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Assessing channel response of a long river influenced by human disturbance

A. Latapie [a], B. Camenen [a], S. Rodrigues [b], A. Paquier [a], J.P. Bouchard [c], F. Moatar [b]

[a] Irstea Lyon, 5 rue de la Doua CS70077, 69626 Villeurbanne Cedex, France
[b] Université François Rabelais de Tours, E.A. 6293 GéHCO, GéoHydosystèmes Continentaux, Faculté des Sciences et Techniques, Parc de Grandmont, 37200 Tours, France
[c] EDF-LNHE, 6 Quai Watier, 78400 Chatou, France

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ABSTRACT

This paper describes an approach to assess channel changes of a long anthropogenised river (the Middle Loire River) over decadal timescales. Channel changes are evaluated along geomorphically homogeneous river reaches. The classic geomorphic parameters (active channel width, bed slope, grain size) are complemented with parameters extracted from a 1D hydraulic model: width–depth ratio, effective bed shear stress and specific stream power calculated for the biennial discharge assimilated to bankfull flow conditions. The delineation of reaches is undertaken by combining visual inspection with the implementation of simple statistical tests to corroborate discontinuities in flow and sediment transport. The 450 km long study area has been divided into 167 homogeneous reaches. The general trends observed over the last fifty years are narrowing of the active channel width and incision of the river bed. However, changes in bed level and active channel width are not consistently correlated. Channel changes at the reach scale are mainly controlled by the presence of former sediment extraction sites. Significant incision is observed at the peak of the in-stream sediment mining period. This was followed by channel recovery when extractions stopped. The 1D numerical model provides a more rigorous manner to derive hydraulic parameters. The effective bed shear stress made dimensionless by its critical value and the width–depth ratio helps to explain observed channel responses more effectively by relating patterns to geological units along the Middle Loire.

1. Introduction

Natural alluvial channels adjust their slope and shape in response to water and/or sediment inputs, whether as a consequence of climate change or anthropogenic influences. Since channel changes can have detrimental effects on flood extent, groundwater recharge and the stability of infrastructure and ecology (Bravard et al., 1999), better understanding of channel adjustments is crucial to predict future evolution and thus adapt river management strategies.

As river managers are working to understand and/or reverse channel changes, geomorphic reach scale assessments are being developed to support restoration interventions (e.g. Brierley and Fryirs, 2005; Kellerhals et al., 1976; Montgomery and Buffington, 1997; Rinaldi et al., 2013; Rosgen, 1994). These approaches tend to perform poorly on anthropogenised reaches as human influences such as channel embankments and gravel extraction have significantly altered some of the basic variables that go into most classification schemes.

Often, designation of reach boundaries can be subjective and difficult to reproduce (Miller and Ritter, 1996; Simon et al., 2007). In order to improve the detection of threshold conditions along the river continuum, statistical algorithms have been implemented to enhance the robustness of reach definitions (Leviandier et al., 2012; Orlowski et al., 1995). The use of statistical algorithms for detecting homogeneous patches along a continuum has been widely applied in hydrology, ecology and geography (e.g. Buishand, 1984; Clark et al., 2008; Clément and Piégay, 2003).

Whilst reach scale approaches are undeniably valuable, they generally contain limited analysis of vertical characteristics, with water depth often estimated on site (Rosgen, 1994), or using "hydraulic geometry" relationships (Leopold and Maddock, 1953), or a simple Manning Strickler equation, or more recently using hydraulic models (Armas et al., 2012). Site assessment is obviously not appropriate for long river reaches. Although empirical equations can provide an acceptable approximation, hydraulic models provide more robust information (see Aggett and Wilson, 2009; Armas et al., 2012; Zilani and Surian, 2012).

This paper uses multi-disciplinary tools to analyse channel changes among a relatively large river, the Middle Loire (France), that has been characterized by different channel types and influenced by human disturbances. The specific objectives are: (1) to delineate homogeneous river reaches using a visual distinction of changes approach and simple statistical tests, (2) to analyse channel changes observed on the Middle Loire River over the last 50 years and to assess if reaches delimited by natural features behave differently from "anthropogenized" ones, (3)

E-mail address: benoit.camenen@irstea.fr (B. Camenen).

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to relate channel adjustments to hydraulic parameters computed with a 1D hydraulic model, and (4) to assess the influence of instream sediment mining on the evolution of the Middle Loire River.

2. Study area

The Loire River is the longest river in France with a length of 1012 km. Its drainage area covers 117,000 km^2, one fifth of France's area. Four major tributaries feed the river: Allier, Cher, Vienne and Maine. Bedload sediment inputs come mainly from the Allier and the Vienne. The reach studied is the Middle Loire, which extends from the confluence with the Allier River to the confluence with the Maine River. The downstream boundary was extended to the gauging station of Montjean-sur-Loire to facilitate hydraulic modelling, that is a distance of about 450 km (Fig. 1). The Middle Loire River is characterized by a section with a multiple channel configuration downstream of the confluence with the Allier River, a short meandering section upstream of Orléans and a multiple channel system with the presence of numerous vegetated islands and sand bars in the downstream section.

2.1. Hydrologic characteristics

The Middle Loire River has a highly variable hydrologic regime: very low discharge during the summer and high magnitude flows in winter and spring. Cumulative departure from the mean annual discharge for the period 1863–2011 is presented for Blois gauging station in Fig. 2a. Blois is representative of the hydrologic regime of the Middle Loire; it is located 250 km downstream of the confluence with the Allier River. The curve ascends during wet periods and descends during drier periods. Despite major flood events in 1846, 1856 and 1866, the end of the nineteenth century presents a relatively stable flow regime. Alternating wet (from 1905 to 1941 and from 1973 to 1984) and dry periods (1941–1964 and 1984-today) are evident.

The last major flood events on the Loire River were recorded in the second half of the nineteenth century. These extreme events had an estimated return period of 200 years and reached an estimated discharge of 7 200 m^3/s at Gien (Dacharry, 1996; Duband, 1996). Since then, other floods happened, but on a smaller scale. Dams built at the upstream end of the catchment have only impacted upon the 1996, 2003 and 2008 floods.

At Gien, located 564 km downstream from source, flood events with a return period of 2 years correspond to a discharge of 1600 m^3/s. Fig. 2b examines the flood frequency and magnitudes of flow recorded at Gien between 1936 and 2011. The data were compiled from peak annual discharges with a threshold of 1600 m^3/s. Floods above 2700 m^3/s (equivalent to an event with a ten year return period) have been relatively rare throughout the period (5 occurrences).

2.2. Geological settings

The Loire River basin is characterized by various lithological units influencing its layout and valley setting (Babonaux, 1970; Brossé, 1982). Upstream of Gien (Fig. 1), the north/south alignment of the river is associated with faults in the Hercynian socle (Alcaydé and Gigout, 1976; Debrand-Passard et al., 1998; Nelhig, 2010). On the Middle Loire, four geological units can be distinguished: Jurassic limestones from the confluence with the Allier River to 90 km downstream, then Tertiary formation (lacustrine limestones and alluvial formation) to downstream of Blois (located at a distance of 696 km from source), Cretaceous chalks to the confluence with the Maine River and Hercynian metamorphic rocks on the downstream section (Fig. 3). The first two geological units are characterized by similar mean slope ($s_{b1} \approx s_{b2} \approx 0.4$ m/km), whereas units 3 and 4 have a lower mean slope value ($s_{b3} = 0.29$ m/km; $s_{b4} = 0.18$ m/km).

The nature of sediment available is associated with crystalline and volcanic rocks from the upstream Loire, locally enriched by flint coming from sedimentary formations of the Parisian Basin. Sediments are dominated by coarse sands, quartz, feldspar and gravels (Macaire et al., 2013). Champion et al. (1971) investigated the thickness of alluvia in the substratum and reported layers varying between 3 m at Amboise (730 km from source) to 10 m at Cosne-Cours-sur-Loire (522 km from source) with an average value of 5 m. Alluvia thickness is the largest where the floodplain is wide and in confluences zones (Donsimoni et al., 2008).

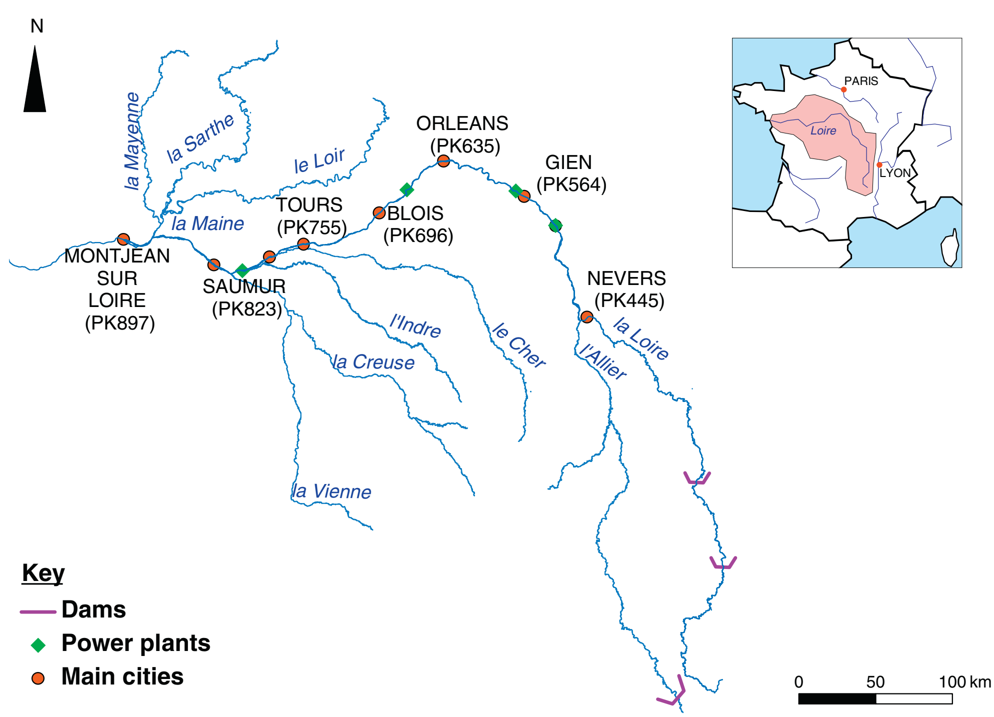

Fig. 1. Location map showing the study reach.

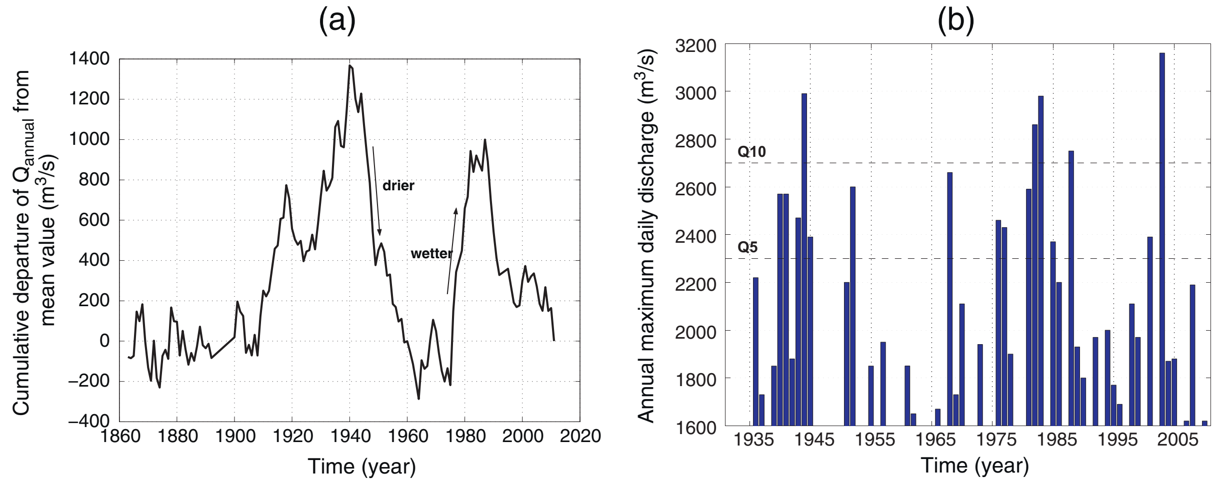

Fig. 2. (a) Cumulative departure from the mean annual discharge for the period 1863–2011 at Blois gauging station, (b) Annual maximum daily discharge above Q_2 ($Q_2 = 1\,600\ m^3/s$) for the period 1936–2011 at Gien gauging station.

The valley of the Middle Loire River is naturally large, 3.5 km wide on average. Lateral migration of the channel did not occur over the last centuries because of anthropogenic influences.

2.3. Anthropogenic influences

The Loire River has been intensively modified over the last centuries. Flood embankments were constructed between the 13th and 18th century and have been raised following flood events (Dion, 1961). The Middle Loire River is now constricted along 300 km of its length. Flood embankments have confined the flow and prevented lateral migration of the channel. Oblique groynes were erected in the 19th century to maintain a single channel, to ensure sufficient depth conditions during the low flow season and thus facilitate navigation in the main channel. These structures have caused the deepening of the main channel as intended but sediments have accumulated behind them, inducing the development of vegetation, closing secondary channels and thus reducing flood conveyance (Rodrigues et al., 2006).

The construction of bridges also influences the river by confining the flow and stabilizing the river bed: from 30 bridges in 1850, 50 bridges can now be found on the Middle Loire. The presence of old bridge piers also induces some flow disruption. As energy needs grew during the 20th century, three dams were constructed at the upstream end of the catchment, along with four nuclear power stations in the Middle Loire (Fig. 1).

Sand and gravel extraction in the main channel started in an industrialized manner at the beginning of the 1950s. Dambre and Malaval (1993) reported that nearly $83 \times 10^6\ m^3$ of sediment was extracted between 1949 and 1992 (i.e., about $2 \times 10^6\ m^3$/year in average). Given that the mean annual total sediment transport (i.e., bedload and suspended load) in the Loire River was estimated at 405,000 m^3 for the period 1953–1968 (Berthois, 1971), the sediment extraction rate was higher than the replenishment rate. Extractions in the main channel were significantly reduced following a ministerial recommendation in 1981 before being formally prohibited in 1995. The decision to reduce mining in the main channel was also dictated by the collapse of the Wilson's Bridge in Tours in 1978, due to the scouring of a pier. Changes in agricultural and human uses of the river banks should also be noted. Islands and river banks used to be maintained as pasture lands (Gautier et al., 2000). As this practice stopped, the vegetation developed, affecting the connection of secondary channels at low flow and sediment transport.

Since the end of granular extractions, local remedial actions have been undertaken: protecting the toe of embankments, increasing flow capacity by cutting down vegetation in secondary channels, removing oblique groynes to restore flow conveyance etc. (Belleudy, 2000).

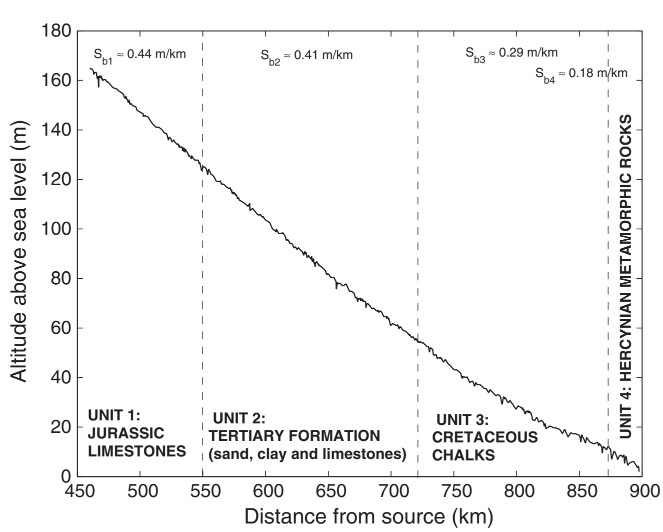

Fig. 3. Longitudinal profile and the four main geological units of the Middle Loire River, with their average slope.

3. Data and methods

3.1. Data and methodological framework

The regional environment agency (DREAL Centre) regularly monitored two hundred sites to record water levels at low and high flows since 1978. Aerial photographs taken during low flow conditions are available for 1955, 1984, 1995, 2002 and 2010. A topographic survey of the Middle Loire River was undertaken in 1995. Cross sections, surveyed every 2 km on average, cover the main channel and can be completed with floodplain data extracted from Lidar data collected in 2003. These data have allowed the determination of geomorphic characteristics and the construction of a hydraulic model.

3.2. Geomorphic parameters

3.2.1. Active channel width and change in river bed level

The longitudinal pattern of the active channel width was defined using aerial photographs. The active channel width *B* corresponds to the non-vegetated river width and thus includes secondary channels and sand bars frequently altered during flood events. The channel active widths were measured on the 2002 and 2010 aerial photographs every 500 m in a GIS environment. This distance is consistent with the size of the macroforms and complements previous studies undertaken by Ginestet (1999) on the older photography dataset (1955, 1984, 1995). The floodplain width B_f was extracted from the 2003 Lidar data. The resolution of the aerial photographs used to determine the active channel width is relatively good but we cannot exclude distortion effects for measurements away from the central photograph area. In particular, the digitalization of river banks is challenging in areas covered by vegetation. The error is estimated at a maximum of ±25 m for the dataset, that is an error of about 7%.

Changes in river bed levels were calculated by assimilating the low water profile to the bed profile. Comparisons were made for low water levels recorded at similar discharges (1978–1986, 1986–1995, 1995–2002 and 2003–2011). These data were also used to estimate the river bed slope. Errors associated with low water level measurements are estimated to be in the range of ±3 cm.

3.2.2. Median grain size

The river bed material median grain size d_{50} was determined for all granulometric sample analysis available in the main channel between 1970 and 2008 provided by the DREAL Centre. Despite the uncertainties associated with the definition of a single river bed material grain size, due to transverse variability in grain size between the main channel, sand bars and islands (Babonaux, 1970), a grain diameter was associated to variations in the longitudinal gradient so as to relate changes in median grain size with changes in stream power and in shear stress (Fig. 4). The sediments available on the Middle Loire originated mainly from the upstream Loire, locally enriched by flint from sedimentary formations of the Parisian Basin. A downstream fining exponential law in the form of the Sternberg (1875) formulation was adopted:

$$d_{50} = d_{50(x=0)} exp(-ax) \quad (1)$$

with d_{50} as the river bed material median grain size at a distance x from upstream, $d_{50(x=0)}$ is the river bed material median grain size measured upstream ($d_{50(x=0)} = 4.4$ mm) and a is a coefficient ($a = 4.65 \times 10^{-6}$ m^{-1} in our case). As observed in Fig. 4, there is a significant scatter and a general lack of data. The proposed downstream variation of the grain size is thus imprecise. Valverde et al. (2013) made a recent extensive survey on the main channel grain size characterisation. Their first results indicated that the coefficient a may be slightly smaller. Thus, one should be aware of uncertainties linked to the determination of d_{50} as well as related parameters.

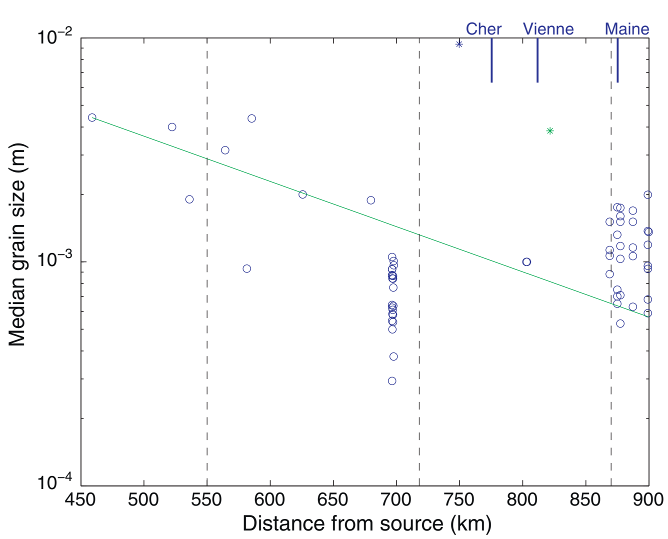

Fig. 4. Downstream variation in median grain size for the main channel (circles indicate measured values, crosses are measured d_{50} which have been excluded from the analysis). Solid line represents the exponential law in the form of the Sternberg formulation. The vertical dotted lines indicate the four geological units and the blue segments the location of major tributaries.

3.3. Hydraulic parameters

The geomorphic characteristics are complemented by parameters extracted from a hydraulic model. The one dimensional hydraulic model RubarBE, developed by Irstea (El Kadi Abderrezzak and Paquier, 2009), which solves the Barré-de-St-Venant equations by an explicit second order Godunov type numerical scheme was selected. The model allows the consideration of two roughness coefficients: one for the main channel and one for the floodplain. The main channel Strickler's coefficient K_{mc} was calibrated for the 1996 flood event and varies between 28 and 32 m$^{1/3}$/s along the studied reach. For the floodplain, K_{fp} was set at 15 m$^{1/3}$/s. Adjustments to the resistance coefficient were locally made in order to obtain a good reproduction of the measured water levels available. Once calibrated, the model can be run for a succession of steady discharges from low flows to extreme events. Using the model outputs, the river width to mean water depth ratio (W/D) (width–depth ratio) can be determined for different discharges. In the same way, the mean bed shear stress τ, defined by the following equation can be calculated:

$$\tau = \rho g R_h S \quad (2)$$

with ρ as the density of water, g, the acceleration of gravity R_h as the hydraulic radius, and S as the energy slope. As this study focused on effective sediment transport, the biennial discharge Q_2, assimilated to the bankfull or effective discharge (Andrews, 1980) was used. Lateral flow inputs from the three main tributaries were estimated to maintain the estimated biennial discharge along the whole Middle Loire River.

The mean bed shear stress τ is the sum of the stresses acting due to the friction attributable to the grains themselves or skin friction, τ_{sf}, the resistance created by the presence of bed forms or form drag τ_{fd}, and the adding resistance due to bank effect, river sinuosity, etc., or side drag τ_{sd} (i.e., $\tau = \tau_{sf} + \tau_{fd} + \tau_{sd}$). Bed forms reduce the ability of the flow to transport sediment and should ideally be included (Frings and Kleinhans, 2008); however due to the scale of the present study and the amount of data available, only skin friction is considered. Moreover, according to Meyer-Peter and Müller (1948), the effective shear stress, $\tau_{eff} \approx \tau_{sf}$, is the part responsible for transporting sediment. τ_{eff} was calculated using the following relationship (Meyer-Peter and Müller, 1948):

$$\tau_{eff} = \left(\frac{K}{K_g}\right)^{3/2} \tau \quad (3)$$

with K_g as the Strickler coefficient due to skin friction, $K_g = 21/(d_{50})^{1/6}$ (Strickler, 1923), and K as the total Strickler coefficient. In order to characterize the potential sediment transport, values obtained for the effective shear stress τ_{eff} are compared to the critical bed shear stress for inception of transport τ_{cr}, calculated using the equation of Soulsby and Whitehouse (1997).

Specific stream power ω, has been determined with the following relationship (Bagnold, 1980; Parker et al., 2011):

$$\omega = \rho g \frac{QS}{W} \quad (4)$$

where the energy slope S and the width W are computed for the assumed bankfull discharge, i.e., $Q_{bf} = Q_2$.

3.4. Delineation of homogeneous reaches along the fluvial continuum

The delineation of reaches along the fluvial continuum generally consists in a visual distinction of changes (Orr et al., 2008). A first division of the river into homogeneous geomorphic reaches was conducted in two steps (Latapie et al., 2009):

1. Identifying discontinuities on low water profiles (1978, 1986, 1995, 2002, 2011).
2. Assessing the presence of singularities affecting the flow, sediment transport and thus river behaviour. The presence of artificial structures (bridge, dam, groyne, …), bedrock outcrops, confluences and transition from a single channel to a multiple channel configuration (presence of vegetated islands) was checked on the 1995 aerial photographs complemented by the database on bedrock outcrops compiled by Rethoret (2001).

The 1995 aerial photography dataset was selected in step 2. It is an intermediate value in the period analysed. It corresponds to the official end of the mining period on the Middle Loire. The hydraulic model is based on topographic data surveyed in 1995.

This delineation is pertinent but location of reach boundaries could be corroborated with the implementation of some statistical tests. First, variograms were generated for all geomorphic and hydraulic data to assess the degree and range of spatial autocorrelation and how they change over distance. The range, defined by fitting an experimental variogram gives an indication of the data spatial dependence and can thus be regarded as the maximum length a reach can have. Second, detection of changes on the longitudinal plots of the geomorphic and hydraulic parameters was considered. In order to dismiss discontinuities linked to uncertainties associated with the derivation of the parameters and limit the detection to main discontinuities, threshold values have been defined as ± 50 m for the active channel width B, ± 6 cm for the bed variations Δz and $\pm 20\%$ for the hydraulic parameters. Results of these tests are referred to as "Data Over Threshold" or DOT. Finally, the test of Pettitt (1979) was implemented on all the parameters available to identify discontinuities along the stream network. This test was initially designed to detect a single point of change. However, Alber and Piégay (2011) implemented the approach on the Rhône basin and ran the algorithm iteratively as long as a change point was detected to define homogeneous river reaches (with an α risk equal to 0.05). Combining these approaches to detect changes on the longitudinal plots of the geomorphic and hydraulic parameters allowed the identification of the most significant discontinuities.

4. Results

4.1. Reach definition

The first delineation based on a visual detection of discontinuities on low water long profile and aerial photographs differentiated 167 reaches with length ranging from 250 m to 4750 m and an average length of 2500 m. Due to the presence of numerous structures in the cities of Orléans and Tours, all singularities were not accounted for in those areas; reaches corresponding to those locations have simply been characterized as heavily influenced by human disturbance.

The variogram analysis was performed on the active channel width, floodplain width, changes in bed level and hydraulic parameters. Results illustrated that the active channel width, floodplain width and the hydraulic parameters data are not spatially correlated. On the other hand, changes in bed levels between 1986 and 1995 and between 1995 and 2002 provided a range value equal to 4 and 5 km respectively. Those lengths are consistent with the length of the reach identified with the visual preliminary approach.

Finally, discontinuities identified in relation to geomorphic, hydraulic parameters and temporal variation in active channel width ΔB and river bed level Δz were assessed using the Data Over Threshold (DOT) test and the Pettitt's test (Table 1).

The number of inflection points detected with the DOT approach is highly dependent on the spatial resolution used for calculation; except for the velocity, the number of discontinuities identified on the hydraulic parameters is nearly twice the values calculated on the geomorphic parameters. If discontinuities in lateral and vertical changes are considered, the results appear to be very sensitive to the period considered. However, the "multi-temporal" analysis allows the distinction of permanent structures from transitory ones; those permanent structures identified with the DOT approach were then combined with results from the Pettitt's test to detect robust discontinuities.

If we assume a tolerance of 250 m to account for differences in the data resolution, 170 reaches are identified. With the exception of three boundaries, they all coincide with the boundaries of the 167 reaches previously defined. The additional discontinuities identified correspond to structures located in the cities of Orléans and Tours; and as previously mentioned, those reaches are merged.

Each reach defined is characterized by an average value calculated for every geomorphic, hydraulic and temporal change derived. The following discussion is based on these average values only.

4.2. Changes in active channel width

An example of the longitudinal analysis of the active channel width between 1955 and 2010 is given in Fig. 5a. The observed changes in active channel width can be linked with the four geological units described in Part 2.2. In geological unit 1, the active channel width decreased between 1955 and 2010 mainly because the Loire River evolved from a multiple channel system to a single (constrained) channel. In the other geological units, corresponding to more urbanized areas, the active channel width remained stable except for reaches located upstream of the confluence with the Cher River and downstream of the confluence with the Maine River, where channel narrowing occurred. The reduction in active channel width corresponds to areas where sediments have accumulated behind oblique groynes, favouring the development of vegetation.

Table 1
Number of discontinuities identified on the geomorphic and hydraulic parameters and on temporal lateral and vertical changes with the Data Over Threshold test (noted DOT in the table) and the Pettitt's test.

	Geomorphic parameters						Hydraulic parameters (Q_2)			
	B					B_f	τ_{eff}	ω	W/D	U
Date	1955	1984	1995	2002	2010	2003	1995			
Nb. values	858						1827			
DOT	347	370	343	339	311	366	655	748	265	41
Pettitt	20	20	17	21	24	56	70	72	106	107

	Temporal changes							
	ΔB				Δz			
Date	55–84	84–95	95–02	02–10	78–86	86–95	95–02	03–11
Nb. values	858				86	145	145	184
DOT	177	95	121	76	34	74	62	70
Pettitt	13	5	13	9	70	62	53	47

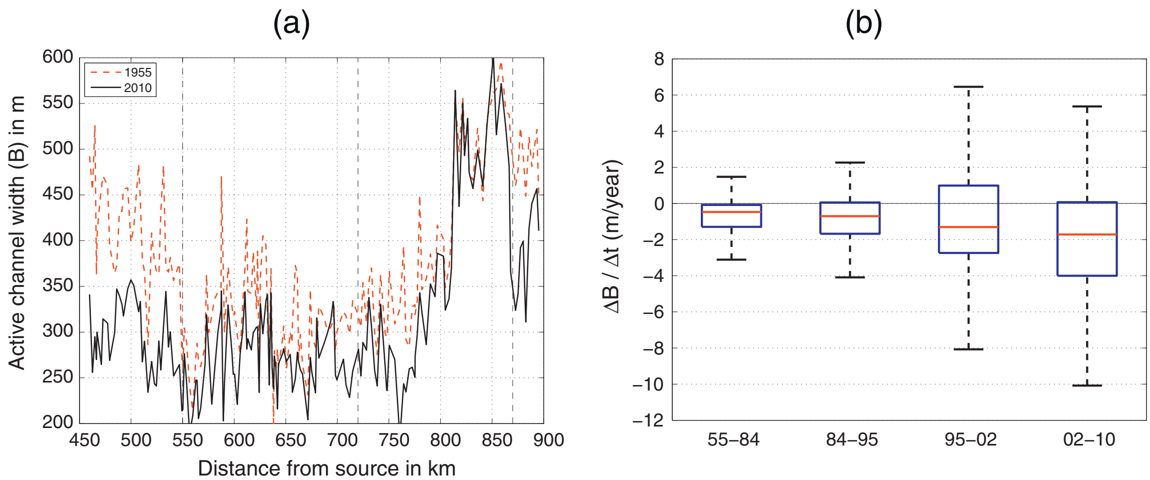

Fig. 5. (a) Measured active channel width *B* for 1955 and 2010 (b) Rate of change in active channel width for the four periods considered (the red line in the boxplot represents the median, the limits of the box provide the 25th and 75th percentiles and the whiskers extend to the most extreme data points not considered outliers). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The rate of change in active channel width ΔB during the period considered is presented in Fig. 5b. A reduction in active channel width is observed for all periods, with a slight increase in the rate of change over the last two decades.

The river reach scale approach complements longitudinal analysis by allowing the identification and comparison of reaches with similar behaviour along the study area. Thus, the reach boundaries are considered to check whether the presence of a natural or artificial features could be linked to a specific channel response. In order to facilitate representation and discussion of the results, we distinguished 4 types of boundaries:

- Type 1 characterizes a reach with "fixed" boundaries delimited by artificial features or bedrock outcrops at the upstream and downstream end,
- Type 2 represents "mixed" reaches (i.e., with a "fixed" boundary upstream or downstream and a "movable" boundary downstream or upstream),
- Type 3 characterizes a reach with "movable" boundaries associated with the presence of islands at both ends,
- Type 4 indicates the presence of tributaries.

Fig. 6 illustrates the rate of changes in active channel width for the different periods and the various reach boundaries identified.

Reaches of types 1, 2 and 3 exhibit similar behaviour with relative lateral stability between 1955 and 1995 before showing a tendency to narrow in the next two periods (1995–2002 and 2002–2010). The presence of a confluence in a reach (type 4) has a significant effect upon active channel width, especially over the last decade.

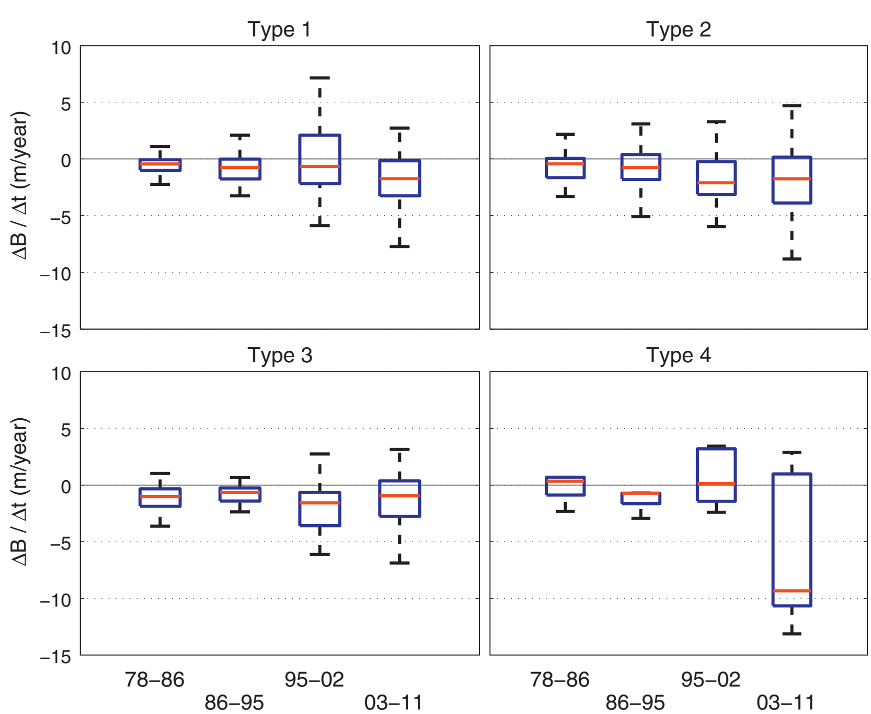

Fig. 6. Rate of change in active channel width for reaches presenting different boundaries (see legend of Fig. 5 for explanation of box-plots).

4.3. Changes in longitudinal profile

Changes in the longitudinal profile as well as the reach-averaged slope were assessed using low water level measurements. Fig. 7 presents the rate of change in reach-averaged slope for the different periods considered for reaches grouped by their types of boundaries. In general, the slope remains stable whatever the type of reach. However, a slight decrease of the slope occurs for reaches delimited by fixed boundaries (type 1). This may correspond to erosion and reduction of slope downstream of structures. On the other hand, a slight increase of the slope occurs for type 4 reaches (confluence), which may have been influenced by sediment input from the confluences together with cessation of instream sediment mining (1995). It is also interesting to note that the rate of change in slope is more variable for reaches presenting at least a fixed boundary (types 1 and 2) since 1995. Inversely, reaches delimited by islands (type 3) present a stable slope for all periods considered.

Fig. 8 presents the rate of change in bed level for several periods for reaches grouped by their types of boundaries. The general trend for all types of reaches is a decrease in the incision rate over the years to attain stability or even aggradation in the last decade. Similar to the rate of change in active channel width, type 1, 2 and 3 reaches behave in a comparable manner (with type 3 reaches, i.e., delineated by islands showing a slightly more pronounced erosion and reduction of the active width for the period 1995–2002). Reaches characterized by the presence of a confluence present a high incision rate between 1978 and 1984 before attaining stability or even aggradation. Apart from the presence of confluences, it is difficult to match reach boundaries with a specific channel response. The slope variation seems however to be sensitive to fixed boundaries with various local variations. Unexpectedly, no correlation was found between the changes in slope and changes in river bed levels. In the same way, the changes in active channel width and changes in river bed levels are not consistently correlated. Thus, the significant reduction of the active channel width observed for many reaches did not systematically lead to erosion nor reduction of the slope. Rinaldi (2003) reported similar behaviour with channel narrowing and no/or limited incision in 4 cases (out of 42 sites) of alluvial rivers in Tuscany. Similarly, the presence of bedrock controlled reaches in the Middle Loire has prevented the upstream migration of bed degradation and the consequent dynamic response in the fluvial system. In the absence of bedrock outcrops, the observed adjustments may reflect a time lag between the disturbance and the channel response (Knighton, 1998). Finally, the “drier” hydrological period observed after 1984 might have enhanced vegetation development and hence contributed to the stabilization of in channel bars and a reduction in active channel width.

5. Use of a 1D model to assess channel changes

As the instream sediment mining period cannot be directly associated to systematic adjustments of channel properties (narrowing and deepening), the hydraulic parameters are considered to assess whether the broad-scale adjustments to river morphology vary in relation to different combinations of width–depth ratio (e.g. Doll et al., 2002).

5.1. Longitudinal evolution of hydraulic parameters

The implementation of a 1D hydraulic model to calculate parameters provides major advantages: multiple modelling scenarios can be envisaged and the derivation is more rigorous; in particular, the specific stream power is generally calculated using the energy slope S assimilated to the bed (or low water) slope S_b (Bernot et al., 1996; Nanson and Knighton, 1996). This assumption can be discussed as the slope should be estimated for the bankfull discharge. Based on the results of the 1D model for the biennial discharge, we found $0.17 < S_{Q2}/S_b < 19$. Significant scatter reflects the presence of artificial and natural singularities, which have a high influence at low to intermediate discharges (such as Q_2).

The hydraulic parameters obtained for the biennial discharge, Q_2, which may be assimilated to the bankfull discharge, are reported in Fig. 9. Q_2 is nearly constant for the first 300 km of the Middle Loire before being affected by the main tributaries which double the discharge (Fig. 9a).

The width–depth ratio computed for Q_2 varies between 57 and 421. It is higher in the upstream and downstream part of the studied area where multiple channels predominate (Fig. 9b). As the mean water depth does not vary significantly from the upstream to the downstream

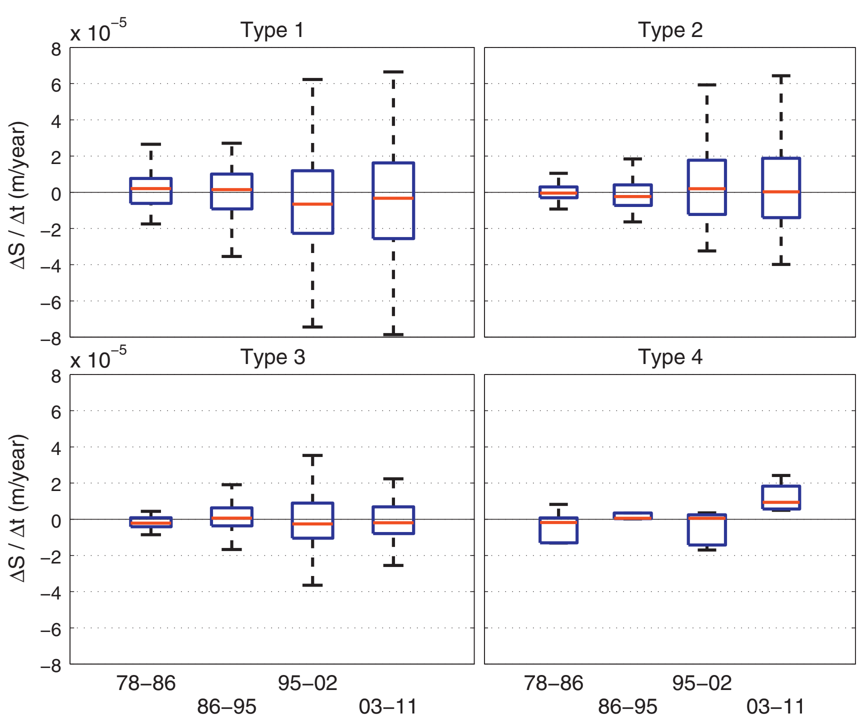

Fig. 7. Rate of change in reach-averaged slope for reaches presenting different boundaries (see legend of Fig. 5 for explanation of box-plots).

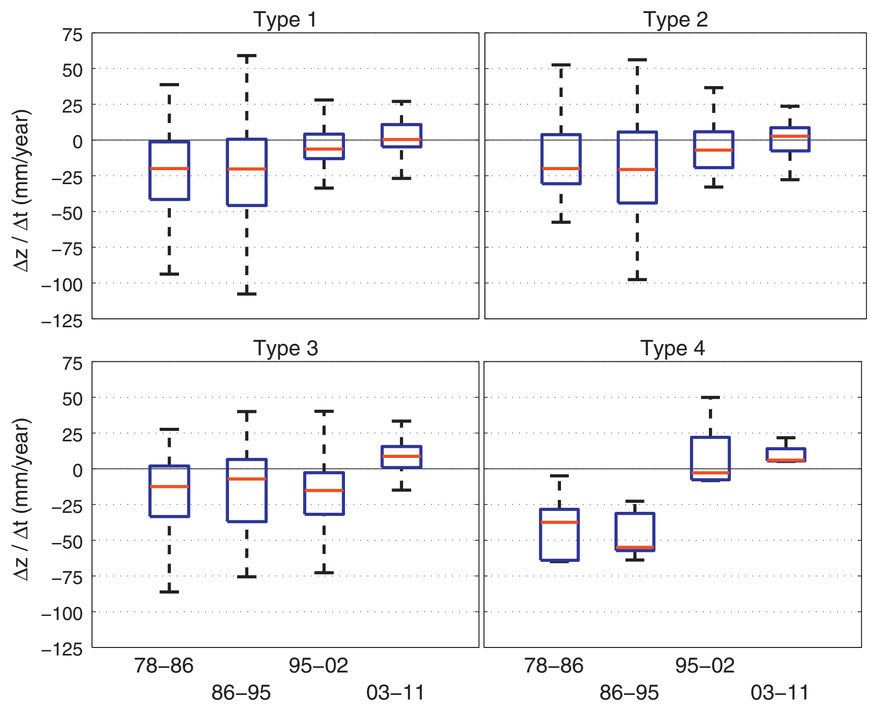

Fig. 8. Rate of change in bed level for reaches presenting different boundaries (see legend of Fig. 5 for explanation of box-plots).

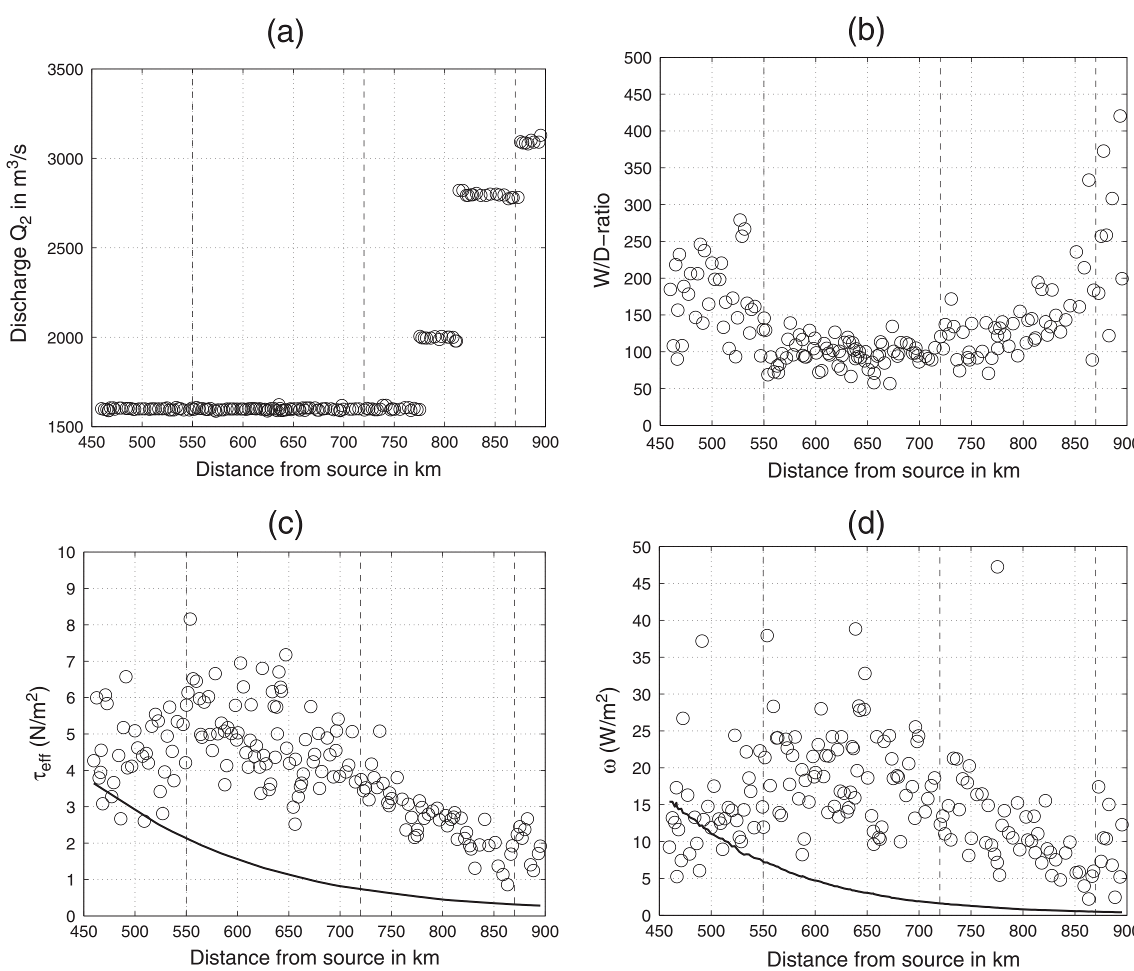

Fig. 9. Longitudinal variation of (a) modeled bankfull discharge ($Q_{bf} \approx Q_2$), (b) width–depth ratio, (c) effective bed shear stress (τ_{cr} in plain line), (d) specific stream power (ω_{cr} in plain line). The vertical dotted lines delineate the four geological units.

part of the Middle Loire River (from $D_{Q2} \approx 3$ m to $D_{Q2} \approx 4$ m), it appears logical that the W/D ratio behaves similarly to the active channel width B ($W_{Q_2}/B \approx 1.5$). In geological unit 1, W/D decreases as the Middle Loire changes from a multiple channel system to a single (constrained) channel. In the middle part of the studied area (geological unit 2), the width–depth ratio is nearly constant and $W/D \approx 100$. In geological units 3 and 4, W/D increases simultaneously with discharge and the presence of multiple channels. A larger dispersion is observed in the downstream part of the model (second part of unit 3 and unit 4). This is mainly due to the presence of multiple channels; the difference in water levels between the two channels cannot be rigorously integrated in our model inducing a larger dispersion in the hydraulic results.

The calculated effective bed shear stress τ_{eff} is within the range of 0.9 to 8.2 N/m^2 (Fig. 9c). In terms of sediment transport magnitude, the results may be affected by the high entrainment threshold. The increasing τ_{eff} in unit 1 indicates a potential for erosion. A maximum is observed for τ_{eff} at a distance of ≈550 km from source. This forms the boundary between unit 1 and unit 2. Finally, the decreasing τ_{eff} in units 2, 3 and 4 indicates a potential for sediment deposition.

The calculated specific stream power ω is within the range of 4 to 47 W/m^2. Downstream patterns of change in ω are highly correlated to downstream changes in channel slope and width. The general trend of the curve is directly the opposite of the width–depth ratio plot. As observed by Knighton (1999), a maximum of specific stream power is evident, in this instance ≈650 km from source. Then, ω decreases to values of less than 10 (except at confluences where a slight increase is noticed). Channel changes have often been associated with specific stream power (e.g. Bledsoe et al., 2002; Brookes, 1987; Orr et al., 2008). Since threshold values are specific to a catchment, the analysis of downstream changes in stream power should be considered as an indicator of zones of potential sediment transport. Large changes in stream power from one reach to the next are generally associated to erosion (increase of ω) or sediment accumulation (decrease of ω), whereas high values alone are not necessary indicative of changes (Reinfelds et al., 2004; Vocal-Ferencevic and Ashmore, 2012). It should be noted that, based on the Strickler (1923) concept, we can derive $\omega \propto \tau^{1.5}$, which explains the similar behaviour of τ and ω albeit the larger dispersion in the specific stream power.

To be more accurate in characterizing the potential sediment transport, the bed shear stress or specific stream power was compared to its critical value for inception of sediment transport. The critical bed shear stress (τ_{cr}) was obtained from the Shields curve based on the grain size estimates. The critical specific stream power (ω_{cr}) was estimated using the development of Bagnold (1980). As the river bed median grain size decreases (from $d_{50} \approx 4$ mm to $d_{50} \approx 0.6$ mm), the critical bed shear stress decreases from $\tau_{cr} = 36$ to 0.3 N/m^2; and the critical specific stream power from $\omega_{cr} = 15$ to 0.4 W/m^2 (see plain line in Fig. 9(c) and (d), respectively). Despite uncertainties in the estimation of the critical bed shear stress and specific stream power, not only due to some sensitivity to the slope (Camenen, 2012) but also because of the scatter in the grain size measurements, Fig. 9(c) and (d) indicates that critical values are generally exceeded all along the river. Results indicate that sediment transport occurs at flows lower than the biennial discharge, which is consistent with measurements and analysis realized around the site of Bréhémont (776 km from source; see Claude et al., 2012). This behaviour is typical in sand–gravel bed rivers where sediment transport is influenced not only by flood events but also by lower discharges occurring over a longer period.

5.2. Interest of the effective bed shear stress and width–depth ratio

The effective bed shear stress made dimensionless by its critical value for inception of transport and the width–depth ratio computed for the biennial discharge is presented in Fig. 10. These two parameters allow a clear distinction between the four geological units. For units 1 and 4, the large W/D values are directly connected to the presence of multiple channels and islands. Since d_{50} is larger in unit 1 than in unit 4, τ_{eff}/τ_{cr} differs in those two units.

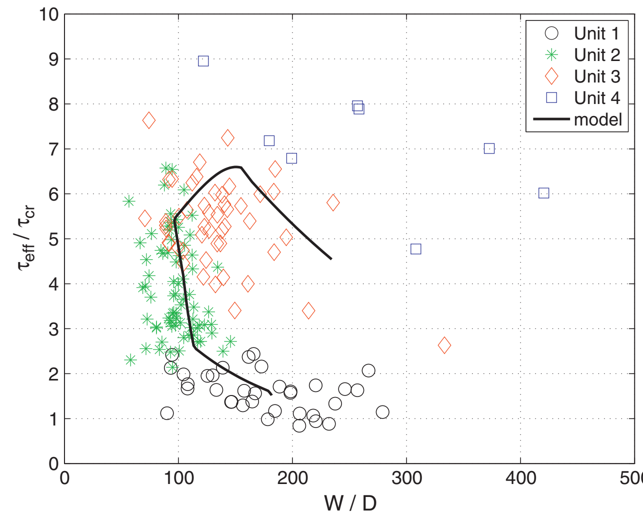

Fig. 10. Effective bed shear stress made dimensionless by its critical value for inception of transport versus the width–depth ratio computed for Q_2.

- Unit 1: The τ_{eff}/τ_{cr} ratio is relatively small ($\tau_{eff}/\tau_{cr} \approx 1.5$) and slightly decreases with the W/D ratio ($80 < W/D < 280$).
- Unit 2: The τ_{eff}/τ_{cr} ratio is intermediate ($2 < \tau_{eff}/\tau_{cr} < 6.5$) but decreases rapidly with the W/D ratio ($60 < W/D < 130$).
- Unit 3: The τ_{eff}/τ_{cr} ratio is relatively high ($3 < \tau_{eff}/\tau_{cr} < 7.5$), increasing with the W/D ratio ($70 < W/D < 330$).
- Unit 4: The τ_{eff}/τ_{cr} ratio is high ($5 < \tau_{eff}/\tau_{cr} < 9$) and slightly decreases with the W/D ratio ($120 < W/D < 420$).

Using a continuous fit for each parameter (τ_{eff}, D, and W) in a similar way as for the median grain size (Eq. (1)), it is possible to obtain a curve for the $\tau_{eff}/\tau_{cr} - W/D$ relationship that is function of the longitudinal distance (solid line in Fig. 10). It appears from this analysis that the hydraulic and geomorphic parameters allows the distinction of different trends of channel response but the latter changes need to be associated with human disturbance (in particular instream sediment mining).

Fig. 11 illustrates the rate of change in river bed level considering the effective shear stress made dimensionless by its critical value and the width–depth ratio for the periods 1986–1995 and 1995–2002 (where 1995 is the year corresponding to the cross section data used to construct the hydraulic model and official termination of instream mining). Different trends can be distinguished for the two periods. Between 1984 and 1995, the rate of change in bed level decreases as the ratio τ/τ_{cr} increases. During the following period (1995–2002), the contrary is observed (i.e., the rate of change in bed level increases as the ratio τ/τ_{cr} decreases). The width–depth ratio equally illustrates different behaviours for the two periods but with larger dispersion. Those trends indicate river recovery since extraction stopped (Fryirs and Brierley, 2000).

6. Impact of sediment mining upon channel changes

Instream mining has directly altered the channel geometry and bed elevation in the Middle Loire. One hundred and two "official" sites have been identified from archive data between Nevers and Saumur (located respectively 445 km and 823 km downstream from source, Fig. 1). Unfortunately, the amount of sediment extracted is not always quantified in the historical database. Based on the data available, we distinguished reaches with low average annual extraction rate (i.e., less than 1000 T/year) from reaches with moderate extraction rate (i.e., less than 100,000 T/year) and intensive extraction rate (i.e., more than 100,000 T/year). The annual rate of change in bed level considering

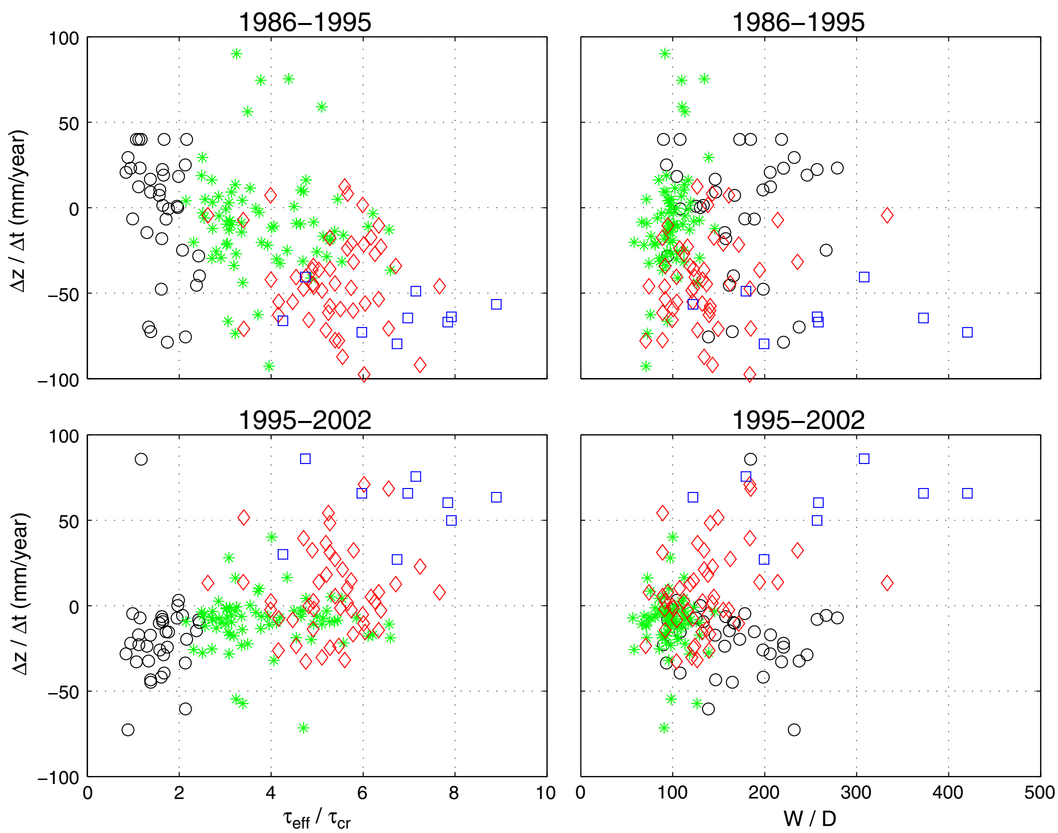

Fig. 11. Rate of change in bed level related to the effective bed shear stress made dimensionless by its critical value and to the width–depth ratio (legend for the distinction of the four geological units is the same as for Fig. 10).

the amount of sediment extracted per reach is presented for different periods between 1978 and 2010 in Fig. 12.

The general trend for all the reaches is river bed incision for the first three periods. For the latest date considered (2003–2011), incision has stopped and some aggradation is visible independent of the former rate of extraction sustained by the reach. Until the end of the instream mining period (1995), reaches affected by high sediment mining tend to have eroded more significantly.

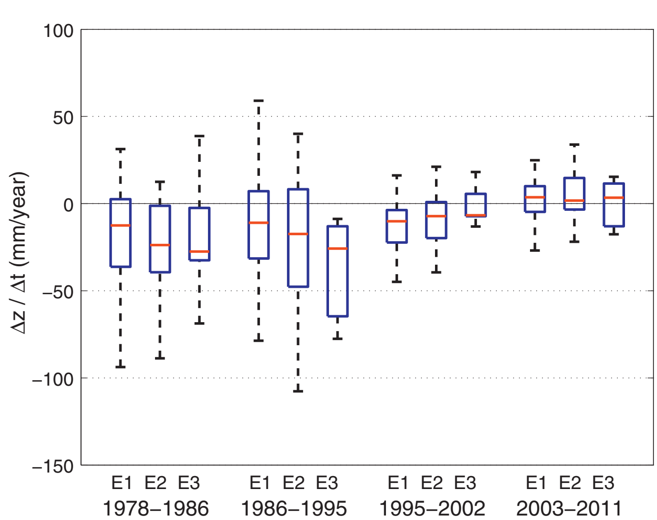

Fig. 12. Annual changes in bed level considering the amount of sediment extracted per reach (E1: low extraction rate, E2: moderate extraction rate and E3: high extraction rate; same explanation for each box as in Fig. 5).

As the data collected do not allow quantification of volume extracted for each reach of the study area, five reaches that were the most affected by instream mining are considered. The authorized volume of sediment mined (V_{ex}) is compared to the volume calculated from changes in low water level for the period 1978–2002. This volume of deposition or erosion ($V_{d/e}$) was approximated by multiplying the change in low water level by the active channel width and the length of the reach (i.e., $V_{d/e} = \Delta z \times B \times L_t$). As a result, $V_{d/e} > 0$ means aggradation whereas $V_{d/e} < 0$ means erosion. Results shown in Table 2 provide an insight into the localized effects of instream sediment mining.

The volume of sediment officially extracted from the active channel with permission from the water authorities is generally greater than the volume calculated from the low water levels for the five reaches considered (i.e., $V_{ex} > V_{d/e}$). Prior to describing the above results in more detail, the uncertainties associated with low water level records available for 1978 and with the location of extraction sites are explained.

The reach located 502.65 km from source has a bridge at its downstream boundary. Aggradation of the river bed occurred during the period corresponding to the main extraction period. This behaviour is the opposite to what is expected and it is probably due to the presence of a localized mining pit which is not visible on the low water level long profile. A period of incision is observed from 1984 to 1996 despite a reduction in the amount of sediment removed. For this particular reach, it appears that the channel response was poorly influenced by the extensive extractions at the reach scale.

The reach located 536.29 km from source has been subjected to intensive sediment mining to allow the construction of a nuclear power plant. This reach is located just downstream of the transverse sill of the nuclear power plant, which constrains sediment transport. The volume of erosion calculated from available topographic data between 1978 and 1984 is -8.3×10^4 (m^3/year). This differs from the aggradation observed from low water levels. The recalibration of the river prior

Table 2
Comparison between the volume of sediment annually extracted (V_{ex}) and the calculated volume of deposition or erosion ($V_{d/e}$) for five reaches located by their distance from source (in km).

Distance from source	1978–1984		1984–1996		1996–2002	2003–2011
	V_{ex} (10^4 m^3)	$V_{d/e}$ (10^4 m^3)	V_{ex} (10^4 m^3)	$V_{d/e}$ (10^4 m^3)	$V_{d/e}$ (10^4 m^3)	$V_{d/e}$ (10^4 m^3)
502.65	11.5	9.4	2.8	−6.1	−8.2	14.6
536.29	78.6	9.2	0.5	0.03	−0.4	0.02
625.35	13.4	−3.6	4.8	−0.6	−0.6	−4.8
705.81	15.1	−2.9	4.3	−1.6	−0.5	−3.8
748.28	15.8	−0.4	6.1	−2.8	0.4	5.6

to the construction of the nuclear power plant has had a larger influence on the channel response than extractions. It is assumed that as records of low water levels are not evenly distributed, gravel pits could be located in between two measures, leading to an underestimation of changes in bed levels at the reach scale. Another explanation could be that the degradation is very localized and calculated volumes at the reach scale are incorrectly spread over the whole length of the reach.

The three other reaches presented in Table 2 present an expected behaviour indicating the influence of extractions. Significant erosion is observed during the extraction period before the reach starts its recovery at the end of the mining period (1995).

7. Conclusion

An understanding of channel response over recent decades is a prerequisite for assessing recovery potential and predicting how a reach may respond to future disturbance (Fryirs and Brierley, 2000). Customary analyses using longitudinal profiles show salient features and spatial interrelationships. These are enhanced by reach determinations, which enable spatial distributions to be appraised for reach by reach comparison.

The general trends observed on the Middle Loire River over the last 50 years are a narrowing of the active channel width and an incision of the river bed (Gasowski, 1994). This has led to adjustments of island widths (Détriché et al., 2010) and secondary channels (Rodrigues et al., 2006). These adjustments are similar to those reported on other European rivers affected by human disturbances (Bravard et al., 1997; Surian and Rinaldi, 2003). Changes in channel pattern have not occurred on the Middle Loire River as it is highly constricted by flood embankments. However lateral adjustments associated to bank erosion occurred in the last 50 years. This lateral stability (i.e., no change in channel pattern) differs from changes observed on the Upper Loire River, upstream of the confluence with the Allier River, which is not confined (Leteinturier et al., 2000).

The reach scale approach implemented on the Middle Loire River complements observed longitudinal variation of geomorphic characteristics. Statistical tests corroborate the location of clear discontinuities and so reach definitions. Given the Water Framework Directive context, this approach could inform decision makers about further localized studies to support decisions to take to achieve good conditions. Results show that channel changes at the reach scale are largely influenced by the presence of former extraction sites. Sediment mining caused significant erosion but the river bed has been restored since gravel mining stopped in the 1990s. Several reaches that were in severe erosion are now in aggradation. Fryirs et al. (2009) refer to this as a response gradient. On the other hand, the channel response for the active width appears slower since no clear indication of recovery was observed.

Hydraulic parameters derived from a 1-D hydraulic model allow a more precise definition of parameters, supporting modelling scenarios. The effective bed shear stress made dimensionless by its critical value for inception of transport τ_{eff}/τ_{cr} and the width–depth ratio W/D computed for the biennial discharge help in the understanding of channel responses. Although a 1D hydraulic model requires a significant amount of topographic and hydrologic data, it provides several additional indicators such as τ_{eff}/τ_{cr} and W/D for different discharges. With the development of Lidar data acquisition, which hopefully will give access to bathymetric data as well, the application of the approach outlined here will possibly be easier over long reaches.

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