes have a key role in the following phase of the methodology (fig. 4). In fact monitoring channel changes in the near future will be fundamental to assess if a river reach is improving, or not, its morphological condition and to evaluate the effects of specific management activities.

Identification of potential channel recovery

When improvement of morphological quality is a goal, it becomes important to evaluate to which extent channel recovery could be expected. Potentials and limitations for channel recovery can be assessed if recent and present channel evolution and driving factors (e.g. channel forming discharges and sediment regime) are well known.

The potential of channel recovery was analysed in five gravel-bed rivers of north-eastern Italy (Brenta, Piave, Cellina, Tagliamento, and Torre Rivers) (Surian & *alii*, 2009b). The studied rivers have undergone notable adjustments in the last 100 years, specifically narrowing by up to 76%, in-

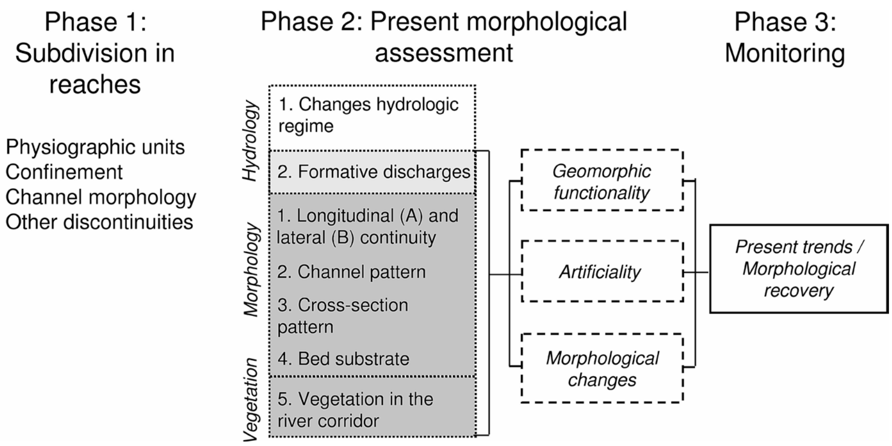

FIG. 4 - General methodological framework of the stream hydromorphological assessment (from Rinaldi & *alii*, 2010).

cision by up to 8.5 m, and changes in channel configuration. Alteration of sediment fluxes, mainly due to in-channel mining, has been the main factor driving such channel adjustments. Evolutionary trends show that channel recovery is on-going in several of the selected reaches, since widening and aggradation have occurred over the last 15-20 years. This channel recovery has been possible because sediment mining has significantly decreased or ceased along the study reaches. However, several constraints still exist on sediment fluxes (e.g. dams).

To assess the potentials and limitations of channel recovery, the analysis proceeded in two steps (Surian & *alii*, 2009b): first, the identification of the trajectories of channel evolution over the last 100 years; second, the definition of three different scenarios of channel evolution over the next 40-50 years according to different management strategies (i.e. basin and reach scale interventions, reach scale only, and no interventions). Trajectories of channel evolution allowed to define four categories of channel taking into account the evolution over the last 15-20 years: (A) high recovery; (B) moderate recovery; (C) slight recovery or no significant changes in channel morphology; (D) no channel recovery. Future channel evolution was then analysed in the context of an intermediate time scale (40-50 years), assuming simplified boundary conditions. It is assumed that there will be no dramatic changes in land use and human activities within the fluvial system in the next 40-50 years (e.g. dams will not be removed). Besides the morphological effects of very large flood events (e.g. >100 yrs return period), are not taken into account because of the great uncertainty in assessing such effects using a simple conceptual model. Figure 5 shows how different sediment management strategies (reach and basin scale interventions) could affect future channel dynamics (note that only three of the channel categories previously defined, A, B, and C, are shown in this figure). Without any intervention,

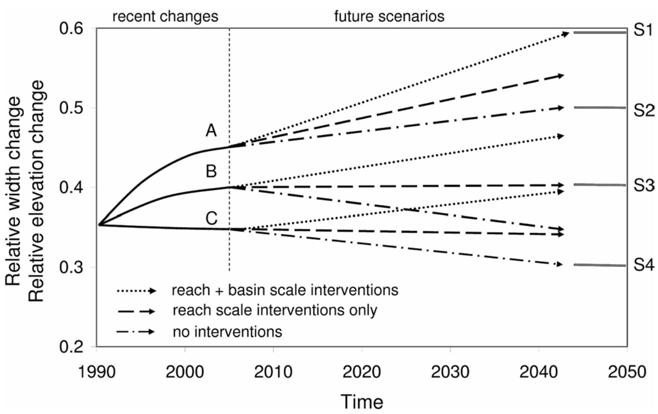

FIG. 5 - Future scenarios of channel changes according to different strategies of sediment management. Relative magnitude of width and bed-level changes are calculated referring to channel morphology at end of the 19th century or early 20th century. Different trajectories of recent channel evolution are shown: A: high morphological recovery; B: moderate morphological recovery; C: slight recovery or no significant changes in channel morphology. (from Surian & *alii*, 2009b).

channel recovery would be possible in those reaches which have a relatively high degree of connectivity with upstream sediment sources or tributaries (e.g. category A in fig. 5). However, further incision and narrowing are expected in those reaches where connectivity is low or very low. Reach scale interventions, such as the definition of an erodible corridor and removal of some bank protections, are the most feasible interventions to allow an increase in the supply of coarse sediment. This should help those reaches suffering from reduced upstream connectivity to reach an equilibrium condition (e.g. categories B and C in fig. 5), while it could lead to significant channel recovery in those reaches where bed-load transport has been altered to a minor extent (e.g. category A in fig. 5). A more substantial channel recovery could be obtained through interventions at the basin scale (e.g. adoption of open check dams and sediment transfer downstream of dams).

As for limitation for channel recovery, this study pointed out that even though both reach and basin-scale interventions may be carried out, it is likely that channels will not recover to the morphology they exhibited in the first half of the 20th century since sediment yield and connectivity will remain less than during the 19th century and the first half of the 20th century. The main factors that have determined a reduction in sediment yield and connectivity at basin-scale are dams, torrent control works and reforestation. This limitation for channel recovery is shown in fig. 5, where relative width and bed-level values will be 0.5 or 0.6 in the best cases, that is significantly different from the «original» values of about 100 years ago. This issue is very relevant to define realistic goals, and to use appropriate reference conditions, in river restoration.

Sustainable sediment management at basin scale

The case of the Magra River (Central-Northern Italy) illustrates a methodology used to define a scientifically sound strategy for promoting future sustainable management of sediment and channel processes (Rinaldi & *alii*, 2009). The Magra River and its main tributary (Vara River) have been heavily affected by sediment mining and other human disturbances which caused channel incision and a series of associated negative effects. As a consequence, the Basin Authority of the Magra River has undertaken a new river management policy based on the comprehension and analysis of geomorphic processes. The methodology includes (i) a retrospective analyses of channel geometry, (ii) analysis of causes of changes, and (iii) hydraulic sediment budgets to evaluate potential sediment transport (this type of budget differs from a morphological sediment budget since it does not account for observed changes of the river channel in a given time interval, but rather expresses the tendency of a reach to aggrade or degrade given its hydraulic and sedimentary characteristics). The procedure is composed of four main aspects that are synthetically described as follows.

(a) Synthesis step: simplification of diagnosis data to establish a single indicator of geomorphic health. Four indicators were used to summarize the diagnosis information: (1) secular bed-level changes (at the scale of about 100 years, i.e. from 1900 to 2006); (2) decennial trend of bed-level adjustments (from 1989 to 2006); (3) bed-level recovery since 1950; (4) hydraulic sediment budget. From the combination of all possible cases of the above four indicators, six classes of the geomorphic health index were defined, and three macro-classes were used (1: prevailing stability-aggradation conditions; 2: intermediate conditions; 3: past incision, present tendency to incision and low recovery) to which specific management actions were assigned.

(b) Strategic step: proposed actions based on the previous synthesis. A series of management actions to promote sediment recovery at the scale of the main alluvial channels (Magra and Vara) were defined and associated to each of the macro-classes of channel conditions defined in the previous step. Then, a series of reaches where the functional mobility corridor (FMC) should be encouraged to promote additional sediment supply from eroding banks were identified. The concept of "erodible river corridor" or "functional mobility corridor" has been extensively applied to the Magra and Vara rivers, and obtained by GIS analysis by overlapping the corridor of historical (last 50 years) channel shifting with zones of possible future erosion (next 50 years). Finally, a series of conservation measures (for example do not stabilise landslides or hillslopes in direct connection with the river channel network) were associated to the catchment areas and features identified as zones of natural sediment recharge.

(c) Practical methodology to promote sediment delivery based on the definition of the functional mobility corridor, and to identify suitable areas for potential sediment recharge to promote active restoration of sediment transport. In order to define an overall plan for sediment management at a catchment scale, some basic evaluation of potential recharge at the sub-catchment scale was carried out. A semi-quantitative approach was used, similar to that recently applied to the catchment of the Drôme River, France (Liébault & *alii*, 2008), to obtain a classification of the basin areas with relative potential for sediment recharge.

(d) Communication strategy for sediment management at the catchment scale based on a simplified map. The aspects of morphological evolution, sediment budget assessment, areas of potential sediment recharge, described above, were synthesised in a "map of strategies for sediment management", which reports river segments and associated sediment management recommendations, and identifies suitable areas for potential bedload recharge and associated management actions and/or measures at both network and catchment scales (fig. 6).

CONCLUSIONS

Knowledge on channel adjustments in Italian rivers has significantly improved over the last few years, through a

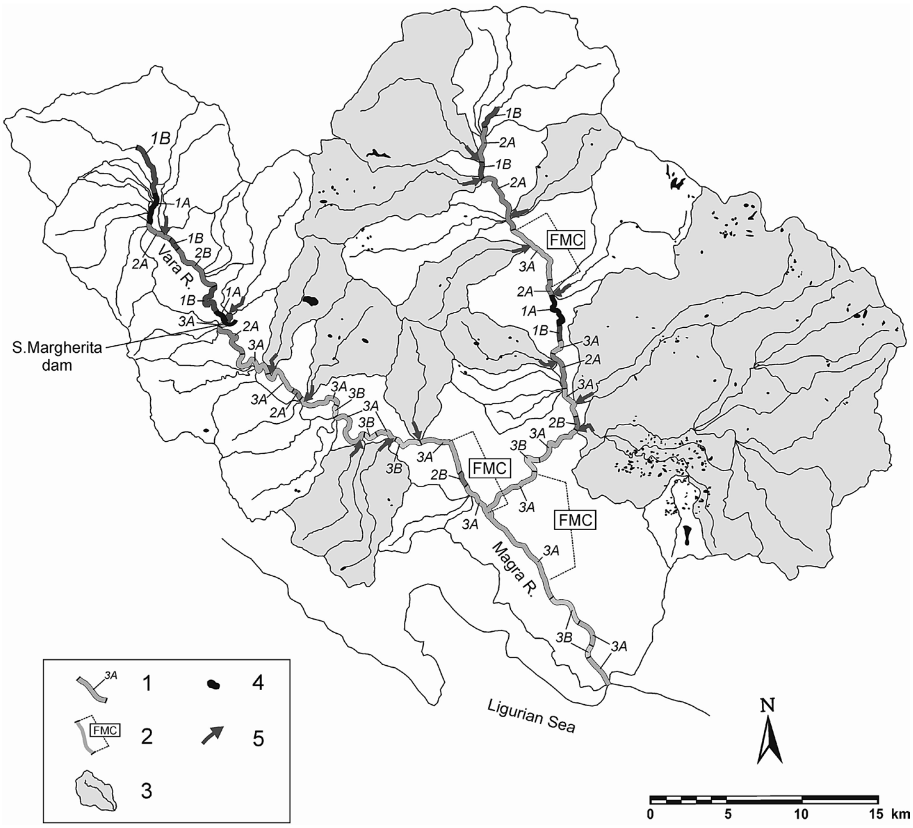

FIG. 6 - Schematic representation of the main elements included in the «map of strategies for sediment management» (from Rinaldi & *alii*, 2009). 1) Classification of the river segments based on the geomorphic health index. Codes from 1A to 3B, follow a grey scale from black, corresponding to class 1A, to light grey, corresponding to class 3B. 2) Reaches where the Functional Mobility Corridor (FMC) can be promoted. 3) Sub-catchments selected for potential sediment recharge. 4) Landslides selected for potential sediment recharge. 5) Main tributaries with high sediment delivery.

better definition of trajectories of evolution and causes of adjustment. This knowledge is crucial in river management and restoration. As the examples used in this paper have tried to illustrate, channel adjustments are key elements in different management issues, from the definition of present morphological condition (quality) of Italian rivers to identification of sustainable strategies of sediment management. Reconstruction of trajectories of channel evolution allows also to define realistic restoration goals. This means appreciation of potential and limitation of channel recovery, without taking as reference condition a pristine morphology that reflects different conditions and human influence at catchment and reach scale. Though the aim of this paper was to illustrate the practical implication of studying channel adjustments, the three examples show how is often needed to combine knowledge on channel changes with other information, such as sediment sources and budgets.

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