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Regime theories in gravel bed rivers: models, controlling variables and applications in disturbed Italian rivers

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ABSTRACT

Downstream hydraulic geometry relationships describe the shape of alluvial channels in terms of bankfull width, flow depth, flow velocity, and channel slope. Recent investigations have stressed the difference in spatial scales associated with these variables, and thus the time span required for their adjustment after a disturbance. The aim of this study is to explore the consequences in regime models considering the hypothesis that, while channel width and depth adjust quickly to changes in water and sediment supply, reach slope requires a longer time span. Three theoretical models were applied. One model incorporates an extremal hypothesis (Millar, 2005), and the other two are fully physically based (Ikeda et al., 1988 and Parker et al., 2007). In order to evaluate the performance of models introducing the slope as an independent variable we propose two modifications to previous models.

The performance of regime models was tested against published data from 142 river reaches and new hydraulic geometry data from gravel bed rivers in Patagonia (Argentina) and Northeastern Italy.

Models that assume slope as a control (Ikeda et al., 1988; or Millar, 2005) predict channel depth and width reasonably well. Parker et al.'s model (2007) improved predictions because it filters the scatter in slope data with a relation slope-discharge. The extremal hypothesis model of Millar (2005) predicts comparably to the other physically based models.

Millar's model was chosen to describe the recent changes in the Piave and Brenta rivers due to human intervention -mainly in-channel gravel mining. The change in sediment supply and recovery was estimated for these rivers. This study supports the interpretation that sediment supply is the key factor guiding morphological changes in these rivers.

Keywords: Regime theory; Hydraulic geometry; Northeastern Italy; Patagonia-Argentina; River recovery; River management.

1. Introduction

A regime theory consists of a set of equations to estimate the width, depth and slope of a stable channel if liquid discharge and sediment supply are known. Regime theories were created in the XIX century within the context of hydraulic engineering in order to design stable irrigation canals (e.g. Kennedy, 1895). Lindley (1919) first recognized three degrees of freedom for a channel to convey sediment supply, namely its width, depth and slope. However, it was much later when Lacey (1929) formulated for the first time a quantitative model relating these variables. Leopold and Maddock (1953) introduced the quantitative concept of hydraulic geometry and showed that alluvial rivers adjust both their slope and channel in order to be in equilibrium for a certain representative discharge. Later studies focused on defining which discharge should be considered representative, thus equivalent to the range of discharges observed in a natural river. Wolman & Miller (1960) proposed the concept of effective discharge, as the flow rate that is most effective in the long-term transport of sediment, thus incorporating both the magnitude of sediment-transporting events and their frequency of occurrence. Further research (e.g. Leopold et al., 1964; Andrews, 1980) showed that this discharge should correspond to the bankfull discharge (Hey & Thorne, 1986), which is the maximum flow rate that a channel can convey without overflowing onto its floodplain, and is equal to the 1.5 to 2 year recurrence interval flow event (e.g., Bray, 1982).

Besides the empirical research on the relationships between liquid discharge and geometrical characteristics of the river (slope, width, and depth), there has also been an intense theoretical work focused on explaining regime relations. Parker (1978) demonstrated the importance of the bank erodibility, and the need of using improved hydraulic models to calculate the shear stress distribution on irregular cross-sections. Using the lateral turbulent diffusion model proposed by Lundgren & Jonsson (1964), Parker derived a new theoretical expression that combined a central region with active bed and lateral stable banks. Parker's models has been subsequently improved to consider graduated materials (Ikeda el al., 1988), and bank vegetation (Ikeda & Izumi, 1990), and has also been applied to model lateral sediment transport (Pizzuto, 1990).

Alternative conceptual approaches have been used to explore geometrical channel properties. Leopold & Langbein (1962) took advantage of thermodynamic principles to suggest that the distribution of energy in a river system tends towards the most probable state. Following their approach, this condition is reached when the exponents of the power-law relationships between liquid discharge and channel properties (width, depth, and velocity) attains a minimum variance. After this first pioneering work, further so-called "extremal" hypotheses were proposed such as: minimum unit stream power (Yang and Song, 1979), minimum stream power (Chang, 1980), minimum energy dissipation rate (Brebner and Wilson, 1967; Yang et al., 1981), maximum sediment transport rate (White et al., 1982), maximum friction factor (Davies and Sutherland, 1983) and maximum resistance to flow (Eaton et al, 2004). Millar & Quick (1993), Cao & Knight (1998), and Millar (2005) proposed models that take into account the bank strength, a distinctive condition not considered in previous works. Because of their lack of physical-based principles, extremal hypothesis approaches to explain and predict channel geometry have been extensively criticized (Ferguson, 1986; Parker et al., 2007). Defenders claimed their validity based on the principle of least action (Nanson and Huang, 2008) or on the opposed feedback processes acting at the cross-section scale (Eaton et al., 2006).

Regime models usually consider three degrees of freedom (width, depth, and slope) and four external control variables (liquid discharge, sediment supply, bed grain size, and bank strength). However, these variables reflect geomorphic processes acting at different temporal and spatial scales, and this is not considered in regime models. Weicher et al. (2009) suggested that at the micro-scale (10^{-1} to 10^{-2} channel widths) the channel responds to external alteration by changing the surface grain-size (e.g., armouring the bed); at the meso-scale and macro-scale (10^{0} to 10^{1} channel widths) the channel reacts by generating bed forms and increasing roughness; and at the reach-scale (10^{2} channel widths) a river reacts by adjusting its slope. However, there are issues related to the spatial scale at which channel geometry and grain size are usually measured, as well as the length of water discharge database and the availability of sediment transport measurements.

Regime approaches have been used to design alluvial stable channels (Park, 1977; Hey and Thorne, 1986; Dingman and Sharma, 1997; Cao and Knight, 1998), to interpret channel changes (Chew and Ashmore, 2001) and to quantify channel changes due to human intervention (Shin and Julien, 2010). Many rivers in Italy have experienced dramatic

morphological changes such as narrowing, bed incision and pattern migration from braided to single-thread due to human disturbances such as phases of deforestation/reforestation, bank protection, channel rectifications and gravel mining (e.g., Surian and Rinaldi, 2004). The aims of the present work are (i) to explore the consequences in regime models of considering the hypothesis that, while channel width and depth adjust quickly to changes in water and sediment supply, reach slope requires longer time spans; and (ii) to use regime models to explain recent morphological changes and potential recovery of Italian rivers. In order to assess the first objective, new hydraulic geometry data are used from five river reaches in the Northeastern Italian Alps and nine river reaches in the Eastern side of the Patagonian Andes (Argentina). Published hydraulic geometry of gravel-bed rivers in other geographical regions (92 streams reaches) and laboratory data (36 small stream) are also used in the analysis. Performance of model prediction is analyzed for the entire data set of 142 observed reaches. With regards to the second objective, two disturbed rivers in Italy are analyzed.

2. Materials and methods

2.1 Selection of models and proposed modifications

Three models, all of them incorporating a bank stability criterion, were considered in this study. One model incorporates an extremal hypothesis (Millar, 2005), whereas the others are fully physically-based (Ikeda et al., 1988; Parker et al., 2007).

Millar's (2005) extremal hypothesis model considers a simplified trapezoidal cross section defined by means of its bottom width, central depth and bank slope. Because the longitudinal slope represents the fourth dependent variable, four constrains are thus needed: flow resistance, sediment transport, bank stability and a further extremal hypothesis defined as the maximum sediment transport efficiency, expressed as the ratio of sediment concentration and slope. For a given sediment supply, water discharge, and bank strength, the model predicts the cross section geometry that maximizes sediment transport:

$$B^* = 28.1 Q^{*0.50} C^{*-1.12} \mu'^{-1.66} \quad (1)$$

$$H^* = 0.0764 Q^{*0.37} C^{*1.16} \mu'^{1.22} \quad (2)$$

$$S = 1.98 Q^{*-0.33} C^{*-1.86} \mu'^{-0.93} \quad (3)$$

where B^*, H^* and $Q^*$are the dimensionless width, depth and discharge, respectively; S is the channel slope; C* is a log-transformed variable for C, the dimensionless sediment

concentration (C* = -log C) and $\mu'$is the bank strength. Sediment supply can be eliminated using S as the independent variable:

$$B^* = 16.5Q^{*0.70}S^{0.60}\mu'^{-1.10} \quad (4)$$

$$H^* = 0.125Q^{*0.16}S^{-0.62}\mu'^{0.64} \quad (5)$$

Parker et al. (2007) proposed a physical based model where the hydraulic geometry is described by means of three reach-averaged variables: width, mean depth and slope. The external controls are the liquid discharge, sediment supply and median grain size of surface material. The physics comprise several constrains: flow resistance, sediment transport, and a stability criterion that considers the mean cross-sectional shear stress. Besides, the model includes an empirical relation (the so-called gravel yield) for the sediment supply which depends on bankfull discharge and sediment grain size. The slope is derived from the sediment transport model:

$$q_b^* = 11.2(\tau^*)^{3/2}\left(1 - \frac{\tau_c^*}{\tau^*}\right)^{4.5} \quad (6)$$

In which q_b^* is the dimensionless sediment transport, τ^* and τ_c^* are mean cross section and critical dimensional shear stresses, respectively. The sediment transport is calculated with the empirical relation aforementioned (a potential-type formula on the discharge), and τ_c^* is not constant but a weak function of the dimensionless discharge, as well (see Parker et al. 2007, for further details).

Depth is evaluated with a stability relation:

$$\tau^* = r\tau_c^* \quad (7)$$

where r is a parameter related to the bank strength. Finally, width is derived from the flow resistance equation:

$$\frac{Q}{BH\sqrt{gHS}} = \alpha_r\left(\frac{H}{D_{50}}\right)^{n_r} \quad (8)$$

wherein D_{50} is the median diameter, α_r and n_r are calibrated parameters ($\alpha_r = 3.71$ and $n_r = 0.263$).

The third selected model analyzes processes occurring at the cross section scale. Ikeda et al., (1988) improved by extending it to the case of bed material composed of heterogeneous mixtures, a previous model proposed by Parker (1978) which solved the transverse shear stress distribution using Lundgren & Jonsson's (1964) area approach. The cross-section shape is calculated imposing a stability constraint on the banks and the flow resistance relation, while the slope is treated as an independent variable.

The flow resistance equation is used for deriving the width:

$$B = \frac{Q}{H_c\sqrt{gH_cS}2.5ln\left(11\frac{H_c}{k_s}\right)} + \left[2.571 + \frac{2.066}{ln\left(11\frac{H_c}{k_s}\right)}\right]H_c \quad (9)$$

Wherein H_c is the depth at the channel center and k_s is the roughness height. A similar expression to eq. 7 is used for depth but the critical shear stress is evaluated with Egiazaroff (1956) relation:

$$\frac{gH_cS}{R_sgD_{90}} = 1.23\left\{\frac{0.05}{\left[log\left(19\frac{D_{90}}{D_{50}}\right)\right]^2}\right\} \quad (10)$$

In order to evaluate the performance of the models introducing the slope as an independent variable, two modifications are proposed. The first modified model (hereafter MM1) is based on Parker et al. (2007), but slope is introduced as an external control instead of being correlated against liquid discharge as in the original model. Therefore, the same relation is used for the stability criterion (eq. 7) and equation 45 of Parker et al. (2007) is used for the flow resistance because it was calibrated using S as an independent variable ($\alpha_r = 4.39$ and $n_r = 0.210$).

The second modified model (hereafter MM2) considers the Keulegan (1938) equation for energy dissipation with Bray's (1979) calibration for roughness height, as previously used by Millar (2005):

$$\frac{Q}{BH\sqrt{gHS}} = 2.5ln\left(11\frac{H}{xxD_{50}}\right) \quad (11)$$

The stability criterion consists of a comparison between mean shear stress and the reference shear stress for sediment transport, as used by Parker et al. (2007), but introducing the dependence of the reference shear stress on slope as proposed by Muller et al. (2005).

$$\tau_c^* = 2.18S + 0.021 \quad (12)$$

A summary of the main features of each model can be found in Table 1.

A normal practice in experimental research is the use of dimensionless parameters. For the present study five dimensional variables are identified: width (B, m), depth (H, m), discharge (Q, $m^3\ s^{-1}$), acceleration due to gravity (g, $m\ s^{-2}$), and a representative grain diameter (D_{50}, m); and nondimensional longitudinal channel slope S (--). As there are only two dimensions (length and time), it is possible to define three independent dimensionless parameters in the terms previously adopted by Millar (2005):

$$H^* = HD_{50}{}^{-1} \quad (13)$$

$$B^* = BD_{50}{}^{-1} \quad (14)$$

$$Q^* = Qg^{-1/2}D_{50}{}^{-5/2} \quad (15)$$

2.2. Channel pattern criterion

Millar (2005) also proposed a criterion to distinguish between single thread (meandering) and braided channels. A river reach will develop a single-thread meandering pattern only in two situations, a) the valley slope is higher than the minimum slope required to convey sediment load; or b) the required channel slope is below the transition slope for meandering-braiding. When condition a) is not verified the channel aggrades and a braided pattern may emerge. In the second case, the channel is too steep and flow-sediment instability drives channel to a braided configuration (Parker, 1976). Millar's equation for the transition slope of meandering-braiding reads as follows:

$$S^* = 0{,}0975Q^{*-0.25}\mu' \quad (16)$$

wherein S^* is meandering-braiding transition slope.

2.2. Study rivers and hydraulic geometry data acquisition

Several reaches belonging to gravel-bed rivers were selected in Argentinean Patagonia and in the Italian north eastern Alps (Figure 1). The Argentinean rivers are located along the Cordillera mountain range (Chubut and Rio Negro Provinces, Argentina). Some river reaches were selected within the mountain range where a humid climate predominates, with mean annual precipitation around 1000 mm and a rain-snowmelt regime. Other reaches lie in the pre-cordillera region, located eastward, where the climate is drier and the regime is snowmelt dominated. In general, the geologic setting is comprised of plutonic rocks in the mountain range while fluvial-glacial deposits and continental sediments predominate in the pre-cordillera region. The Italian river reaches belong to the Brenta and Piave River (Veneto and Trentino-Alto Adige Regions; Surian et al., 2009; Comiti et al., 2011). The streams are subjected to intense floods with a distinct regime: rainfall floods in autumn and rainfall-snowmelt floods in spring. Basins are covered mainly by forest and the predominant bedrock are limestones and dolomites.

River reaches were chosen for their morphological homogeneity and for having at least 20 years of continuous flow record. In Argentina gauge stations are managed by the *Subsecretaria de Recursos Hídricos de Nación*. Systematic measurements began by the

middle of twentieth century. For the selected gauge stations records cover a time span ranging from 25 to 63 years. Water discharge has been measured at the Brenta River since 1924 at the Barzizza station, located about 5 km upstream of the study reaches. For the Piave River, flow records are derived from three gauging stations managed by the ARPAV-Veneto Region and from two historical flow records (Segusino: 1926-1960; Busche: 1961-2007; Comiti et al., 2011).

Reaches were selected for being completely alluvial and having at least one bank free to evolve. In some cases a thick vegetation was growing in the banks, and in few cases one of the banks was protected with groynes. All selected reaches start and finish at riffles and extend along a whole wave length comprising three riffles and two pools. Five cross sections were surveyed using total station or DGPS, one at each morphological unit. Channel width and mean depth at bankfull stage were evaluated from cross-section profiles (Table 2). Bankfull stage was recognized in the field as a clear threshold in channel geometry, sediments, and vegetation composition (Leopold, 1994). Bankfull discharge was calculated following Leopold's (1994) approach for Patagonian rivers, and from direct observation of water stages during flood events in Italian streams (Table 2). Surface grain size was measured at each cross section by using the Wolman's (1954) random walk approach and collecting at least 120 clasts. Rather than using the thalweg, the slope was calculated from a linear regression model of bankfull stages against downstream distance (Hey & Thorne, 1986).

Tables 2 shows the averaged values of hydraulic geometry variables of the nine selected gravel-bed reaches in Patagonia and five in Italy. Because each variable that describes the hydraulic geometry at the reach scale is subject to a certain within-reach natural variability, a confidence interval was calculated considering empirical cumulated frequency functions based on data from each cross section.

The Monte Carlo approach was used to calculate the confidence interval for dimensionless parameters. A large number (10,000) of random values for H, B, Q and D_{50} were generated and dimensionless parameters were calculated. Their confidence interval was then evaluated from the corresponding cumulated frequency functions.

2.3. Hydraulic geometry data

Hydraulic geometry of gravel-bed rivers in other geographical regions were collected from literature and have been selected for having no or low density of bank vegetation, and

complete description of surface grain size distribution and channel geometry. The database (Table 3) is composed of 33 river reaches from Alberta, Canada (Bray 1979, and Kellerhals et al., 1972), 13 reaches from Britain (Hey and Thorne, 1986), 32 from Idaho, USA (Mueller et al, 2005), 14 from Colorado, USA (Andrews, 1984), and 36 small laboratory streams (Ikeda et al., 1988; Eaton and Church, 2004).

2.4. Record of channel adjustments of the Brenta and Piave rivers

A range of human impacts (channelization, sediment mining, dam construction, reforestation) has taken place in the Brenta and Piave rivers during the past centuries, and particularly during the last 100 years. These interventions consist of both direct (e.g. levees and groins) and indirect (e.g. reforestation) actions. The chronology of human interventions is quite similar in both rivers, with bank protection occurring mainly during the 19th century, implementation of torrent control works from the 1920s and then more intensively following the catastrophic 1966 flood event (Surian et al., 2009). Natural reforestation at the basin scale and dams construction was particularity intense from the 1950s, whereas gravel mining was very intense between the 1950s and the 1980s (Surian et al., 2009; Comiti et al., 2011). As a result, the Brenta river in the study reach has experienced a dramatic channel contraction during the last decades, being around 440 m wide by the beginning of 20th century and narrowing to ca. 220 m in 2003 (Figure 2). This process has been accompanied by channel incision of up to 2.5 m, particularly from the 1960s. However, in the study reach slope has increased only slightly (0.0033 to 0.0036 m m^{-1}), channel narrowing far the most important river reaction to the reduced supply of sediments from the upper reaches (Surian et al., 2009).

The case of the Piave is quite similar to the Brenta River (Surian et al., 2009; Comiti et al., 2011). An analysis of the historical maps and aerial photographs shows that during the 20th century the active channel progressively narrowed, reaching in 1991 an extension of approximately one-third of its extent in at the beginning of 1800. The active channel area was reduced in two different stages (Figure 2). A first phase of adjustment took place during the first half of the twentieth century and was characterized by a loss of about 35% of the initial active channel area, at a rate of about 11 ha year^{-1}. The mean active channel width, calculated as the ratio between channel area and reach length, narrowed at an average rate of 3.8 m year^{-1}. This trend was interrupted by the 1966 high magnitude (200 year recurrence interval) flood, and the subsequent narrowing phase (from 1970 to 1991) was even more intense, ca. 32 ha

year^{-1} (10.6 m year^{-1} in terms of channel width). Interestly, during the following period (1991–2003), a reversal occurred with an evident sharp widening tendency that extended the active channel at a rate of 27 ha year^{-1}. As to the long-term bed level changes, bed elevation in 1929 was about 1 m higher than present days, with a rather complex trend of bed level adjustments (Comiti et al., 2011). Like in the Brenta River, channel narrowing has been the major channel reaction to changes in sediment supply while slope has slightly changed (0.0044 to 0.0045).

3. Results

3.1 Performance of regime models

Figure 3 shows the comparison of dimensionless predicted parameters H* and B* against observed values. A quick visual inspection reveals that Parker et al.'s model provides the best performance, and good results are also attained by Millar's and Ikeda et al.'s models. However, when slope is introduced as an external control in Parker et al.'s model the prediction capacity is lower and scatter is higher (MM1, Figure 3, d). On the other hand, the second modified model (MM2 based on Millar's model) presents an evident systematic deviation.

Model's performance was quantified using two indexes: the average deviation (AD) defined as the mean value of the relative difference between predicted and observed values, and the mean square-root deviation (RMD), which expresses the dispersion of predicted values with regards to the mean prediction:

$$AD = \frac{1}{N}\sum_{k=1}^{N}\frac{x_k^{pred}-x_k^{obs}}{x_k^{obs}} \quad (17)$$

$$RMD = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}\left(\frac{x_k^{pred}-x_k^{obs}}{x_k^{obs}} - AD\right)^2} \quad (18)$$

Table 4 contains the results of the predictions of dimensionless depth applying both indexes to each data set, and to the whole data base. The table also contains the correlation coefficient between predicted and observed values and its standard error. Millar's model shows the best performance, being the mean predicted depth 2.4% lower than observed, while Ikeda et al.'s model and the MM1, also give good predictions (AD equal +4.3% and -5%, respectively). However, these statistics refer to the overall data. A closer inspection to model performance

on each data set reveals that British streams are largely underpredicted. Ikeda et al.'s model predicts fairly well each dataset giving more uniform values of AD, however the scatter is larger within each dataset (see RMDA and SE). Parker et al.'s model presents some discrepancies as results from Italy, Britain and Alberta datasets. On the contrary the overall performance is good. A zero value of AD was obtained with the MM2 calibrating the stability criterion. For the whole database, the mean shear stress is 1.38 times the reference shear stress. The scatter is quite similar among models, with a lowest RMD value of 26.3% (Parker et al.'s model) and highest value of 55.8% (MM1).

With regards to width (Table 5), Ikeda et al.'s model and Parker et al.'s model give the best prediction for the whole data set with AD values of -2% and -6%, respectively. Although AD values are very similar, Parker et al.'s model presents the lowest RMD value and SE, as well. Millar's model also has a good performance. Width is overpredicted by 15%, and fails particularly in laboratory cases. However, if only natural stream are considered its performance is better: AD=0.07 and RMD = 0.22. The performance of modified methods is lower than previous models, having larger values of AD and scatter.

3.2 Variability in source data

Table 2 shows the confidence intervals (95%) for each variable used in the applications of regime models. The highest uncertainty is related to the assessment of bankfull discharge which, on average, is within the range -29% to 36% around the best estimate. Width and depth have similar confidence intervals. On average, there is a 95% of probability to find the depth within the range -26% to +38% of the reach average, and the width within the range -24% to +32%. Reach average grain size distribution has a narrower confidence interval. Considering the median grain size, its range is between -7.7% and 8.6%. With regards to the bankfull water surface slope, it has been found to be within the range -19% to 19%.

The natural variability of hydraulic geometry parameters is propagated into dimensionless parameters H*, B* and Q*. Confidence intervals for each parameter are also reported in Table 2. Dimensionless depth is expected to be found within a relative range of -28% to 40%, i.e., similar to the depth interval. Dimensionless width has also a similar interval: -26% to 35%. On the contrary, dimensionless discharge exhibits a wider range than its dimensional counterpart; the range is between -34% to 45%. The incidence of data variability in the prediction accuracy is also shown in Figure 3. The abscise axes contains the confidence

interval for dimensionless parameters as results from variability in H, B and D_{50}. The ordinates show the confidence interval for the determination of H* and B* subject to the variability in independent variables, i.e., bankfull discharge, mean diameter and slope. It is evident how the variability in source data affects accuracy of prediction. Table 6 reports the mean confidence interval for predicted H* and B* considering data from Patagonian and Italian streams. Almost all the models seem to have the same sensitivity to source data variability. In particular, Parker et al.'s model has the narrowest confidence interval for B* prediction, however, the MM1, has one of the widest intervals. In the case of H* all the models exhibit similar performances.

4. Discussion

4.1 The slope as an external control at the reach scale.

When the slope is introduced as an independent variable in Parker et al.'s model (2007), its performance decreases abruptly (as inferred from Figure 3, d), and the scatter (RMD) for B* and H* increases (Tables 4 and 5). In Parker et al.'s model S is a dependent variable related to the dimensionless discharge Q*. The dependence of H*, B* and S with Q* is explained by the physical constrains: flow resistance (eq. 8), sediment transport (eq. 6), channel stability (eq. 7) and sediment supply - a relation between sediment transport at bankfull discharge and bankfull discharge. This is an empirical constrain that gives the sediment supply from the basin in terms of the bankfull discharge. Therefore, if dimensionless discharge defines the sediment supply, and this, in turn, is related to the slope, it follows that slope directly depends on discharge. Furthermore, the model entails an extra empirical relationship between the reference shear stress and the dimensionless discharge. Then, the mean depth is directly related to the dimensionless discharge by means of the stability constrain (eq. 7). B* depends on Q* in a flow resistance equation (eq. 8), where S and H are replaced by an expression of Q*. Assuming S as a dependent variable, the model filters the noise in S with the relationship S-Q*, and in this manner reduces the deviations in B* and H*.

Modified Model 1 incorporates a resistance law calibrated by Parker et al. using information about width, depth, discharge and slope. This means that the modified model considers the slope as an external control and does not use the resistance law where S is related to Q (equation 44 in Parker et al., 2007). However, the modified model also adopts the same

stability criterion relating the critical shear stress with dimensionless discharge. This model has the worst performance for predicting B*, the highest values of AD and RMD (Table 5) and has a good performance only in the case of Colorado dataset. With regards to depth, although the overall result seems quite good (AD value of -0.05) the RMD index varies considerably.

Modified Model 2 presents a systematic deviation as is evident from the slopes in Figure 3, e: 0.70 for H* and 1.39 for B*; both of them are significantly different to 1 with a p-value below 0.01. This deviation is a result of the model structure and can be explained linking predicted and observed dimensionless depth (hereafter H^*_{pred} and H^*_{obs}, respectively). Mueller et al. (2005) proposed a linear relationship between the reference Shields stress and the channel slope (eq. 12). Shear stress is linked to water depth (H^*_{pred}) using the uniform flow approximation.

$$\tau^* = \frac{H^*_{pred} S}{R} \quad (19)$$

Replacing eq. 12 and eq. 19 into eq. 7, and solving for H^*_{pred} it results an expression like this one:

$$H^*_{pred} = a + bS^{-1} \quad (20)$$

wherein a and b are two coefficients. On the other hand, a regression model relating Slope and observed values of depth (H^*_{obs}) can be fitted showing that the slope is nearly inversely proportional to H^*_{obs}.

$$S = 0{,}084 H^{*-1.02}_{obs} \quad (21)$$

Finally, adopting a unit exponent and including eq. 21 into eq. 20, a linear relationship is found between H^*_{pred} and H^*_{obs} with a slope coefficient below 1:

$$H^*_{pred} = 0{,}56 H^*_{obs} + 4{,}96 \quad (22)$$

This expression indicates that there will be underestimations when $H^*_{obs} > 11.3$. Finally, an error in the determination of H* affects B* estimation. An underestimation in H* will required a wider channel in order to verify the flow resistance equation. That's why the slope in the width scatterplot is higher than 1 (Figure 3, e).

4.2 Variability and uncertainty of hydraulic geometry parameters.

Plots of hydraulic geometry exhibits a wide scatter even in a log-plot scale (Figure 4), likely due to both natural variability of river shapes and uncertainty related to the survey methods

and devices. A simple t-test was performed in order to depict which of these two potential sources of uncertainty is responsible for the variability of hydraulic geometry parameters. A regression model relating width to dimensionless discharge was created. After that, for each reach there were 5 residuals and it was stated that their mean value was equal to zero (null hypothesis). As a result, 5 reaches out of 9 had mean values significantly different from zero (with $p<0.05$ but 2 out of 12 with $p<0.01$). Therefore, when considering five cross sections, the scatter seen in regime plots can be attributed to significant differences between river reaches.

Bankfull discharge is subject to uncertainties due to measurements error and model errors. Measurement errors are found in the observation of bankfull stages along the study reach. Besides, rating curves derived from regression models also introduce an uncertainty when calculating the discharge for a given stage. Measurements errors have been reduced taking a large sample of bankfull stage recognized in the field. Width regards to model errors, the last years were considered showing a consistent rating curve.

Due to the natural uncertainty in bankfull discharge and variability of grain size models results are also uncertain. Is the difference between predicted and observed values significant? The information available from the new river reaches enables to perform a study of variability propagation into predictions. Each bankfull discharge determination, slope and median grain size had its probability distribution. Performing a Monte Carlo procedure it was possible to calculate the probability distribution for predicted dimensionless parameters (mean values are shown in Table 6). If Millar's model is considered, because predictions are best distributed around the perfect agreement line, and a significance level of 5% is chosen it turns out that in 9 reaches out of 14 predicted B* are significantly different to observed values, and in 12 reaches out of 14 predicted H* are significantly different to observed ones. Therefore, scatter in prediction/observed plots cannot be attributed to uncertainty in control variables.

4.3 Interpretation of recent channel changes in the Piave and Brenta rivers.

As most of Italian rivers, the Piave and Brenta rivers have experienced dramatic morphological changes due to human interventions, extensively studied by means of historical maps and aerial photos (Surian, 1999; Comiti et al., 2011; Surian and Cisotto, 2007). Evidence support the hypothesis that sediment supply rather than flow regime was the key factor driving the narrowing trends of both rivers (e.g. Surian et al., 2009; Comiti et al.,

2011). In particular, a first phase of narrowing is attributed to river training structures and an increase in forest cover on slopes, besides a climate change following the Little Ice Age. Then, a second and more accelerated narrowing phase is claimed to be due to stronger human interventions such as in-channel gravel mining activities that reduced sediment availability.

Regime models are here used to interpret recent channel changes. However, because regime models suppose channel equilibrium, a condition which is not satisfied for these rivers, the interpretation and management extrapolations have to be considered and used cautiously.

Changes in Piave and Brenta rivers are interpreted using Millar's (2005) regime model because it incorporates sediment supply as an independent variable, and Millar's (2005) meandering-braiding criterion. As suggested by field evidence (Comiti et al. 2011; Surian & Cisotto, 2007), channel-forming discharge is assumed to have remained constant during the study period because dams have not significantly altered flow regime. Mean grain diameter is also assumed to remain constant at the spatial and temporal scales considered in this analysis (Surian, 2002). Therefore a change in width must only be a consequence of an alteration in sediment supply or bank strength. Millar (2005) calibrated the μ' parameter against Hey and Thorne's (1986) and Andrews's (1984) data. A condition of scarce vegetation, i.e., lowest strength, corresponds to μ' = 1.In the case of thick vegetation (type IV for Hey and Thorne) μ' assumes a maximum value of 1.50.

The change in sediment supply has been back-calculated from reach average values of width, under scenarios of different bank strengths. In the Brenta River there is a clear reduction in sediment supply since 1930 up to the end of 20th century, but interrupted in the 60's with a peak in supply (Figure 5a). The lowest value is attained in 1990 (between 5% and 12%). After that there is a low recovery been the load in the last surveys (2011) between 13 – 25% of the initial survey. Bank strength seems to have a minor role in explaining change in width.

With regards to Piave River, a similar trend has been found, with a first reduction phase from 1930 to 1960 where sediment supply decreases 40%, and a second phase after a low increase in the 60's, from 1970 to 1990 with a reduction of 42% (Figure 5b). The lowest sediment supply is attained in 1991, 24% of sediment supply of the initial situation. After 1990 there is a low recovery reaching 40% by 2006.

As documented by historical maps and aerial photos, the Piave River had a braided pattern until 1930 (Comiti et al., 2011). During the narrowing phases channel pattern gradually migrated from braiding to a wandering pattern. Besides, the braiding index (the mean number

of channels) reduced from about 3.4 to 1.5 (Surian, 1999). Equation 16 has been used to check if a morphological pattern adjustment was related to a change in sediment supply, and results show that the threshold slope for Piave River is about 0.0060. However, the actual slope of the Piave River (0.0045) within the study reach is 75% of this value. This would entail that the original braided pattern should be attributed to a condition of sediment overloading, i.e the channel was not steep enough to convey sediment supply and the channel aggraded. As a consequence, a reduction in sediment supply would imply a direct change in channel pattern because a single-thread channel would be hydraulically stable for that slope. In the case of Brenta River, its mean slope is 0.0036 while the threshold slope is between 0.0036 (for $\mu' = 1.0$) and 0.0045 (for $\mu' = 1.25$). The threshold value is much closer to the actual mean slope. Sub-reaches with slope above the threshold are expected to remain in a multi-thread configuration even under conditions of sediment supply reduction.

An interesting question regards the role of gravel mining in the narrowing of Piave River. Gravel mining basically stopped by 1990, and soon a channel width recovery has been observed afterwards. However, the complete recovery of the channel width at the 1800 conditions would be impossible to be reached. In fact, the recovery is seriously conditioned by the presence of dams and by long-term land use changes at the basin scale. Near 73% of the drainage area upstream of the study reach is under dam regulation. In any case along the study reach there are 6 unregulated tributaries that still furnish sediments into the river (drainage area 269 km^2). Supposing similar basin conditions now and before the closure of major dams (around 1950 according to Surian, 1999), the available sediment supply would be about 63% of the sediment supply in 1950. Under these conditions, channel width should be about 250 – 300 m (depending on the chosen value of μ'). That the Piave River is wider than these estimations rises the question whether the observed recovery phase is a transitional adjustment, after the end of gravel-mining, and if channel narrowing is to be expected in the future. Surian et al. (2009) hypothesized that the Piave River in the study reach should have the potential for a further widening even without direct intervention at the reach or the basin scale. The presented analysis seems to suggest the contrary, but further modeling efforts are to be carried out. Sediment mobility and transport has been recently measured in the field using sediment tracers and evaluating morphological changes at the cross-section scale. Along six cross sections of the intermediate course of the Piave River, various scour chains were installed and a series of sites were selected as representatives of different morphological unit

(ranging from the channel to the higher bars) and were spray-painted. The effects of a range of floods occurred from 2008 to 2011 were assessed in terms of burying/exposure of scour chains and displacement length of painted tracers (Mao et al., 2011), and sediment transport rates are being assessed using the morphological approach (Liébault & Laronne, 2008). These estimations have the potential of quantifying the sediment budget at the reach scale, and inform further modeling efforts being able to estimate future morphological tendencies of the river reach under different scenarios of sediment supply from the upstream reaches.

5. Conclusions

Three existing river regime models, all of them incorporating a bank stability criterion, have been considered in this study: Ikeda et al., 1988; Millar, 2005; Parker et al., 2007. In order to evaluate the performance of these models introducing the slope as an independent variable, two modifications have been proposed: Modified Model 1 (MM1) and Modified Model 2 (MM2). The performance of the five river regime models prediction (three plus two modified) has been analyzed for both, an existing data base of 142 river reaches and new hydraulic geometry data coming from gravel bed rivers in Patagonia (Argentina) and Northeastern Italy. Three independent dimensionless parameters have been defined and used in the test: dimensionless channel depth (H*), dimensionless channel width (B*) and dimensionless discharge (Q*).

Models that assume slope as a control (Ikeda et al., 1988; or Millar, 2005, as used in this study) are capable of predicting channel depth and width reasonably well. Considering the dimensionless channel width, the absolute differences (AD) are -0.02 for Ikeda et al.'s model and 0.15 for Millar's model. Parker et al.'s model (2007) improves predictions because it filters the scatter in slope data with a relation S-Q* (AD for B* is equal to -0.06). However, when slope is introduced as a control (model MM1), its performance decreases abruptly (AD is 0.62 for). The MM2 produces a systematic deviation in prediction due to the structure of the model and the AD is 0.29.

Dimensionless parameters are affected by natural variability within river reaches and uncertainty in models used to evaluate its bankfull discharge. The uncertainty in variables used as external control then affects regime model prediction. However, the difference between predicted and observed hydraulic geometry parameters may not be significantly attributed to uncertainties in the input values of the control variables.

The application of Millar's regime model has explained morphological changes observed in Italian rivers, supporting the interpretation that sediment supply is the key factor guiding morphological changes, as presented in other studies.

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TABLES

Table 1. Comparison of main features of the models used in this study (B, channel width; H, channel depth; S, reach slope; Q, liquid discharge; Gb, solid discharge; ϕ, bank sediment friction angle; D_{50}-D_{90}, representative grain diameters).

Model	Dependent variables	Independent variables	Flow resistance equation	Sediment transport	Bank stability
Millar (2005)	B H S	Q Gb ϕ D_{50}	Keulegan (1972)-Bray (1979)	Parker's (1990) model	Shear stress less than critical value in banks
Parker et al (2007)	B H S Gb	Q D_{50}	Parker (1990) calibrated	Parker's (1978) Model.	Mean shear stress
Ikeda et al (1988)	B H	Q S D_{50} D_{90}	Keulegan (1938) Ks = 1.5 d_{90}	Not necessary	Shear stress equal threshold value in banks
Modified Model 1	B H	Q S D_{50} D_{90}	Parker et al. (2007) calibrated	Not necessary	Mean shear stress
Modified Model 2	B H	Q S D_{50} D_{90}	Keulegan (1938)-Bray (1979)	Not necessary	Mean shear stress

Table 2. Hydraulic geometry parameters of studied gravel bed rivers in Italy and Argentina (Patagonia): reach average width (m), depth (m), median grain size (mm), slope (m m^{-1}) and bankfull discharge (m^3 s^{-1}). Variability corresponding to a 95% probability is quantified by the mean distance to the mean value (number between brackets). (*) this reach has a wide confidence interval for the bankfull discharge, 18 - 340 m^3 s^{-1}.

Code	Stream	Location	Slope (--)	Depth (m)	Width (m)	Bankfull discharge ($m^3 s^{-1}$)	D_{50} (mm)	Depth (--)	Width (--)	Bankfull discharge (--)
2211	Gualjaina River	Loc. Gualjaina	**0.0011** (± 0.0001)	**1.33** (±0.20)	**40.55** (±13.39)	**49.8** (±12.8)	**19.5** (±1.2)	**67.9** (±11.8)	2074.3 (±698.6)	**2.98E+05** (± 9.00E+4)
2228	Lepá Creek	Loc. Gualjaina	**0.0027** (± 0.0005)	**0.57** (±0.22)	**51.15** (±16.93)	**25.6** (±8.4)	**26.9** (±1.7)	**21.4** (±8.4)	1902.1 (±670.4)	**6.88E+04** (± 2.52E+4)
2206	Chubut River	Loc. El Maitén	**0.0022** (± 0.0004)	**1.18** (±0.28)	**44.60** (±6.80)	**78.4** (*)	**28.8** (±2.3)	**41.0** (±10.4)	1546.8 (±268.7)	**1.77E+05** (± 4.80E+5)
2204	Carrileufu River	Loc. Cholila	**0.0008** (± 0.0003)	**1.81** (±0.65)	**59.89** (±10.78)	**129** (±23.3)	**36.0** (±2.4)	**50.3** (±18.7)	1664.4 (±324.1)	**1.68E+05** (± 4.40E+4)
2230	Cohihues Creek	P.N. Los Alerces	**0.0185** (± 0.0041)	**0.28** (±0.14)	**10.38** (±3.38)	**4.23** (±0.0)	**52.1** (±3.2)	**5.4** (±2.8)	199.1 (±66.1)	**2.18E+03** (± 0.00E+0)
2212	Mayo River	Loc. Río Mayo	**0.0015** (± 0.0001)	**0.77** (±0.54)	**61.93** (±44.85)	**41.7** (±9.6)	**27.0** (±1.9)	**28.5** (±20.1)	2297.2 (±1694.6)	**1.12E+05** (± 3.31E+4)
1811	Quemquemtreu River	Escuela Nº 139	**0.0113** (± 0.0013)	**0.78** (±0.16)	**44.29** (±16.49)	**49.8** (±34.8)	**60.1** (±4.2)	**12.9** (±2.9)	737.1 (±283.3)	**1.80E+04** (± 1.26E+4)
1817	Azul River	El Azul	**0.0044** (± 0.0009)	**0.86** (±0.15)	**64.11** (±11.70)	**77.1** (±23.3)	**67.3** (±6.2)	**12.7** (±2.6)	952.7 (±208.7)	**2.10E+04** (± 7.74E+3)
2208	Epuyén River	La Angostura	**0.0053** (± 0.0012)	**1.01** (±0.44)	**29.58** (±10.18)	**45.5** (±12.9)	**43.7** (±4.5)	**23.1** (±10.3)	676.8 (±250.9)	**3.64E+04** (± 1.42E+4)
IT01	Piave River (P)	Perarolo	**0.0054** (± 0.0002)	**0.62** (±0.25)	**44.60** (±4.96)	**57.0** (±23.2)	**50.3** (±3.9)	**12.3** (±5.3)	886.1 (±130.1)	**3.20E+04** (± 1.30E+4)
IT02	Piave River (BL)	Belluno	**0.0034** (± 0.0003)	**0.91** (±0.23)	**62.21** (±14.51)	**100** (±60.2)	**42.7** (±2.7)	**21.3** (±5.4)	1458.2 (±359.6)	**8.49E+04** (± 5.08E+4)
IT03	Piave River (S)	Segusino	**0.0022** (± 0.0012)	**1.23** (±0.34)	**99.90** (±22.90)	**220** (±64.6)	**35.6** (±3.8)	**34.5** (±10.7)	2806.1 (±766.2)	**2.94E+05** (± 8.72E+4)
IT04	Brenta River	Bassano del Grappa	**0.0056** (± 0.0009)	**1.42** (±0.10)	**73.15** (±9.99)	**350** (±42.1)	**48.2** (±5.5)	**29.4** (±2.0)	1516.7 (±208.2)	**2.19E+05** (± 2.58E+4)
IT05	Cordevole River	Ponte Mas	**0.0060** (± 0.0006)	**0.59** (±0.18)	**37.58** (±10.20)	**83.0** (±45.4)	**49.1** (±5.5)	**12.0** (±3.9)	765.6 (±227.7)	**4.96E+04** (± 2.84E+4)

Table 3. Summary of the properties of river reaches selected used in this study including data from literature.

Dataset	Depth (m)		Width (m)		Discharge ($m^3 s^{-1}$)		Surface D_{50} (mm)		Slope (--)		Reference
	min	max	min	max	min	max	min	max	min	max	
Patagonia	0.28	1.81	10.3	64.1	4.2	129	20	67	0.000	0.018	this study
Italy	0.59	1.42	37.5	99.9	57.0	298	36	50	0.002	0.006	this study
Britain	0.77	5.25	12.3	77.1	7.1	424	20	91	0.001	0.010	Hey and Thorne
Colorado	0.34	1.85	7.25	83.8	2.2	255	23	122	0.000	0.011	Andrews (1984)
Idaho	0.24	2.78	2.80	89.2	0.6	652	27	207	0.000	0.050	Mueller et al
Alberta	0.71	6.83	26.2	545	23.8	7220	26	117	0.000	0.005	Bray (1979)
Alberta	0.58	6.95	18.0	280	11.9	5440	27	145	0.000	0.015	Kellerhals et al
Lab. Nº 1	0.01	0.01	0.48	0.99	0.003	0.004	1.4	1.8	0.009	0.011	Eaton and
Lab. Nº 2	0.02	0.04	0.52	0.70	0.005	0.010	1.3	1.5	0.002	0.003	Ikeda et al

Table 4. Performance indexes (Average deviation AD, and Mean square-root deviation RMD) applied to predictions of dimensionless depth, and correlation coefficient (Cor) with its standard error (SE_{cor}) for the entire dataset. Underlined values indicate the lowest AD value for each dataset.

Streams	Millar (2005)		Parker et al.		Ikeda et al.		MM1 (after		MM2 (after	
	AD	RMD	AD	RMD	AD	RMD	AD	RMD	AD	RMD
Patagonia	0.08	0.30	0.29	0.26	0.19	0.41	0.08	0.50	**0.01**	0.31
Italy	0.14	0.23	0.88	0.28	0.18	0.28	**-0.10**	0.22	-0.13	0.24
Idaho	-0.02	0.51	**0.01**	0.21	0.14	0.64	-0.01	0.91	0.35	0.63
Britain	-0.40	0.19	-0.41	0.10	**-0.29**	0.24	-0.37	0.31	-0.35	0.33
Colorado	0.13	0.16	**0.10**	0.19	0.24	0.23	0.15	0.25	0.17	0.21
Alberta	0.09	0.33	0.39	0.24	**0.08**	0.44	0.10	0.61	-0.11	0.44
Laboratory	-0.10	0.07	0.22	0.37	**-0.08**	0.09	-0.21	0.17	-0.13	0.10
All Data	**-0.02**	**0.31**	**0.17**	**0.26**	**0.04**	**0.40**	**-0.05**	**0.56**	**0.00**	**0.40**
Cor (SE_{cor})	**0.941**	**(0.026)**	**0.951**	**(0.026)**	**0.911**	**(0.035)**	**0.870**	**(0.042)**	**0.886**	**(0.039)**

Table 5. Performance indexes (Average deviation AD, and Mean square-root deviation RMD) applied to predictions of dimensionless width. The last row contains the correlation coefficient (Cor) with its standard error (SE_{cor}) for the whole dataset. Underlined values indicate the lowest RMD value for each dataset.

Streams	Millar (2005)		Parker et al		Ikeda et al		MM1 (after		MM2 (after	
	AD	RMD	AD	RMD	AD	RMD	AD	RMD	AD	RMD
Patagonia	-0.13	0.39	-0.31	0.18	-0.28	0.41	0.23	0.91	**-0.01**	0.52
Italy	0.26	0.52	-0.26	0.16	**0.14**	0.66	1.19	1.39	1.14	1.21
Idaho	0.19	0.50	**-0.01**	0.21	-0.10	0.43	0.72	1.18	-0.36	0.36
Britain	**-0.02**	0.36	-0.07	0.12	-0.25	0.34	0.12	0.68	0.07	0.78
Colorado	-0.08	0.13	**-0.04**	0.14	-0.34	0.12	**-0.07**	0.23	-0.14	0.33
Alberta	**0.07**	0.59	-0.24	0.16	0.16	0.95	0.70	1.73	0.96	1.68
Laboratory	0.41	0.15	0.16	0.36	**0.14**	0.17	0.92	0.65	0.44	0.27
All Data	**0.15**	**0.41**	**-0.06**	**0.23**	**-0.02**	**0.53**	**0.62**	**1.11**	**0.29**	**0.89**
Cor (SE_{cor})	**0.942**	**(0.028)**	**0.973**	**(0.020)**	**0.894**	**(0.038)**	**0.787**	**(0.052)**	**0.92**	**(0.033)**

Table 6. Mean confidence interval (95%) for predicted variables H* and B* according to different regime models. All values in percent.

Model	H* (2.5)	H* (97.5)	B* (2.5)	B* (97.5)
Millar	-12	19	-31	45
Parker et al.	-17	21	-19	25

Ikeda et al.	-13	22	-35	66
MM1	-15	28	-41	71
MM2	-11	22	-41	74

FIGURE CAPTION

Figure 1. Location of study reaches in Italy-Veneto Region (a) and Argentina-Patagonia (b). Numbers (for instance 1811, IT05) refer to gaging station codes at each river reach. Hydraulic geometry data are displayed in Table 2. Triangles represent main cities in the region.

Figure 2. Morphological changes in the Brenta and Piave rivers over the last 200 years (mod. from Surian et al., 2009; Comiti et al., 2011). Continuous lines represent variation in the active channel width, while dashed lines denote channel slope changes.

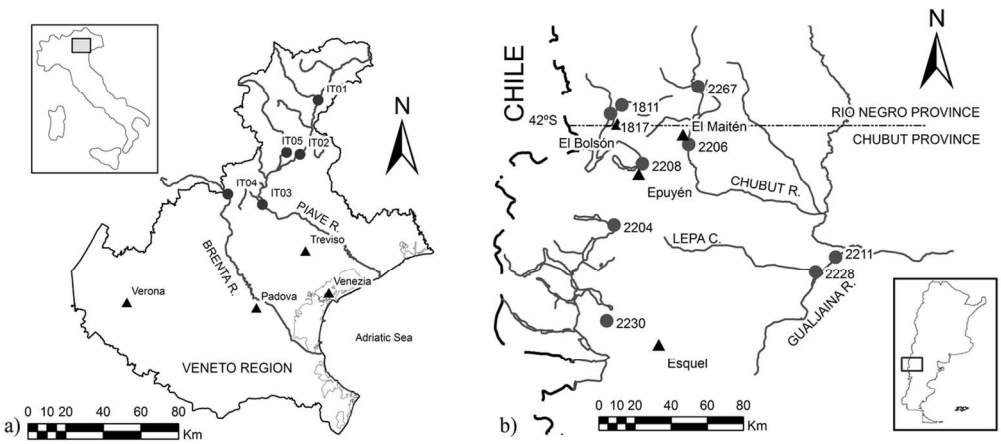
Figure 3. Performances of regime models: a) Millar's model; b) Parker et al.'s model; c) Ikeda et al.'s model; d) MM1 after Parker's; and e) MM2 after Millar's. Graphs show dimensionless water depth (H*) and dimensionless channel width (B*) and on the left and right, respectively. Dashed lines indicate a two-time overprediction and one half-time underprediction. Bars represent the confidence interval (with a probability of 95%) associated with data (horizontal bar) and its propagation into predicted values (vertical bar).

Figure 4. Dimensionless hydraulic geometry for the entire Dataset. Bar lines show variability in Patagonian and Italian river reaches (confidence interval 95%). Vertical bars refers to in-channel natural variability for width (B), depth (H), and grain size. Horizontal bars include both natural variability and model uncertainties in the calculation of bankfull discharge.

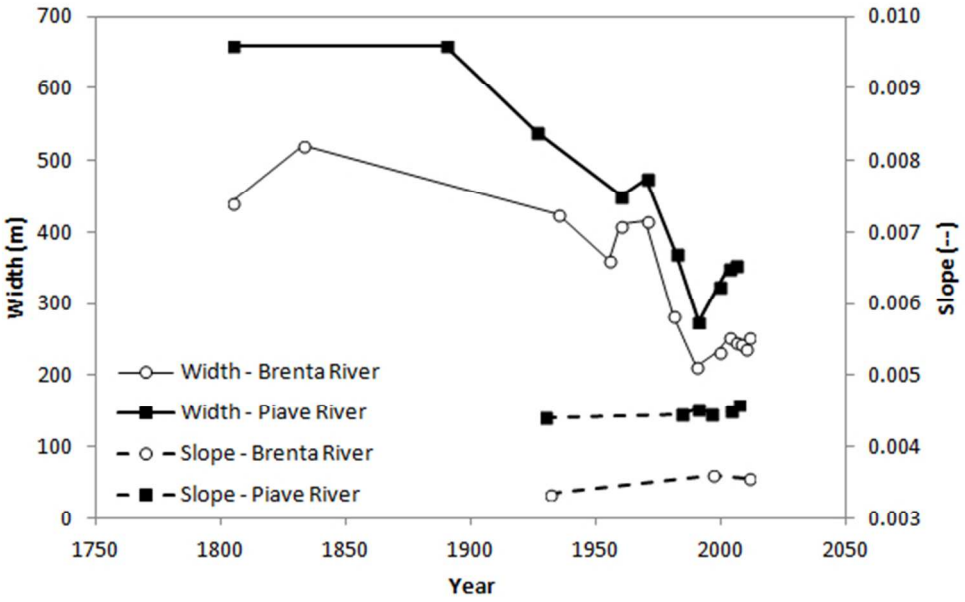
Figure 5. Morphological changes in the Brenta (a) and Piave (b) rivers and the corresponding sediment supply variation as calculated applying Millar's model. Calculations have been made for different values of bank strength (μ), between sparse vegetation ($\mu = 1$) to moderate bank density vegetation (between categories II and III according Hey and Thorne, 1986).

730

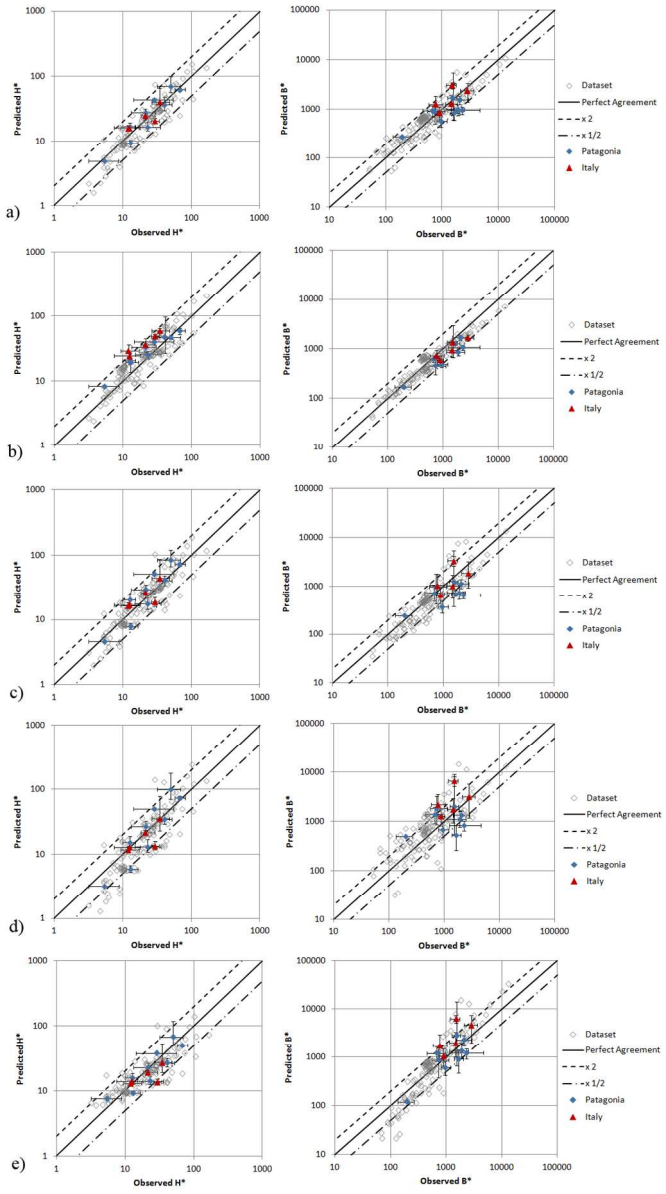
731



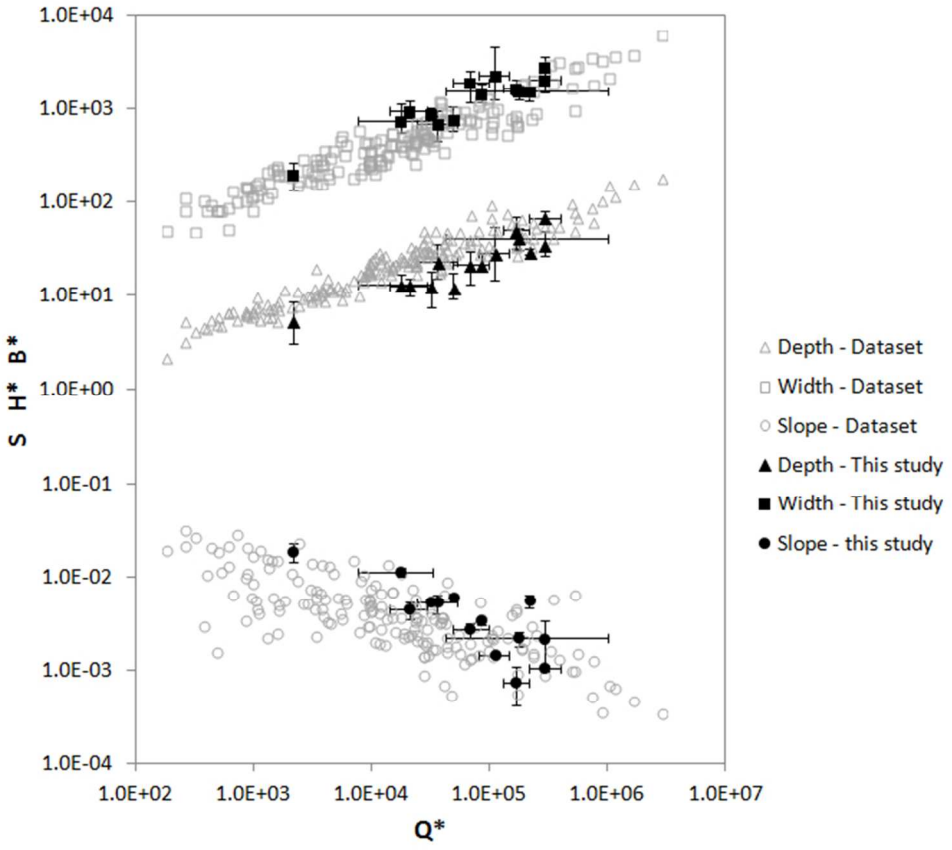
Location of study reaches in Italy-Veneto Region (a) and Argentina-Patagonia (b). Numbers (for instance 1811, IT05) refer to gauging station codes at each river reach. Hydraulic geometry data are displayed in Table 2. Triangles represent main cities in the region.
118x52mm (300 x 300 DPI)



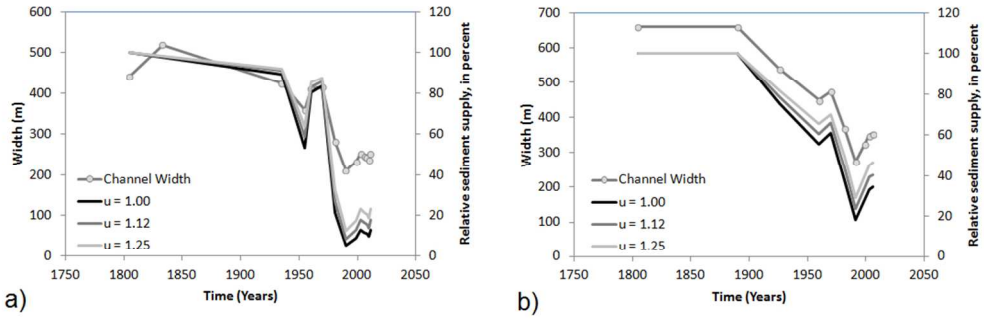
Morphological changes in the Brenta and Piave rivers over the last 200 years (mod. from Surian et al., 2009; Comiti et al., 2011). Continuous lines represent variation in the active channel width, while dashed lines denote channel slope changes.
161x103mm (96 x 96 DPI)



Performances of regime models: a) Millar's model; b) Parker et al.'s model; c) Ikeda et al.'s model; d) MM1 after Parker's; and e) MM2 after Millar's. Graphs show dimensionless water depth (H*) and dimensionless channel width (B*) and on the left and right, respectively. Dashed lines indicate a two-time overprediction and one half-time underprediction. Bars represent the confidence interval (with a probability of 95%) associated with data (horizontal bar) and its propagation into predicted values (vertical bar).
386x698mm (72 x 72 DPI)



Dimensionless hydraulic geometry for the entire Dataset. Bar lines show variability in Patagonian and Italian river reaches (confidence interval 95%). Vertical bars refers to in-channel natural variability for width (B), depth (H), and grain size. Horizontal bars include both natural variability and model uncertainties in the calculation of bankfull discharge.
184x169mm (96 x 96 DPI)



Morphological changes in the Brenta (a) and Piave (b) rivers and the corresponding sediment supply variation as calculated applying Millar's model. Calculations have been made for different values of bank strength (u), between sparse vegetation (u = 1) to moderate bank density vegetation (between categories II and III according Hey and Thorne, 1986).
289x97mm (96 x 96 DPI)