

“Assessment of the geomorphic effectiveness of controlled floods in a braided river using a reduced-complexity numerical model”

Ziliani et al.

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General Response to reviewers

Dear Editor,

We thank the reviewers for their thoughtful and useful comments. All comments are
10 constructive, they are very useful to clarify and improve some specific aspects of the manuscript.
In this rebuttal we address all the reviewer comments: detailed responses are provided in bold
below.

Both reviewers pointed out some problems with English: copy editing was carried by a
professional mother tongue.

15 Regards

Nicola Surian

April 30, 2020

20

Response to reviewer 1 (Anonymous)

25 The authors apply a 2D reduced complexity morphodynamic model to a 7 km-long reach of the
braided Piave River. Their goal is to establish that the model credibly represents changes in
channel morphology and to ask whether artificial floods might change the future morphology.

The applied interest is maintaining channel width and braiding complexity on a river that is progressively narrowing and simplifying due to water management.

30 The paper is generally well organized and written clearly, with an appropriate amount of documentation. There are about 25-30 small examples in which a careful copy editor is needed to correct English phrasing. These errors rarely produce ambiguity, but should be corrected. I did not have time to mark them myself.

The authors do a good job explaining the model and testing its suitability. They approach the
35 difficult issue of matching model prediction and reality with care. My comments are intended to suggest additional means to explain, evaluate, and justify the model results. I think they should be addressed by the authors, although they do not all need to be acted on.

(1) My first look at the test hydrographs (Figure 7.c, d, e) suggested to me that little difference
40 in predicted channel morphology should be anticipated. The controlled floods in Scenarios 2 and 3 are too small and the controlled floods in Scenario 4 are too infrequent (and no larger than natural floods). Presumably the flood scenarios chosen are as large as can be released given the water infrastructure in the basin. Hence, the (not too surprising) result is that the modest or infrequent floods that are feasible are not sufficient to produce significant changes in the forecast channel morphology.

45
Thanks for this comment. As suggested by the reviewer, we did not expect major changes in channel morphology but, considering the controlled floods used in the three Scenarios, some significant changes could be expected. As already explained in the manuscript, the controlled floods are feasible, that is taking into account the water infrastructure in the basin. On the other hand, it is worth noting that the floods in Scenarios 2 and 3 are not so small (these are formative discharges and are released for 5 days) (Table 2). We agree that controlled floods in Scenario 4 are infrequent, but those floods are quite large (recurrence interval = 5 years) and released for 1 day (Table 2). Therefore, some effects on channel morphology (i.e. some geomorphic recovery) could be expected. The results show that any significant recovery took place. A main outcome of this paper, that could not be anticipated when we started this research, is that controlled floods may

60 **have any significant effects in a strongly regulated river, specifically if formative discharges have been strongly altered. In terms of changes in the manuscript, we carried out small changes in the Discussion (Section 5.1; L 454-456) and in the Conclusions (L 525-526).**

65 (2) An interesting way to present the results would be in terms of 'limits of prediction'. That is, conduct multiple runs driven by small changes in parameter or initial conditions or in the sequencing of floods, in order to show how variable the results would be given uncertainty of the input. I would guess that the range of predicted width and braiding index (Figure 7.a, b) would comfortably encompass the predictions from the different scenarios, indicating that the model is unable to demonstrate that the available floods would produce different morphologies.

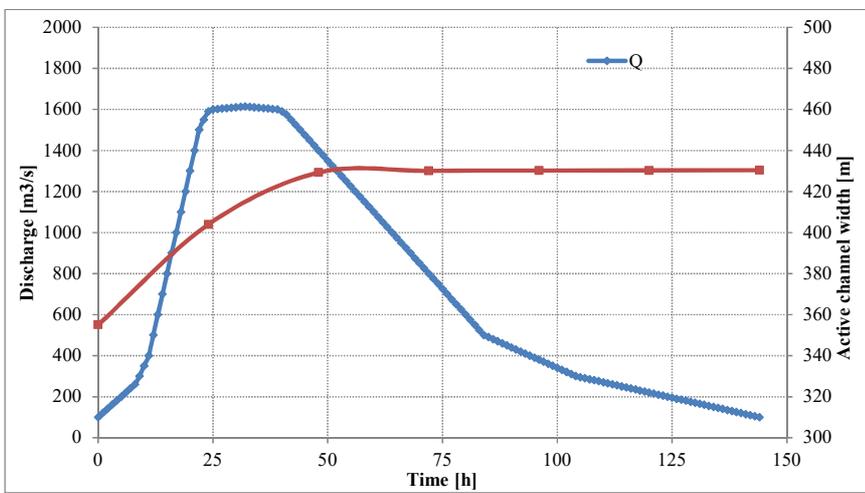
70 **We agree with the reviewer, a sensitivity analysis would be needed for better assessment of the results and associated uncertainty. On the other hand, since a comprehensive testing of the model is very complex (this is also pointed out by reviewer 2 "...to evaluate/test a morphodynamic model (which is a complex and far from straightforward exercise)...") and we could rely upon a sensitivity analysis that we carried out in a similar river (Ziliani et al, 2013, JGR), the sensitivity analysis was out of the scopes of this work. That said, we carried out a calibration (Section 4.3) which shows a very good performance of the model, specifically as for estimate of channel width and braiding index.**

80 (3) I do wonder whether the model is able to predict larger widths. Is the model capable of predicting a width of, say, 430 m, as observed in 1970? I realize that flows up to 1970 are outside of the calibration range, but I would be concerned about whether the apparently firm upper bound on width of 350 m (Figure 7.a) is somehow an artifact of the model.

85 **Thanks for this comment. We think that the model should be able to simulate larger widths and that the lack of very large floods in the scenarios prevented further**

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widening (i.e. channel widths larger than 350 m). To confirm this hypothesis, we run a new simulation which includes a large flood (peak value = $1600 \text{ m}^3\text{s}^{-1}$; RI = 30 years). This flood produced a remarkable widening being average channel width 355 m and 430 m, respectively before and after the flood (Fig. 1).



95 **Figure 1. This new run shows the effects of a large flood (peak value = $1600 \text{ m}^3\text{s}^{-1}$; RI = 30 years) on channel morphology. Channel width increases up to 430 m, confirming that the model is able to produce width larger than 350 m.**

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(4) The test for sediment transport rate is quite weak: the authors find that the computed transport rates are within typical range for such gravel-bed braided rivers. A more sensitive test would be to evaluate how the bed grain size changes over time. You specify an initial grain size - does that grain size shift dramatically over the course of the model run?

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Thanks for pointing out this. We analyzed grain size changes, specifically we compare D50 of bed sediment at the beginning (i.e. 24.9 mm) and at the end of each

Scenario. The D50 changes are small, since D50 is 22.7, 24.3, 23.6 and 23.1 respectively at the end of Scenario 1, 2, 3 and 4. In the revised manuscript this information was included in Section 5.2 (“Assessment of CAESAR-LISFLOOD performance”; L 486-487).

(5) River are a combination of sediment-feed and sediment-recirculating systems. I suspect that the model results are sensitive to this choice. The problem, of course, is specifying an upstream sediment boundary condition. I would be interested in learning how an increase in sediment supply changes the predicted channel morphology. Perhaps that is beyond the scope of the paper, although the authors do mention that sediment mining was practiced and then halted. Model runs with and without substantial sediment removals would certainly be interesting!

We agree, in general for such dynamic systems it is crucial to take into account also possible changes in sediment supply. In this case study sediment supply was kept constant for two reasons. First, including changes in sediment supply would imply to carry out several other Scenarios, adding complexity to the modelling and to the overall work. Second, and most importantly, there is evidence that the study sector is not undergoing significant vertical changes (i.e. incision or aggradation) over the recent period (see lines 123-124 of the manuscript). Besides, it is not likely that sediment mining will be carried out in the study sector in the near future. For such reasons, the sediment recirculation option of the model (i.e. sediment transport equilibrium condition) was adopted for this study.

Response to reviewer 2 (Tom Coulthard)

This is a really neat study looking at how a reduced complexity morphodynamic model can be used to investigate how the hydrological perturbation of flows within a managed braided river

affect the morphology. Ultimately, it shows how controlled releases of larger flows have some but not significant impacts on channel widths and depths within the reach studied.

In doing so it also provides an excellent opportunity to evaluate/test a morphodynamic model (which is a complex and far from straightforward exercise) demonstrating how such methods can be used as management tools in such environment to answer questions about hydro-geomorphic interactions.

The paper is well written, produced and structured. As per R1, there are several minor grammatical/typo mistakes that can be picked up in proof reading if the paper progresses.

Some specific comments and suggestions for further literature that has not been cited (some has only just come out) are provided below.

- 65 Impellent?

We changed this adjective

- 70 A reference to Larsen et al <https://doi.org/10.1002/2014EO320001> might be useful in the RCM description section here.

The suggested paper was cited, as it properly emphasizes the exploratory purpose of RCMs application in fluvial geomorphology as well as in other complex Earth and environmental systems.

- 230-236 - felt a bit clunky and repetitive - might be worth having a closer look at this section. Also there have been a series of CL papers and studies since 2013 that might be useful for the paper to cite here as well. There are others but two more recent ones CL Sensitivity analysis paper: https://www.geosci-modeldev.net/11/4873/2018/Calibrating_valley_floor_re-working_in_CL_Feeney_et_al.,_2020 <https://doi.org/10.1002/esp.4804>.

Thanks for pointing out these two papers which represent the most recent applications of the CL model. Skinner et al. (2018) is focused on a global sensitivity analysis applied to CL model (catchment mode application) used as Landscape Evolution Model. Feeney et al. (2020) focuses on the effectiveness of CL model in reproducing historical channel lateral erosion and modelling floodplain turnover (in single thread sinuous o meandering reaches, locally wandering).

We revised the last part of section 3.3. (L 224-228), including the suggested papers and also Coulthard and Van De Wiel (2017).

- 170
- 237 Section 3.4. The two references above are also really relevant for this section there have been more thoughts and studies on validation/calibration methods. Both compliment what you are doing here I think.

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We agree with the Reviewer. Both papers were cited in the revised version of the manuscript, since they are complementary to our work (Skinner et al., 2018, see L 226; Feeney et al., 2020, see L 227 and L 240).

Assessment of the geomorphic effectiveness of controlled floods in a braided river using a reduced-complexity numerical model

Luca Ziliani¹, Nicola Surian^{1*}, Gianluca Botter², Luca Mao³

¹ Department of Geosciences, University of Padova, Italy

² Department of Civil, Environmental and Architectural Engineering, University of Padova, Italy

³ School of Geography, University of Lincoln, United Kingdom

185 Correspondence to: Nicola Surian (nicola.surian@unipd.it)

Abstract. Most Alpine rivers have undergone ~~strong alteration of~~ significant alterations in flow and sediment regimes. These alterations have notable effects on river morphology and ecology. One option to mitigate such effects is ~~the~~ flow regime management, specifically ~~by~~ through the ~~re-introduction~~ reintroduction of channel-forming discharges. The aim of this work is to assess the morphological changes induced in the Piave River (Italy) ~~due to~~ by two ~~different~~ distinct controlled flood strategies, the first characterized by a single artificial flood per year and the second by higher magnitude, but less frequent, floods. ~~The~~ This work ~~was carried out~~ involved applying a 2D reduced-complexity morphodynamic model (CAESAR-LISFLOOD) to a 7-km-long reach, characterized by a braided pattern and highly regulated discharges. ~~The numerical~~ Numerical modelling allowed the assessment of morphological changes for four long-term scenarios (2009-2034). The scenarios were defined ~~taking into~~ account ~~considering~~ the current flow regime and the natural regime, which was estimated by a stochastic physically-based hydrologic model. Changes in channel morphology were assessed by measuring active channel width and braiding intensity. ~~Comparing~~ A comparison of controlled flood scenarios to a baseline scenario (i.e., ~~no controlled floods~~) ~~it turned out~~ showed that artificial floods had ~~small effects~~ little effect on channel morphology. ~~The highest~~ More channel widening (13.5%) ~~was produced by~~ resulted from the ~~release strategy with higher~~ high magnitude floods, ~~while~~ flood strategy than from the application of the other ~~strategies produced lower widening~~ strategy (8.6%). Negligible change was observed in terms of braiding intensity. ~~Results pointed out~~ The results indicate that controlled floods ~~may do~~ not represent an effective solution for morphological recovery in braided rivers ~~with~~ strongly impacted ~~in their~~ flow and sediment regimes.

1 Introduction

Human activities in riverine areas (i.e., river damming, ~~river and~~ engineering, gravel mining, land-use change in the drainage basin) have historically led to notable changes in ~~the~~ flow ~~regime~~ regimes (Gore and Petts, 1989; Poff et al., 1997; Magilligan and Nislow, 2005; Poff et al., 2007; Zolezzi et al., 2011; Magilligan et al., 2013; Ferrazzi and Botter, 2019), ~~along with~~ and in ecological (Collier, 2002; C er ghino et al., 2004; Paetzold et al., 2008; McDonald et al., 2010; Overeem et al., 2013; Espa et al., 2015) and geomorphic functioning of river systems (Hicks et al., 2003; Petts and Gurnell, 2005; Melis, 2011; Ziliani and

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Surian, 2012; Magilligan et al., 2013; Mueller et al., 2014; Lobera et al., 2016). ~~Nowadays, dam~~ Dam construction is now considered a viable strategy to ~~support the increasing~~ meet energy and water demands due to climate change and population growth (World Bank, 2009; Lehner et al., 2011). As outlined by Overeem et al. (2013), large reservoirs with ~~a volume~~ volumes greater than 0.5 km³ intercept globally more than 40% of river discharge and ~26% of the sediments transported by the rivers, reducing ~~the~~ global sediment delivery to oceans, and commonly leading to coastal erosion.

Several metrics have been developed to assess ~~both~~ the magnitude and temporal ~~trend of~~ trends in alterations ~~of~~ in river flow regime in rivers regimes induced by hydraulic ~~infrastructures~~ infrastructure (Richter et al., 1996; Richter et al., 1997; Martínez Santa-María et al., 2008; Yin et al., 2015), ~~and~~. As well, extensive sediment monitoring efforts ~~or~~ and sediment budget estimations have quantified sediment flux alterations (Surian and Cisotto, 2007; Schmidt and Wilcock, 2008; Melis, 2011; Trinity Management Council, 2014; Espa et al., 2015). Several studies have documented the hydrologic impacts following the of extensive ~~realization of~~ dam systems, in particular in the Alpine region over the 20th century (Botter et al., 2010; Comiti, 2012; Bocchiola and Rosso, 2014). Overall, flow regime alteration has implied significant changes in flow magnitude, frequency, timing and duration, and thermo-peaking ~~phenomena~~ (Gore and Petts, 1989; Frutiger, 2004; Zolezzi et al., 2009; Zolezzi et al., 2011). ~~Impacts~~ The effects of damming on sediment ~~fluxes~~ flux have been assessed ~~on~~ in reaches directly ~~impacted by damming~~ affected (Graf, 1980; Williams and Wolman, 1984; Gacuman et al., 2005; Petts and Gurnell, 2005; Schmidt and Wilcock, 2008; Grant, 2012), as well as in lowland gravel-bed rivers affected by cascading connected reservoirs and other human disturbances at the basin scale (Rinaldi and Simon, 1998; Surian and Rinaldi, 2003; Bilotta and Brazier, 2008; Surian, et al., 2009; Zawiejska and Wyżga, 2010; Ziliani and Surian, 2012; Scorpio et al., 2015).

~~Overall, it~~ is widely acknowledged that ~~a~~ reduced sediment flux due to dam construction or sediment supply alteration at the basin scale (e.g. due to afforestation, torrent-control works) produces channel changes ~~—~~, namely, narrowing, ~~incision~~ incisions, ~~reduced~~ braiding intensity ~~reduction~~, and coarsening of bed sediment. ~~Since the 1970s, growing~~ There has been increasing attention ~~was paid to~~ since the 1970s on the environmental effects of large dams (Turner, 1971; Vörösmarty et al., 2003).

Different river management strategies have been adopted to address dam-related impacts using structural ~~or~~, operational strategies (e.g., Kondolf et al., 2014), or process-based approaches ~~oriented toward restoring~~ to restore water and sediment fluxes (Wohl et al., 2015a). Flow releases from dams have been ~~eventually~~ regulated to reproduce ~~some aspects~~ of the natural regimes (flow and sediment), via ~~increasing or recovering~~ seasonal baseflow ~~increase or recovery~~ (McKinney et al., 2001; Sabaton et al., 2008), ~~control in~~ controlling the timing and recession rates of releases (Rood et al., 2003; Shafroth et al., 2010), artificial gravel augmentation or sediment bypassing (McManamay et al., 2013; Kondolf et al., 2014), flood releases (Collier, 2002; Dyer and Thoms, 2006) ~~or high flow~~ and experimental ~~high-flow~~ releases (Melis, 2011; Olden et al., 2014). In other cases, ~~the~~ management strategies have focused directly on recovering morphological features ~~recovery through dam removal~~ by removing dams (Poulos et al., 2014; O'Connor et al., 2015), or ~~mechanical~~ by mechanically removing vegetation removal (Environment Canterbury Regional Council, 2015).

Environmental flow management plans ~~aim to mitigate some~~ are aimed at mitigating undesired channel adjustments due to dam operations. ~~Due to~~ Given the ~~costs~~ of these programs, decision-makers are increasingly requesting the scientific

community to develop appropriate tools ~~able to~~capable of (i) ~~identify~~identifying and ~~control~~controlling the factors that cause channel alterations, and (ii) ~~to assess~~of assessing the effectiveness of management programs. Environmental agencies in several countries require dam operations to respect ~~releasing protocol in an attempt~~release protocols to mitigate adverse impacts on downstream ecosystems (Schmidt and Wilcock, 2008; Olden and Naiman, 2010; Watts et al., 2011; Konrad et al., 2012). ~~Besides some~~Although successful empirical experiences ~~do exist~~ (Souchon et al., 2008; Konrad et al., 2011), robust predictive tools and models are ~~becoming much more impellent~~urgently needed to predict channel ~~response~~responses to dam operations and interruption of the longitudinal river continuum (Bliesner et al., 2009; McDonald et al., 2010; Melis, 2011; Coulthard and Van De Wiel, 2013; Gaeuman, 2014).

The ~~assessment of future~~ evolutionary trajectory of channel morphology ~~may can~~ be ~~achieved~~assessed using conceptual ~~models~~ (e.g., Channel Evolution Models – CEMs, as described in Schumm et al., 1984; Simon and Hupp, 1986; Simon, 1989), empirical (Lane, 1955; Schumm, 1977; Rhoads, 1992) ~~or and~~ numerical models, either Computational Fluid Dynamic (CFD) models or Reduced Complexity Models (RCM) ~~)(Larsen et al., 2014)~~. Previous applications of RCMs on braided rivers have focused mainly on theoretical scale-independent analysis (Murray and Paola, 1994), laboratory experiments (Doeschl-Wilson and Ashmore, 2005; Doeschl et al., 2006; Nicholas, 2010), or short gravel-bed river reaches (Coulthard et al., 2002; Thomas and Nicholas, 2002; Coulthard et al., 2007; Thomas et al., 2007; Van De Wiel et al., 2007). In this study, ~~such as~~ in Ziliani et al. (2013) and Ziliani and Surian (2016), ~~an attempt has been made to we~~ apply ~~aan~~ RCM model at mesospatial (i.e., 5-50 km) and mesotemporal (i.e., 10–100 years) scales. In particular, the CAESAR – LISFLOOD model (Bates et al., 2010; Coulthard et al., 2013) ~~has been here in~~ is applied to a 7–km–long braided reach of the Piave River (Italy), one of the most heavily and historically regulated river ~~systems~~systems in Italy.

We applied ~~the~~ CAESAR – LISFLOOD model (hereafter C-L) to assess the morphological effects ~~related to of~~ two ~~different kinds of~~ flow regime management strategies: ~~the~~. The first ~~is~~ is characterized by yearly controlled floods with peaks ~~able to transport~~capable of transporting sediments, ~~while~~ the second ~~with more infrequent and~~consists of ~~less frequent~~ higher magnitude floods (i.e., floods with ~~5-year recurrence interval equal to 5 years~~intervals) released only when notable channel narrowing is observed in the evolutionary trajectory. Both strategies have been developed according to two main criteria: (i) ~~to~~ maximize ~~the~~ flow regime “re-naturalization”, meaning that the “Controlled Flood” (CF) duration ~~has to be set in order of the controlled flood (CF) is designed to increase its yearly likelihood to occur approaching the approach natural scenario condition~~conditions as much as possible; ~~and~~ (ii) the “feasibility” of the strategy, ~~which is~~ verified by the fact that the cumulative volume released per year ~~has to be lower is less~~ than the maximum volume ~~stocked~~ in the reservoirs ~~existing~~ upstream ~~off from~~ the ~~study~~studied reach.

This paper ~~aims to address~~addresses two main issues: (i) ~~to what extent the effectiveness of~~ controlled floods ~~can be effective~~ for the geomorphic recovery of a strongly regulated braided river?, and (ii) ~~can~~the suitability and reliability of the reduced-complexity CAESAR-LISFLOOD morphodynamic model ~~CAESAR-LISFLOOD be considered a suitable and reliable tool to reproduce the morphological evolution of a large gravel bed river~~ at the given mesoscales?. In the first section of the paper, we provide a brief description of the studied river reach. The second section presents the available data, the two models

used (i.e., the morphodynamic ~~model~~ CAESAR-LISFLOOD ~~model~~ (Bates et al., 2010; Coulthard et al., 2013), and the hydrological model; (Botter et al., 2007)), and the criteria ~~adopted for to design~~ the scenario strategy ~~design~~. The third section presents the results ~~concerning in terms of~~ (i) ~~the~~ historical ~~river reach~~ morphological ~~river reach~~ adjustments, (ii) ~~the~~ flow regime ~~alterational~~ alterations, (iii) the CAESAR-LISFLOOD calibration, and (iv) the simulations of three ~~different~~ "Controlled Floods" (CFs) ~~releases~~ controlled flood release scenarios. Finally, we critically discuss ~~the~~ results and examine ~~the~~ strengths and weaknesses of CAESAR-LISFLOOD and ~~the~~ effectiveness of the flow management strategies under investigation.

2 General setting of the study area

2.1 The Piave River basin

The Piave River is located in ~~north-eastern of northeastern~~ Italy, ~~and it~~. It flows for about 220 km from the Alps to the Adriatic Sea (Fig. 1). The basin area is about 3,900 km², and its average elevation is about 1,300 m a.s.l. (maximum elevation is 3,364 m a.s.l.). The climate is temperate-humid, with ~~an~~ average annual precipitation of ~~about~~ approximately 1,350 mm. ~~Significant annual variations in the Annual~~ rainfall ~~amount have been measured~~ varied substantially over the 20th century, but without any statistically ~~relevant~~ significant trends (Surian, 1999).

~~As~~ Like most ~~of the Italian~~ Alpine ~~Italian~~ rivers (Surian and Rinaldi, 2003; Surian et al., 2009; Comiti, 2012), the Piave River has suffered heavy human impact, which ~~has~~ altered the basin and ~~the~~ river channel dynamics (Surian, 1999; Botter et al., 2010; Comiti et al., 2011; Comiti, 2012). ~~Especially during the 20th century, the~~ The Piave basin ~~has~~ experienced a rapid increase ~~of in~~ anthropogenic exploitation ~~by in the 20th century, with~~ the construction of a series of dams and reservoirs ~~(nowadays there between the 1930s and 60s. There are now 13 major reservoirs, (Botter et al., 2010) built along the main stem and some tributaries from the 1930s to 1960s. At present, a (Botter et al., 2010). A complex regulation scheme exists in place~~ (for details see Surian, 1999; Botter et al., 2010), ~~designed~~ to maximize ~~production of~~ hydroelectric power ~~production~~ and the ~~provision of~~ provide irrigation water (Fig. 1). Flow regulation alters both ~~the~~ flow duration ~~characteristics~~ and ~~the~~ volume of annual runoff in the river. The reservoirs and diversions along the river and its tributaries also affect sediment transport and supply.

The Piave basin ~~had also experienced~~ ~~has~~ historically ~~experienced~~ strong changes due to land use modifications. ~~Especially after~~ Since the 1950s, ~~the development of industry and tourism boosted the abandonment of~~ traditional agricultural ~~and eropping activities~~ production on the mountain slopes, ~~causing have been abandoned largely because of the development of industry and tourism, resulting in~~ natural reforestation in the upper parts of the basin (Del Favero and Lasen, 1993). In addition to ~~the reductions in sediment supply due to~~ trapping by dams and reforestation, intense in-channel gravel mining has ~~also~~ contributed to ~~alter~~ reducing sediment fluxes since the 1960s. ~~Furthermore, human~~ Human pressure on ~~the~~ river channel dynamics ~~has also~~ resulted from construction of bank protection structures and torrent control works. ~~As, as a result of these bank protection works, at present~~ which the river can still move laterally, although the available width for planform shifting is narrower than its natural braided belt.

2.2. Study reach

The ~~studystudied~~ reach is ~7 km-long (Fig. 1) and is located between Ponte nelle Alpi and Belluno (the drainage area at Belluno is 1,826 km²). ~~In this reach the-~~The morphology ~~of the reach~~ is mainly braided and wandering. The average slope ~~of the reach~~ is 0.47%, and ~~the~~ median surface grain size ranges between 18 and 32 mm (Tomasi, 2009). The active channel width ranges between 43 and 452 m, ~~beingand is~~ 241 m on average, while the fluvial corridor width, defined by the presence of Holocene fluvial terraces, ranges between 106 and 1,110 m, ~~beingand is~~ 672 m on average. Previous studies (Surian, 1999; Surian, et al., 2009; Comiti et al., 2011; Picco et al., 2016) have outlined that, over the last 200 years, the ~~studystudied~~ reach ~~havehas~~ undergone notable lateral adjustments (narrowing up to 66%), but ~~notwith no~~ significant changes ~~ofin~~ channel ~~pattern-~~. ~~In terms of bed level changes, twopatterns.~~ Two phases have been identified: ~~a in terms of changes in bed levels,~~ first a phase of moderate incision (1970-1990s) followed by a more recent phase (1990s-2003/2007) during which the river has exhibited equilibrium or slight aggradation (Surian, et al., 2009; Comiti et al., 2011).

3. Materials and methods

3.1 Channel morphology and reconstruction of ~~its~~ evolutionary trajectory

Channel morphology was analysed ~~in order to~~ gather (i) input data for ~~the~~ CAESAR – LISFLOOD model, (ii) data for model calibration, and (iii) evidence of the evolutionary trajectory of the ~~studystudied~~ reach. ~~RiverThe river~~ channel, islands, flowing ~~channelchannels,~~ bank protection structures and groynes were digitized using the available aerial photos and terrain models covering the ~~studystudied~~ reach (i.e., 2003, 2009 - Table 1). The analysis ~~was carried out usingemployed~~ ArcGIS 10.2. The ~~flowing channels and the unvegetated or sparsely vegetated bars with little or no vegetation were merged to obtain measurement ofmeasure~~ channel width. ~~BraidingThe braiding~~ index was calculated using the average number of anabranches across the river (Ashmore, 1991; Egozi and Ashmore, 2008). The historical analysis ~~carried out byof~~ Comiti et al. (2011), which covered the period 1805 ~~- 2006 has been, was~~ extended ~~up~~ to 2009.

A LiDAR Digital Elevation Model (DEM) was provided by the Autorità di Bacino delle Alpi Orientali. It was created using an airborne LiDAR survey ~~that was acquired~~ in July 2003 (orthometric elevations adopted, vertical error estimate ±20 cm) almost contemporary to ~~one of thean~~ aerial ~~photosphoto~~ used in this study (Table 1). Even though the river reach is characterized at low flow by the presence of rather small inundated areas, it was not possible to obtain bed elevation in the flowing channel areas with the standard LiDAR data. ~~Therefore, to complete theTo obtain~~ bed elevation ~~extraction,~~ the water depth was estimated ~~through the application ofby applying~~ the method proposed by Bertoldi et al. (2011) using the 2003 aerial photos. This is an optical remote sensing technique (Marcus, 2012) for retrieving shallow water depth information using the color of the pixel, ~~as,~~ Legleiter et al. (2009) demonstrated that the log transformation of the green over red band ratio correlates linearly with water depth across a wide range of substrate types. The linear regression ~~is~~ usually ~~should be~~ calibrated by direct

~~measurements~~ measurement of water depths at the time of the aerial survey. Since such data were not available, we calibrated the regression coefficients by referring to the topography of ~~both~~ the 2003 and 2009 cross-section surveys.

340 Sediment grain sizes were surveyed in 2009 (Tomasi, 2009) using volumetric sampling of the surface layer (Fig. 1). A single probability density curve was extracted ($D_{50} \sim 24.5$ mm, $D_{15} \sim 2$ mm, $D_{84} \sim 77$ mm) with nine size classes, as required by the C-L morphodynamic model.

3.2 Analysis of ~~the~~ hydrologic regime ~~in~~ of the Piave River

345 ~~A variety of~~ There are several approaches ~~is available~~ to analyse the impact of ~~river~~ regulation on the natural flow regime of rivers (Richter et al., 1996; Richter et al., 1997; Martínez Santa-María et al., 2008; Yin et al., 2015). In the case of the Piave River, although several studies have investigated the degree of ~~alteration to~~ its hydrological regime ~~alteration~~ (Villi and Bacchi, 2001; Botter et al., 2010; Comiti et al., 2011), such analysis ~~was~~ has been hampered by (i) the ~~unavailability~~ lack of a long-term flow data series, and (ii) the difficulty in ~~sorting~~ distinguishing between natural and artificial ~~component~~ components of the flow regime. In Da Canal et al. (2007) and Comiti et al. (2011), flow records derived from two gauging stations (Busche and Segusino; Fig. 1) were modified using a specific corrective factor (Villi and Bacchi, 2001) and then merged. Comiti et al. (2011) confirmed that the largest flood event at Busche (Fig. 1) occurred in 1966 and reached almost $4,000 \text{ m}^3\text{s}^{-1}$. Furthermore, their analysis showed that ~~the discharged~~ discharges with ~~Recurrence Interval~~ recurrence interval (RI) of 2 years ~~was~~ were not statistically different if calculated separately for pre- and post-regulation periods (1954 was used as ~~the~~ the separation date between the periods). However, ~~higher frequency~~ the peak discharges of the more frequent events ($\text{RI} \leq 1.5$ year) ~~show a~~ reduction of peak discharge ~~decreased~~ after 1954. ~~Similar outcomes have also been reported in~~ Picco et al. (2016) reported similar outcomes.

360 ~~Botter et al. A (2010) offered a~~ more detailed analysis of the impact of regulation on river regimes ~~has been presented by with~~ the application of ~~Botter et al. (2010), who applied a~~ physically-based modelling approach to assess the alterations ~~of in~~ the streamflow regime observed in various cross sections of the drainage network downstream ~~of from~~ dams and weirs. The authors ~~have~~ applied an analytical stochastic model (Botter et al., 2007) to characterize the streamflow probability density function (pdf) by means of climate, soil and vegetation parameters. After ~~applying a~~ preliminary model ~~application~~ to smaller, unregulated sub-catchments (that allowed ~~to for~~ properly ~~verify~~ verifying the capability of the model to reproduce ~~locally~~ the natural streamflow regime) ~~locally~~, the ~~authors have~~ author applied the model ~~also into~~ several regulated sections of the Piave River, including Soverzene (about 5 km upstream ~~of from~~ Ponte nelle Alpi, Fig. 1), in order to evaluate the natural flow regime in regulated cross-sections and, ~~by~~ based on the difference, the effect of regulation on the statistical ~~hydrographic features of~~ the hydrograph. The approach conceptualizes the dynamics of daily streamflow as a sequence of peaks in response to rainfall and decays in between these jumps. These jump-decay dynamics are then linked to a catchment-scale soil-water balance ~~wherein which~~ the input is represented by stochastic daily rainfall. In this setting, flow-producing rainfall events (that lead to streamflow jumps) result from the censoring operated by catchment soils on daily rainfall, ~~and they which~~ are ~~modeled~~ modelled as a marked Poisson process with mean depth α and mean frequency λ . The parameter α identifies the average intensity of

daily rainfall events, while λ is the frequency of flow-producing events, which is ~~smaller~~ less than the underlying precipitation frequency because of the effect of soil moisture dynamics and evapotranspiration. As a consequence, several climate variables (such as rainfall attributes), as well as soil and vegetation properties ~~were, are~~ embedded in λ . ~~Additionally, in that~~ In this framework, streamflow recessions ~~in~~ between flow pulses are assumed ~~asto be~~ exponential, with a mean rate equal to k , which defines the inverse of the time scale of the hydrological response (i.e., the mean water retention time in the upstream catchment). Under these assumptions, it can be shown that the steady-state pdf of the specific daily discharge (discharge per unit catchment area) is a Gamma distribution with shape parameter λ/k and scale parameter ak . The model is applied at the seasonal timescale, and then the annual pdf is calculated as the average of the four seasonal distributions. ~~During winter, the~~ The presence of snow dynamics ~~in winter, in the uppermost regions of the catchment is accounted for~~ by reducing the size of the active contributing catchment and increasing the recession rates as described by Schaeffli et al. (2013), with an elevation threshold of about 1,900 m a.s.l. In spring, a base flow value is added to the ~~modeled~~ modelled streamflow distribution, which corresponds to a rigid rightward shift of the pdf. The probability distribution of ~~the~~ natural daily streamflows estimated by the model is then compared to the pdf of the observed daily flows to assess the extent of the impact of regulation in the lower reaches of the Piave River, and to ~~get some~~ obtain guidelines for devising meaningful ~~strategies of the~~ flow regime management strategies. In particular, the daily streamflow series used in this study ~~has been~~ was recorded from 1995 to 2009 at Belluno gauging station located at the downstream section of the ~~studystudied~~ reach (Fig. 1). The highest flood event peaks observed in the reference periods (1996, 2000 and 2002) were checked and modified combining data ~~at from~~ Belluno and discharge measurements at ~~the~~ Soverzene weir (Braidot, 2003).

3.3 The CAESAR-LISFLOOD model

~~Over the last 20 years the~~ The application of hydro-morphodynamic physically-based numerical models (generally known as Computational Fluid Dynamic models, CFD) ~~over the last 20 years has~~ mainly ~~been~~ focused on ~~laboratory~~ idealized channel configurations ~~at the laboratory scale~~. (Wu et al., 2000; Defina, 2003; R  ther and Olsen, 2005; Abad et al., 2008) or ~~referred to~~ the morphological ~~dynamic~~ dynamics of natural channels over short time periods (Darby et al., 2002; Chen and Duan, 2008; Li et al., 2008; Wang et al., 2008; Zhou et al., 2009). ~~Although their recent development, the restriction of their field~~ The limited ~~range~~ range of application ~~of these models~~ reflects ~~unsolved~~ unresolved issues ~~in terms~~ of data availability and high computational demands (Escauriaza et al., 2017). Only a few recent works (i.e., Nicholas, 2013a; Williams et al., 2016) have shown that CFD models can be applied at larger spatial and temporal ~~context~~ scales. This limitation has ~~driven~~ led to ~~develop~~ the development ~~of alternative~~ two-dimensional ~~alternative~~ models that ~~have been~~ are commonly referred to as cellular automata (Murray, 2007), cellular models (Murray and Paola, 1994; Coulthard et al., 2002; Thomas and Nicholas, 2002; Coulthard et al., 2007; Parsons and Fonstad, 2007; Van De Wiel et al., 2007), exploratory models, ~~and/or~~ reduced-complexity models (RCM – Murray, 2007; Nicholas et al., 2006; 2012). These models have a common solution to the problem ~~that, which~~ is the adoption of simplified hydrodynamic and sediment transport equations derived by ~~the~~ the abstractions of the governing physics.

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A major advantage of RCMs is their computational efficiency ~~that, which~~ allows ~~to simulate for simulating~~ river evolution over historic and Holocene timescales (e.g., Coulthard et al., 2002; Coulthard et al., 2005; Nicholas and Quine, 2007; Thomas et al., 2007; Van De Wiel et al., 2007). However, the physical realism of ~~such these~~ models has received relatively little attention (Nicholas, 2009; Nicholas, 2013b; Ziliani et al., 2013), and ~~there have been only a few studies have shown that deal with the high sensitivity of~~ these models ~~are highly sensitive~~ to the grid resolution of the computational domain (Doeschl-Wilson and Ashmore, 2005; Doeschl et al., 2006; Nicholas and Quine, 2007). Despite the progress ~~shown made~~ in several works (Nicholas, 2009; Nicholas, 2013a), there are still few applications ~~into~~ natural rivers characterized by complex channel morphology (Ziliani et al., 2013; Ziliani and Surian, 2016).

In this study, ~~we applied the~~ CAESAR–LISFLOOD model (Coulthard et al., 2013) ~~has been applied~~ (1.2 version, reach mode; see ~~“the Supplementary material”~~ ~~Material~~ file for details about the model). ~~This model, which~~ is an integration of the LISFLOOD-FP (Bates et al., 2010) and CAESAR (Coulthard et al., 2007; Van De Wiel et al., 2007) models. The C-L model links the hydraulics of the former with the erosion and deposition components of the latter. LISFLOOD-FP is a one-dimensional inertial model derived from the full shallow water equations ~~that is~~ applied in the x and y directions to simulate two-dimensional flow over a rasterized spatial domain (Bates et al., 2010). LISFLOOD-FP has been successfully tested to simulate hydraulics in shallow water environments affected by ~~a~~ strongly unidirectional flow (Bates et al., 2010; Neal et al., 2011; Coulthard and Van De Wiel, 2013; Lewis et al., 2013; Skinner et al., 2015; Wong et al., 2015) and for flood ~~inundation~~ simulations characterized by rapid wetting and drying condition (Bates et al., 2010). ~~The~~ CAESAR model (Coulthard et al., 2007; Van De Wiel et al., 2007; Ziliani et al., 2013) represents the morphodynamic component of the ~~C-L~~ integrated ~~C-L~~ model. Ziliani et al. (2013) submitted CAESAR to a rigorous and objective performance evaluation ~~procedure~~, and ~~showed found~~ that (i) CAESAR can be a very powerful tool for modelling spatial and temporal scales ~~still hardly that are not well~~ supported by 2D – 3D ~~CFD~~ morphodynamic ~~CFD~~ models, (ii) it can be very useful for setting “what-if scenario” strategies over meso-~~spatial and~~ temporal scales, and (iii) it provides reliable bedload sediment budget estimations. From a morphological point of view, Ziliani et al. (2013) ~~have shown showed~~ that CAESAR ~~is able to can~~ reproduce the average change in channel width, but ~~it performed performs~~ poorly in reproducing ~~the~~ braided in-channel pattern ~~dynamic dynamics~~ and the typical topographic complexity of a braided river at low water stages (e.g., braiding intensity). LISFLOOD-FP and CAESAR have been efficiently integrated and tested ~~into in~~ the new CAESAR–LISFLOOD (see Coulthard et al., 2013 for details). ~~Herein the hydraulic element embedded into the model has been verified to be consistent with the LISFLOOD-FP developed by Bates (2010), but the geomorphic component of the~~ The C-L model has ~~not been fully evaluated referring to real case study data. The embedded erosion been applied at reach (Feeney et al., 2020) and deposition modules have been catchment scales (Coulthard and Van De Wiel, 2017), whereas Skinner et al. (2018) assessed only through the intercomparison of CAESAR and C-L sediment yield results the sensitivity of the model. Feeney et al. (2020) used the model to reconstruct geomorphic changes for ten alluvial reaches in northern England, and found that the model accurately reproduces channel and floodplain dynamics at meso-temporal scales.~~

3.4 Morphodynamic model performance assessment

Several works (Darby and Van De Wiel, 2003; Hoey et al., 2003; Wilcock and Iverson, 2003) have emphasized the challenge of a proper calibration of process-based models in fluvial geomorphology due to the increase of increasing uncertainty proportionally with proportional to the increased complexity of the modeled processes modelled process and the number of parameters to be estimated (Formann et al., 2007; Papanicolaou et al., 2008). Despite this intrinsic complexity, it is crucial to understand the limitations and performance of RCMs (Aronica et al., 2002; Hall et al., 2005; Lane, 2006), adopting methods that (i) are able to can include all the limitations inherent in calibration of calibrating this type of model, and (ii) are mainly based on field and remote sensing data (Nicholas, 2010). There are currently no standard international standard methods for the calibration and validation of fluvial morphodynamic models (Mosselman, 2012), and those previously proposed are typically designed for hydrodynamics hydrodynamic CFD models (ASME, 1993; Lane et al., 2005). Furthermore, the calibration of RCMs has to It must also be performed keeping kept in mind that a calibrated RCM model can just be “simply empirically adequate” (Van Fraassen, 1980) and its validation is just simply a “confirmation” (Oreskes et al., 1994) that cannot be considered conclusive (Haff, 1996; Lane et al., 2005; Murray, 2007). Calibration of the C-L model was specifically addressed by Feeney et al. (2020), who pointed out the need for reach-specific calibration to increase model performance.

In light of all the issues above, the C-L was calibrated referring to the July 5th 2003 – August 5th 2009 period (Fig. 2) by comparing the model output (i.e., morphological features such as channel boundaries, islands, wet channel positions) to the channel morphology digitized using the 2009 aerial photos (see “Supplementary material” for a detailed description of model calibration). The hourly discharge series was used as upstream flow boundary condition. At the downstream end of the reach, a constant energy slope was fixed at 0.0047 m⁻¹, equal to the local bed slope. The initial bed sediment grain size was set according to Tomasi (2009) results. The grain size distribution was defined using nine classes and was considered homogeneous in the whole reach. Due to the lack of field estimates of bed load at the upstream end of the reach, we assumed the sediment recirculation option available in C-L (i.e., sediment input equals the output at the downstream end of the reach). The model factor called “Sediment Proportion Recirculated” (SPR) was assumed to be 1, which assumes that upstream sediment load being the same as at the downstream end of the reach (i.e., sediment transport equilibrium condition). Vegetated areas (i.e., islands, recent and old terraces covered by arboreal vegetation) and channelization structures (i.e., bank protection structures, groynes, and levees) were digitized combining 2003 aerial photos and LiDAR Digital Surface Model (DSM, 2 m grid dimension, Table 1). The vegetation cover has been used as the model initial condition for vegetation (maturity fixed to 1). The initial bed elevation was established using a 10 m cell DEM achieved by resampling the 2003 LiDAR DEM (bilinear interpolation, original cell dimension 2×2 m). The 10 m cell dimension was chosen to ensure a reasonable computational time for long term scenario runs and also a spatial resolution higher than previous works (e.g. 25 m in Ziliani et al., 2013). The DEM was corrected in the wetted areas (about 8% of the total spatial domain) through the application of the method proposed in Bertoldi et al. (2011) and forced to be “not erodible” in the areas occupied by both channelization structures still effective in 2003 and undamaged structures built since the 19th century.

470 Given all of the above, the C-L was calibrated with reference to the July 5 2003 – August 5 2009 period (Fig. 2) by comparing
the model output (i.e., morphological features such as channel boundaries, islands, wet channel positions) to the digitized
channel morphology based on the 2009 aerial photos (see Supplementary Material for a detailed description of the model
calibration). The hourly discharge series was used as an upstream flow boundary condition. At the downstream end of the
reach, a constant energy slope was fixed at 0.0047 m m⁻¹, equal to the local bed slope. The initial bed sediment grain size was
475 set according to Tomasi (2009). Nine grain size classes were used to define size distribution, which was considered
homogeneous throughout the reach. Due to the lack of field estimates of bed load at the upstream end of the reach, we assumed
the sediment recirculation option available in C-L (i.e., sediment input equals the output at the downstream end of the reach).
The model factor termed “recirculated sediment proportion” (SPR) was assumed to be 1, which assumes that sediment load
upstream is the same as it is downstream (i.e., sediment transport equilibrium condition). Vegetated areas (i.e., islands and
480 recent and old terraces covered by arboreal vegetation) and channelization structures (i.e., bank protection structures, groynes,
and levees) were digitized combining 2003 aerial photos and the LiDAR Digital Surface Model (DSM, 2 m grid dimension,
Table 1). The vegetation cover was used as the initial modelled vegetation condition (maturity fixed at 1). The initial bed
elevation was established using a 10 m DEM cell obtained by resampling the 2003 LiDAR DEM (bilinear interpolation,
original cell dimension 2×2 m). The 10 m cell dimension was chosen to ensure a reasonable computational time for long-term
scenario runs and for a spatial resolution higher than previous works (e.g. 25 m in Ziliani et al., 2013). The DEM was corrected
485 in the wetted areas (about 8% of the total spatial domain) through the application of the method proposed in Bertoldi et al.
(2011) and forced to be not erodible in the areas occupied by both channelization structures still effective in 2003 and
undamaged structures built since the 19th century.

3.5 Flow-regime management strategies

490 In rivers, Water management of historically regulated, water management rivers may be oriented to restore/restoring the flow
regime to close to the prior that before impact conditions, typically aiming to reactivate/aimed at reactivating physical processes
linked to specific components of the flow regime (Wohl, 2011). Nevertheless, existing priorities in uses of the water
resources/resource use often limit the feasibility and the effectiveness of any flow regime re-naturalization strategies, and in
most cases the strategy is merely reduced to the definition of a minimum volumes/volume of water released for partial
restoration goals. Olden et al. (2014) provided a systematic review of systematically reviewed flood experiments to evaluate
495 globally the success of this practice in flow regime management. They considered 113 flood experiments across/in 20 countries
were reviewed/revealing and found that only 11% of the case studies were aimed directly to at morphological effects and about,
while around 80% of the experiments involved only low magnitude flow events. Major part of/Most experimental flow releases
focuses/are focussed on a biological variable/variables (primarily fishes/fish), aquatic organisms (Konrad et al., 2011) and re-
establishing vegetation reestablishment (Shafroth et al., 2010), rather than on abiotic factor/factors (e.g., channel morphology)
500 (Wohl et al., 2015b). The so-called/What are termed “environmental flows” and “Green Hydro” are concepts widely accepted
even though they/concepts that refer mainly to quantity, timing, duration, frequency and quality of water flows/flow releases,

as required to sustain freshwater, estuarine and near-shore ecosystems; according to social interests (Acreman and Ferguson, 2010; Rivaes et al., 2017).

Thus, there ~~are~~ have been few examples of flow regime recovery strategies ~~which have been designed on a geomorphological basis or rather planned to~~ with primarily ~~achieve~~ morphological ~~targets~~ goals. The Colorado River below the Glen Canyon Dams represents the most ~~relevant~~ important exception: ~~several~~ Several controlled floods (i.e., five ~~High Flood Experiments~~ high flood experiments) were released ~~in the between~~ in the 1996- ~~and~~ 2013 ~~period~~ to maintain and rehabilitate sandbars that occur in lateral flow separation eddies (Schmidt and Wilcock, 2008; Melis, 2011; Mueller et al., 2014). ~~Also the~~ The Trinity River (California, USA) represents ~~another~~ excellent case study, ~~as a in which morphological goals were among the~~ multiple ~~objective~~ flow designed included morphological issue objectives (Trinity Management Council, 2014). ~~Still, Nevertheless, with the exception of the lower Waitaki River in New Zealand, there are no experiences are available on~~ examples of morphological recovery or conservation of braided rivers, ~~with the exception of the Lower Waitaki River (New Zealand), even though~~ and no controlled floods have been used ~~in that river on the Waitaki~~ (Hicks et al., 2003; Hicks et al., 2006; Environment Canterbury Regional Council, 2015).

~~Controlled~~ Provoking ~~controlled~~ floods ~~and or removing~~ vegetation ~~removal actions~~ are ~~expensive~~ costly and ~~potentially forego~~ can preclude other ~~positive feedback effects~~. ~~It is therefore worth to preliminary evaluate and test actions, so it worthwhile to assess~~ these ~~kinds of actions taking into account~~ strategies and consider the morphological effects of different channel-forming discharges (Surian et al., 2009). ~~As emphasized by Rathburn et al. (2009),~~ stressed that flow releases from dams must exceed a series of thresholds to be morphologically effective. Four ~~discharge thresholds of increasing threshold~~ discharges intensity should be identified in a morphological recovery/conservation plan, each ~~able to activate~~ capable of activating a specific morphological process: (i) the mobilization of interstitial sediment essential for ~~the~~ hyporheic exchange maintenance; (ii) the mobilization of the streambed to maintain natural bedforms; (iii) the inundation of overbank units (i.e., berms, floodplains, terraces) to confine encroachment by xeric plants; and (iv) the lateral channel mobility that ~~may promote the removal of~~ can remove senescent woody vegetation and create opportunities for seedlings to germinate and mature. Once each threshold discharge value or range is quantified, the flow duration can be tuned within the limits imposed by the ~~actual available~~ flow availability, assuming, using the natural flow regime as a reference.

~~In this work, the scenarios of~~ The flow regime management ~~scenarios used in this work~~ were defined ~~referring in reference~~ to three flood threshold levels ~~that partially matching~~ match those proposed ~~in by~~ Rathburn et al. (2009): (i) ~~the full~~ in-channel ~~full~~ transport discharge assumed to be ~~able to mobilize~~ capable of mobilizing interstitial sediment, (ii) the bankfull discharge ~~able to maintain~~ capable of maintaining natural bedforms; and (iii) ~~the~~ overbank discharge ~~able to affect~~ capable of affecting the main lateral units by inundation. A field study conducted in the reach using painted sediments similar to ~~(those used in~~ Mao and Surian ~~), (2010), and~~ Mao et al. ~~), (2017)~~ ~~allowed to result in an~~ estimate that of the first reference threshold ~~is about~~ at $80 \text{ m}^3 \text{ s}^{-1}$ ($RI < 1$ year, full transport discharge ~~able to mobilize~~ capable of mobilizing sediments, irrespective of their size). The bankfull discharge was estimated using the calibrated C-L model and was approximated to the discharge filling the active channels and bars without overflowing onto the oldest island assumed to be morphologically equivalent to the recent

fluvial terraces (Williams, 1978; Pickup and Rieger, 1979; Surian et al., 2009). The bankfull discharge is about $500 \text{ m}^3\text{s}^{-1}$, and corresponds to a 2.5 years RI, ~~coherently~~ which is consistent with other ~~literature~~ references in the literature (Leopold, 1994). Only ~~the~~ > $1,000 \text{ m}^3\text{s}^{-1}$ floods were identified ~~to be able to~~ as capable of completely ~~inundate~~ inundating the oldest island and ~~overflowing~~ locally overflow into the recent fluvial terraces.

540 Four simulation scenarios, ~~each were considered, all covering the same 25-years long-year period (2009-2034), were explored~~ (Table 2). The first scenario (i.e., "baseline scenario", SC1) ~~corresponds to~~ is the current condition, characterized by a strongly altered flow regime. In this case, the discharge series ~~measured in for~~ 1995-2009 (hourly data at Belluno gauge station) ~~has been~~ was repeated twice. ~~Scenarios~~ Both scenarios 2 (SC2) and 3 (SC3) ~~were both set up using~~ used a flow regime strategy characterized by one CF per year. ~~In SC2 the~~ The yearly CF ~~in SC2~~ had a constant value of $135 \text{ m}^3\text{s}^{-1}$ (RI ~ 1.08 years). ~~This value has been~~, which was calculated as the average of the maximum annual floods observed in 1995-2009. ~~This was~~ is higher than the reference threshold discharge, i.e. the ~~full~~ in-channel full-transport discharge ($80 \text{ m}^3\text{s}^{-1}$). ~~In SC3, the~~ The yearly CF values ~~for SC3~~ for SC3 were randomly selected above the threshold discharge using the natural streamflow pdf estimated by the model (~~min~~ minimum value = $80 \text{ m}^3\text{s}^{-1}$; ~~max~~ maximum value = $276 \text{ m}^3\text{s}^{-1}$, RI ~ 1.4 years). In this case, the average ~~value~~ of all the CF values ~~was found to be~~ is equal to the ~~SC2~~ yearly CF discharge for SC2, assuming values included in the $[80 - 276] \text{ m}^3\text{s}^{-1}$ range.

555 All the CFs had a fixed duration of 5 days, according to the re-naturalization maximization criteria. In SC2 and SC3, the cumulative likelihood to occur associated ~~to with~~ the released peaks ~~raised~~ increased from 0.025 (actual observed altered regime) to 0.04, ~~being~~ the natural reference value ~~being~~ 0.14. Scenario 4 (SC4) was planned to represent a different management strategy, consisting ~~in of~~ larger CFs released by dams (constant value for one-day) only following the observation of notable channel narrowing. Specifically, we assumed 200 m as a threshold for average channel width, considering the evolutionary trajectory over the last 200 years and, in particular, the most intense narrowing that took place in the early 1990s (Fig. 3). ~~Taking into account the~~ Based on channel width measurements ~~conducted~~ taken by a one-year step ~~during in~~ the SC4 simulation, only two CFs were released, ~~one in 2020 and the other in 2032-respectively~~. The released discharge was fixed ~~equal to at~~ at $600 \text{ m}^3\text{s}^{-1}$ (RI 5 years), ranging between the ~~second and the third~~ second and the third reference threshold discharges discussed above, so that it ~~was surely able to maintain the~~ would undoubtedly be capable of maintaining in-channel ~~bedforms~~ bedform dynamics, ~~while~~ completely avoiding any hydraulic risk issues ~~risks~~ and damages in the overbank units (i.e., recent terraces), locally occupied by secondary roads and cultivated fields.

560 ~~All the CFs have been~~ were released in November ~~avoiding to overlap existing, while overlapping floods were avoided~~. All the scenarios made use of the same model setting ~~achieved, which was obtained~~ in the calibration phase, using the 2009 calibration ~~run~~ output data in raster format as ~~the~~ initial boundary conditions (i.e., bed elevation, ~~not erodible~~ erodible, hydraulic structures, vegetation cover, grain size ~~bed sediment~~ distribution). As reported in Table 2, all the scenarios required ~~the release of a~~ cumulative volume ~~to be released per year (i.e., per flood)~~, which was considerably ~~lower~~ less than the maximum ~~stocked~~ volume in the reservoirs ~~existing~~ upstream of ~~from the~~ studied reach (90.8 Mm^3). SC2 and SC3 required similar volumes of about 58 Mm^3 of water, ~~corresponding to about or around~~ around $1.45 \times 10^3 \text{ Mm}^3$ ~~enover~~ the whole ~~entire~~ scenarios

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period. SC4 represents the ~~cheapest~~last expensive scenario ~~indeed~~ because it needed 51.8 Mm³ per year and 104 Mm³ globally, one order of magnitude ~~lower~~less than in the other scenarios.

4. Results

4.1 Evolutionary trajectory of channel morphology

Using the available dataset on morphological changes of the Piave River (Comiti et al., 2011), we reconstructed and updated the channel adjustments up to 2009. The analysis focused on two sub-reaches, respectively upstream and downstream ~~off~~from San Pietro in Campo, where the river is naturally more confined (Fig. 1). The ~~division in reach was divided into~~ two sub-reaches ~~was used~~ to better describe the morphological adjustments over the 1800-2009 period. The trends in average width ~~trends are similar for both in the~~ sub-reaches are similar, and ~~are~~ characterized by four main adjustment phases (Fig. 3): (i) a first period (during the 19th century and the first half of the 20th century) dominated by a braided pattern, channel width equal to about ~~the~~ 80% of the alluvial plain width, negligible morphological changes and the absence of a dominant process (i.e., channel widening or narrowing), (ii) a second phase of adjustment with channel narrowing of about 60% from the 1950s to the early 1990s (~~whole reach the~~ channel width of the entire reach was 370 ~~and 247, respectively in~~ 1960 and 247 in 1991), interrupted by a large flood event in 1966 (RI ~ 200 years – (Comiti et al., 2011), which caused ~~a~~ temporary widespread channel expansion; (iii) a phase of channel widening during the 1990s (~~whole reach the~~ channel width of the entire reach was 342 m in 1999), mainly related to the 1993 flood event, characterized by a 12-years-year RI (Comiti et al., 2011); and (iv) the most recent adjustment phase characterized by channel narrowing. Focusing on the last 20-25 years, ~~after following~~ the 2002 flood, the river ~~turned to~~entered a new phase (IV in Fig. 3) characterized by narrowing: channel width in 2009 (i.e. 241 m) was the lowest ~~value~~ observed in the ~~studystudied~~ reach over the last 200 years. While widening during phase III ~~widening~~ was likely due to the termination of in-channel gravel mining (Comiti et al., 2011), the most recent ~~phase of~~ narrowing (~~i.e.,~~ phase (phase IV) was likely due to the absence of major floods (see also Fig. 2).

4.2 Flow regime alterations

~~The~~A comparison ~~between~~of the frequency distribution of observed daily streamflows at the Belluno cross-section and the model-based estimate of ~~the~~ streamflow pdf under unregulated conditions (Fig. 4) shows the ~~extent of the~~significant impact of regulation in the lower reaches of the Piave River. The mean and the mode of the streamflow distribution are significantly reduced by ~~the~~ anthropogenic exploitation of water resources (i.e., by-pass flows and diversions). Accordingly, the exceedance probability of moderate to high flows is significantly reduced under current regulated conditions. In particular, the probability to observe discharges larger than 80 m³s⁻¹ is reduced by about one order of magnitude (i.e., from 0.14 to 0.025). Such results are crucial for setting the flow-regime management scenario since (i) they show that a strategy ~~aiming to improve~~aimed at improving the current flow-regime ~~should be implemented~~ is needed, (ii) this strategy should compensate the expected low

morphological dynamism of the river caused by the decreased occurrence of discharges ~~able to mobilize~~capable of mobilizing
600 sediments and ~~produce~~producing significant morphological changes in the ~~studystudied~~ reach.

It is worth ~~to notenoting~~ that the hydrological model underestimates the frequency of the highest flows (i.e., discharges ~~largerof~~
~~more~~ than $300 \text{ m}^3 \text{ s}^{-1}$) because all the non-linearities of the ~~hydrologiehydrological~~ response (e.g., the presence of different flow
components such as surface runoff) are neglected in this version of the model (Basso et al., 2015). As a consequence, the
probability associated ~~to with~~ the highest flows in regulated conditions is ~~largergreater~~ than the corresponding value estimated
605 by the stochastic model for the natural setting. ~~This model-However, this~~ limitation, ~~however,~~ of the model does not ~~bearhave~~
any significant ~~eonsequeenceconsequences~~ for the analysis carried out in this paper, provided that the frequency of such high
flows is relatively low.

4.3 Calibration of the morphodynamic model

The results ~~presented inof~~ Ziliani et al. (2013) and Coulthard et al. (2013) ~~have been takenwere used~~ as a reference to
610 ~~achievecalibrate~~ the C-L ~~ealibrationmodel~~. According to the results of the sensitivity analysis in Ziliani et al. (2013), ~~the~~ lateral
erosion rate and maximum erosion limit ~~have been assumed aswere~~ the most sensitive factors that required accurate tuning.
The other factors (see Table 3), including the main new parameters introduced in the C-L version, were tuned manually ~~through~~
~~a "by trial- and- error" calibration strategy (n- (75 runs in total)~~. Following the performance evaluation techniques used by
Ziliani et al. (2013), the calibration was based on performance indices developed specifically for data available in ~~a~~ raster
615 format (Bates and De Roo, 2000; Horritt and Bates, 2001). The performance indices reported in Table 4 were calculated for
all the calibration runs at the end of the simulation (2009), ~~that isthese being~~ (i) the vegetation performance index (F_{veg}), (ii)
the wet area performance index (F_{wet}) and (iii) the active channel performance index (F_c). In addition, several planimetric
features ~~have beenwere~~ calculated, including (i) average active channel width, (ii) equivalent wet area width (L_w), and (iii) ~~the~~
mean braiding index (Egozi and Ashmore, 2008). The results (see Table 4, Fig. 5, Fig. S3 and S4 in the ~~"Supplementary~~
620 ~~material" fileMaterial File~~) show a ~~"very good performance"~~ (performance class as defined in Henriksen et al., 2003; Allen et
al., 2007) for both the vegetation cover (F_{veg} 69.7%) and the active channel area (F_c 54.2%). Output values of the active channel
width and braiding index ~~values~~ confirmed these results. The difference between ~~the-real and modeledmodelled~~ 2009 active
channel width (6 m) is ~~lowerless~~ than ~~the~~ input DEM cell size (10 m)), and the ~~modeledmodelled~~ braiding index value (1.71)
is very close to the real value (1.69). The model ~~performance is poor~~ only ~~performed poorly~~ in reproducing the flowing channel
625 position (F_w 15.7 %%%), ~~which~~ partially ~~confirmingconfirms the~~ results ~~presented inof~~ Ziliani et al. (2013).

~~In order to integrate the morphological performance evaluations, we carried out an estimation of the~~We ~~estimated~~ mean annual
bed load sediment yield at the downstream end of the reach and along the ~~wholeentire~~ reach. ~~In the 2003-2009 period, the~~
~~modeled-average to integrate morphological performance evaluations. Average modelled~~ bed load sediment yield ~~resulted of~~
~~aboutin the 2003-2009 period was around~~ $21.5 \times 10^3 \text{ m}^3 \text{ yr}^{-1}$. ~~ModeledModelled~~ yield varies significantly along the reach (up
630 to 30%) ~~taking%~~, with higher yearly values in the sub-reach upstream San Pietro in Campo. ~~Significant differences exist~~
~~between the maximumMaximum~~ and minimum annual values; ~~differ significantly~~. The 2006 minimum ~~corresponds to an~~

average annual sediment yield of $\sim 260 \text{ m}^3 \text{ yr}^{-1}$ versus the 2008 maximum of about $53.3 \times 10^3 \text{ m}^3 \text{ yr}^{-1}$. These sediment transport values agree with estimates for gravel-bed rivers with similar characteristics to those of the Piave River reach (Martin and Church, 1995; Ham and Church, 2000; Nicholas, 2000; Liebault et al., 2008; Ziliani et al., 2013; Mao et al., 2017).

635 4.4 Channel response to flow regime management strategies: scenario results

640 Channel adjustments induced by all the different scenarios were assessed by comparing every year (in February) the active channel width and the braiding intensity (BI) in each year (in February) using the same techniques adopted in the calibration phase (Fig. 6). Channel width in Scenarios 2-4 was almost always higher than in SC1 (the "baseline scenario"). On average, during the whole scenario period, SC2 and SC4 produced comparable average channel widening of about 6.4% ($\sim 14 \text{ m}$), while at the end of the scenarios (2034), widening was about 9% ($\sim 25 \text{ m}$) and 13.5% ($\sim 38 \text{ m}$) in SC2 and SC4, respectively. The SC3 induced a slightly lower widening, about 5.4%, during the whole period, and 8.6% ($\sim 24 \text{ m}$) at the end of the simulated period. The maximum annual widening was observed in SC4 ($\sim 120 \text{ m}$ in 2033), followed by SC3 ($\sim 77 \text{ m}$ in 2020) and SC2 ($\sim 43 \text{ m}$ in 2032 - Fig. 7).

645 Results suggest that the CFs scenarios (SC2-4) and the baseline scenario (SC1) provide similar long-term morphological trajectories characterized by alternate phases of widening and narrowing and notable changes in active channel width (width varies between 150 and 360 m). Figure 7 shows that each channel width oscillation takes place in about over a period of 6- to 7 years and it has a $\sim 160 \text{ m}$ amplitude of 160 m in response to the alternation of periods characterized by different magnitude floods series: in the 2011-2015 and 2022-2028 periods, during which seven floods $> 400 \text{ m}^3 \text{ s}^{-1}$ ($\text{RI} \sim 1.9$ years) occur, channel width follows a quasi-steady trend and is larger than 300 m. Instead, channel width decreased during the following periods (2017-2021 and 2029-2031) affected by lower magnitude floods ($200 \text{ m}^3 \text{ s}^{-1}$ maximum peak value), channel width shows decreasing trajectories. Over the whole 25 years, SC1 provides a slightly decreasing trend (Fig. 7) that is not reversed over the entire 25 years (Figure 7). Channel width has quasi-zero slopes in the other CF scenarios. In all the CFs scenarios the channel width trend assumes quasi-zero slope, even if the channel width measured at the end of the simulation is about [8.6-13.5 %] higher than width in the baseline scenario.

650 The braiding index in indices of Scenarios 2-4 was similar to or lower than that of SC1. SC4 resulted the most similar scenario to that of SC1, with an average BI in-time averaged value equal to of 2.78, only which was slightly lower than that of SC1 (-1.5%). During SC2 we measured relative differences in BI were higher differences in SC2 than in the BI value compared to SC1 (-7.3%, 0.21 BI unit - Fig. 7), although these differences were quite small. In terms of behaviour of trajectory, braiding intensity shows a different behaviour in comparison to from channel width, as in that there are no clear oscillation phases but was one period (from 2009 to 2023) with no clear oscillations, and a clearly increasing trend, followed by a decreasing or quasi-steady (SC1) period until the end of the simulation. There is a non-linear correlation between BI and flooding series magnitude or the CFs. In particular, SC1 is the only scenario that does not show an inverse trend inversion after 2023, and while the SC2 scenario has a very anomalous trend showing an anomalously had a consistently

665 lower BI value steadily lower than the other CFsCF scenarios, while SC3 and SC4 show a good agreement in their had very
similar BI trendsvalues.

5. Discussion

5.1 Geomorphic effectiveness of controlled floods

670 ~~Comparing the~~Several insights can be obtained from comparing future scenarios to the historical evolutionary trajectory (Fig.
3) ~~several insights can be obtained~~3), despite the evident mismatch between the temporal frequency of the past and future
channel width series (one value every 16.5 years in the 1805-1970 period and every 6.5 years in the 1970-2009 period; yearly
values for the future series). It can be observed that: (i) the maximum channel widths reached during in all-of-the four future
scenarios (in the periods 2015-2016 and 2028-2029) are close to the width in 1999, (ii) the minimum widths achieved in all
future scenarios (2020 and 2032;) are always below less than 185 m (with the exception of the first minimum during in scenario
675 3) and are significantly lower than the historical minimum observed in 2009 (241 m), (iii) albeit with a low confidence level,
we can state that the trajectory between 1991 and 2009 (phase III and IV described in Par. Section 4.1) seems to follow follows
an oscillatoryoscillating evolution with half the frequency of the oscillation modeledmodelled between 2009 and 2034, (iv)
thethere is a good correlation between the variation of channel width and the flow regime reproduced forin the future scenarios,
whereas this is not always straightforwardthe case in the past evolution. This point is exemplified by the rather major 2002
680 flood event, which did not re-widen the river at the levels of 1999 (about 342 m), despite being relevantsignificant in terms of
magnitude (13-years-year RD). Indeed, the width the following year (2003) the width was approximately 289 m, about 15%
less than in 1999. This may suggestsuggests that the study reach, after a period (phases I and II in Fig-Figure 3) of
morphological instability characterized by a prevalentnarrowing tendency to narrowing, has reached, the studied reach had
acquired a new morphological equilibrium configuration characterized by a-periodic oscillations ofin channel width. Similar
685 new equilibrium conditions, mainly controlled by the flow regime (i.e. frequency and magnitude of formative discharges) and
vegetation establishment, have been observed in the Tagliamento River (Ziliani and Surian, 2016).

The intercomparisoncomparison of our four simulations shows that a few high magnitude floods provide slightly better
morphological recovery/conservation than small yearly floods, alsoand at a significantly lower operational cost. Therefore,
SC4 should be preferredis preferable to SC2 and SC3 from a purepurely morphodynamic point of view. Nevertheless, results
690 suggestthe comparison suggests that (i) none of the CFsCF scenarios are able to change can significantly thechange long-term
channel width and braiding intensity trends, (ii) CFs-releaseCF releases have no significant morphological benefits and do not
represent a solution for atthe morphological recovery inof braided rivers that suffered such strong and historical impacts in
terms of flow and sediment supply regimes. It is worth noting that the selected CFs are feasible, that is taking into account the
water infrastructure in the Piave River basin, and it is unlikely that higher or more frequent floods could be released. These
695 results partially confirm the outcomes of Hicks et al. (2003) referring toon the Waitaki River, a gravel-bed river with similar
characteristics to those of the Piave River. The authors state that, if a wider and more active channel is desired, an approach

~~consisting in the~~ frequent release of “channel maintenance floods” from dams should be pursued; ~~if wider and more active channels are desired.~~ Hicks et al. (2013) ~~showed~~ that this kind of strategy ~~may have been~~ unsuccessful and only multi-year high magnitude CFs can produce ~~temporary stable effective channel widening channel condition.~~

700 The cost of CFs is probably ~~smaller~~ than ~~those that~~ of alternative strategies focused on increasing sediment supply, such as sediment augmentation, because flood releases ~~commonly can be performed without redesign often do not require redesigning~~ reservoir structures. Nevertheless, reintroduction of flood flows implies “loss” of ~~resources~~ stocked for other purposes (e.g., hydroelectric production; ~~and supply of~~ drinking or irrigation water ~~supply~~). Another feasible way for sediment augmentation is the removal (at least in part) of non-strategic bank protections along the reach. However, as ~~suggested by~~ Picco et al. (2016); ~~suggested~~, this kind of strategy should be ~~preventively assessed a last resort~~ since these structures are still viewed by local populations as necessary to protect riparian woodlands that are highly appreciated for recreation and timber production.

Overall, this work gives useful insights for the Piave River management and, in general, for ~~management of~~ braided rivers ~~with~~ heavily impacted ~~in~~-flow and sediment regimes: (i) none of the ~~tested~~ controlled flood strategies ~~that was tested is able to~~ ~~can~~ significantly change ~~the~~ on-going morphological evolution; (ii) the baseline scenario, without controlled flood releases (i.e., the no action strategy), provides ~~a similar~~ morphological ~~evolution evolutionary~~ trajectory ~~similar~~ to that induced by the controlled ~~floods flood~~ release scenarios. ~~Therefore, a main outcome is that controlled floods (including high-magnitude floods, e.g. 5-year RI) may not have any significant effects on regulated rivers, specifically if formative discharges have been strongly altered.~~

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5.2 Assessment of CAESAR-LISFLOOD performance

~~In~~ Ziliani et al. (2013) ~~the authors~~ concluded that the main ~~factors causing reasons for~~ the ~~poor~~ morphological ~~poor~~-response of CAESAR are (i) ~~the~~-DEM cell size, ~~as which has been~~ pointed out ~~also~~ in others works (Doeschl-Wilson and Ashmore, 2005; Doeschl et al., 2006; Nicholas and Quine, 2007), (ii) the quality of data (i.e., lack of wet channel topography), and (iii) the low flow ~~periods period~~ removal, and therefore the ~~cut-off~~ ~~elimination~~ of the consequent morphological “gardening” phenomena (Ziliani et al., 2013). The combination of these factors produced a smoother and simpler braided morphology. The Piave case study represents an effort to achieve a better performance by (i) the flow ~~routines routine~~ refinement included in the LISFLOOD-FP module (one of the most recent and advanced ~~Reduced Complexity Hydraulic Model schemes reduced complexity hydraulic model schemes~~), (ii) the adoption of ~~input data of~~ higher quality ~~input data~~ (higher resolution DEM, bathymetry and hourly boundary conditions) and (iii) the code conversion in parallel programming methods. The results lead to an overall improvement of the model performance considering (i) the good channel width performance in the calibration phase, (ii) the excellent ~~reproduction of~~ braiding complexity ~~reproduction~~, including the ~~pioneer pioneering~~ and complex ~~islands island~~ dynamics, both in the calibration and ~~in the~~ long-term simulations, (iii) the reasonable estimation of bedload transport; ~~and the small changes in bed grain size in the long-term simulations (e.g. D₅₀ changed from 24.9 mm to 22.7, 24.3,~~

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730 ~~23.6 and 23.1 mm respectively in SC 1, 2, 3, and 4~~, and (iv) the adequate computation speed, close to ~~the expectations (i.e., what was expected~~ (about 10 days of computation for 25 years of hourly series).

The suitability of ~~the RCMs application for the investigation of~~investigating river dynamics has been discussed in several ~~previous~~ studies (Doeschl-Wilson and Ashmore, 2005; Brasington and Richards, 2007; Nicholas and Quine, 2007; Murray, 2007; Nicholas, 2012, 2013b; Ziliani et al 2013; Ziliani and Surian, 2016). A general conclusion of these works is that RCMs ~~may provide morphological responses both unrealistic and highly sensitive~~ morphological responses to model grid resolution. These problems are commonly interpreted as a direct consequence of ~~both~~ the adoption of flow routing schemes that neglect the momentum conservation and the use of local bed slopes ~~for their calculating~~ bedload transport ~~calculation~~ (e.g., through the application of the uniform flow approximation).

740 The C-L model ~~may can~~ be considered ~~ana~~ useful tool in the search of an effective combination of simplicity and physical realism in the context of reduced-complexity modelling, overcoming ~~some of the previous problems associated with earlier simplified~~ hydrodynamic ~~simplification issues models~~. The encouraging results ~~achieved in of~~ this case study ~~seem to justify suggest~~ the effort ~~facied in such further development of to develop~~ this RCM. ~~Although is justified. While~~ the physical realism of flow and morphodynamic rules ~~can remain unsolved at smaller small~~ scales (i.e., scales ~~lower than below the~~ DEM cell dimension), the ~~improvements superiority~~ of the C-L model ~~response at reach scales compared to over the older CAESAR earlier CESAR~~ model is evident. ~~Although the reduced at reach scale. Reduced-complexity modelling approach model will~~ probably ~~will not provide insights into some of the answers to key~~ reductionist ~~key~~ questions ~~currently facied by of~~ hydraulic engineers and fluvial geomorphologists, ~~nevertheless~~ the model can provide useful insights for management. ~~Specifically, insights, specifically~~ about ~~their macro morphological macromorphological river~~ features (e.g. average channel width, braiding intensity) and adjustments (e.g. prediction of future evolutionary trajectory) of braided rivers.

750 The inherent ~~limitation in limitations of~~ reduced-complexity ~~modelling approach does models do~~ not preclude ~~the adoption of using RCMs where the aim is to represent meso-scale system behaviour at the mesoscale,~~ rather than ~~to make making~~ reductionist predictions that are theoretically more accurate in quantitative terms. Reproducing ~~the morphodynamic processes at each scale required requires~~ necessarily some forms of simplification, regardless of the level of complexity of the model adopted, ~~and in CFD models as well~~. Nevertheless, this ~~cannot be considered a convincing is not sufficient~~ reason to ~~neessarily~~ ~~calling call~~ into question ~~whether explanation the usefulness of river behaviour based on applying~~ this kind of ~~model have any application in the models in~~ real world ~~situation~~. In ~~the~~ light of the results ~~presented in of~~ this work and of the limitations ~~facied anyway by the of~~ reductionist ~~alternative~~ approaches (Williams et al., 2016), we believe that RCMs, and ~~C-L model specifically,~~ ~~remain an the C-L model are~~ attractive ~~option options~~ for simulating river evolution ~~over historical time period historically~~ and ~~into the~~ future ~~scenarios~~, that is at the scale of interest for river management.

760 This work presents another case study in which an RCM has given realistic outputs in a large gravel-bed river, especially in terms of evolutionary trajectories. The suitability in reproducing macro morphological features and meso-scale processes should not be questioned any longer (Nicholas, 2013b). The capability to model small-scale phenomena remains open for RCMs as for all CFDs that try to reproduce phenomena deeply influenced by initial and boundary conditions, for which a data

gap persists for future scenario application in natural contexts where the addition of modelling details does not guarantee a significant reduction of the overall uncertainty associated to the model results.

This work presents another case study in which an RCM provided realistic outputs regarding a large gravel-bed river, especially in terms of evolutionary trajectories. The suitability in reproducing macromorphological features and mesoscale processes should no longer be in doubt (Nicholas, 2013b). The capability of modelling small-scale phenomena remains open for RCMs as for all CFDs that are applied to reproduce phenomena deeply influenced by initial and boundary conditions, for which a data gap persists for future scenario applications in natural contexts where the addition of modelling details does not guarantee a significant reduction of the overall uncertainty associated with modelling results.

6. Conclusions

Hydrological and morphodynamic models have been applied to assess the long-term geomorphic effectiveness of controlled floods strategies. The simulated future scenarios (with a duration of 25 years) show that: (i) none of the CFs strategies can provide significant long-term morphological benefits and is able to reverse the ongoing channel width trends; (it is worth noting that the selected CFs are feasible and it is unlikely that higher or more frequent floods could be released); (ii) few small number of high magnitude floods (i.e. SC4) provide slightly better morphological recovery than small do yearly low-magnitude floods (i.e. SC2 and SC3), also at a as well as having significantly lower operational cost (the cumulative volume released in SC4 is an order of magnitude lower than in SC2 and SC3). These results suggest that this kind of strategy does not represent a solution for morphological recovery in braided rivers strongly and historically impacted braided rivers.

The This study confirms the suitability of the RCMs for modelling future long-term future scenarios at spatial and temporal scales still hardly that are not well supported by 2D-3D CFD morphodynamic models. From a the morphological point of view perspective, the C-L model has proven to be able to reproduce the capable of reproducing variations in channel width variation, to preserve, preserving the complexity of morphological braiding complexity, including the vegetation dynamics, and to estimate reasonably the estimating average bed load sediment yield. The model performance assessment shows significant improvements of that the C-L model in comparison to performs significantly better than previous CAESAR model version versions (Ziliani et al. 2013). The application of this While the RCM does not provide insights into the spatial and temporal scales of interest for a traditional reductionist approach (e.g., single branch and bar dynamics, local bank erosion) however, it provides does provide useful indications for management of braided rivers at meso-seales mesoscales.

790 Code availability

The CAESAR-LISFLOOD model code is freely available at: <https://sourceforge.net/projects/caesar-lisflood/>

Data availability

LiDAR data and aerial photos (2003) are available upon request at the Autorità di Bacino delle Alpi Orientali.

Hydrological data are available upon request at the Environmental Regional Agency (ARPA Veneto).

795 2009 aerial photos and cross sections are freely available by contacting the authors.

Supplement

The supplementary material related to this article is available online at: <http://researchdata.cab.unipd.it/id/eprint/157>

Author contribution

800 LZ and NS designed the research. LZ performed most of the analyses. GB aided as expert in hydrology and hydrological modelling. LM provided guidance on sediment transport. All authors jointly contributed to the discussion and interpretation of the data. The paper was prepared by LZ, with contributions from NS, GB and LM. NS managed and coordinated research activities.

Competing interests

The authors declare that they have no conflict of interest.

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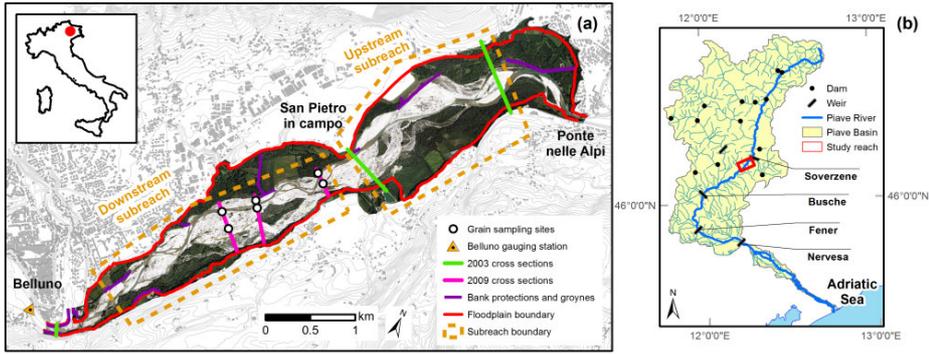
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Figure 1. (a) Study reach location. (b) Water infrastructure system in the Piave Basin



1205 Figure 2. (a) June 1st 1995 - December 31th 2009 hourly discharge series used for the scenarios runs; (b) Hourly discharge series measured at Belluno gauge station used for the calibration run (July 5th 2003 to August 5th 2009)

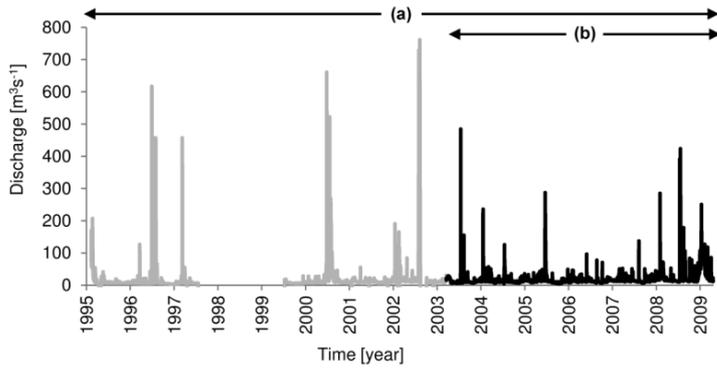
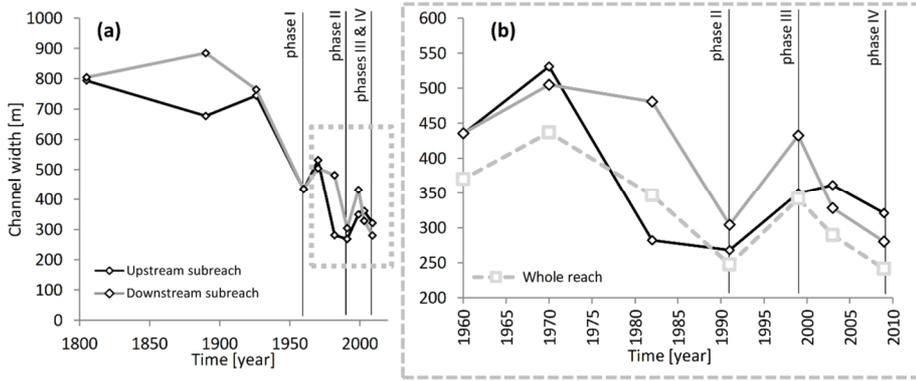


Figure 3. (a) Changes in channel width over the period 1805–2009; (b) changes in channel width over the period 1960–2009



1210 Figure 4. Effect of the anthropogenic regulations in the Piave River at Belluno cross section. Comparison between the pdf $p(Q)$ (a) and the cumulative distribution $D(Q)$ (b) of observed streamflow in the period 1995–2009 and the natural streamflow pdf and $D(Q)$ predicted by the model developed by Botter (2010)

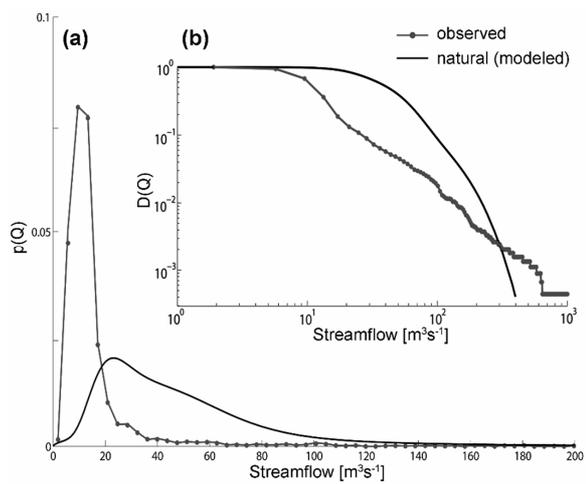


Figure 5. Model performance assessment at the end of the calibration runs (mid frame – see Supplementary material file for the others frames): (a) wet area (b) vegetated area and (c) active channel digitalized using 5th August 2009 aerial photos; (d) overlay between modeled and observed flowing channel; (e) overlay between modeled and vegetated area; (f) overlay between modeled and observed active channel; (g) wet area performance index calculation; (h) vegetated area performance index calculation; (i) active channel performance index calculation

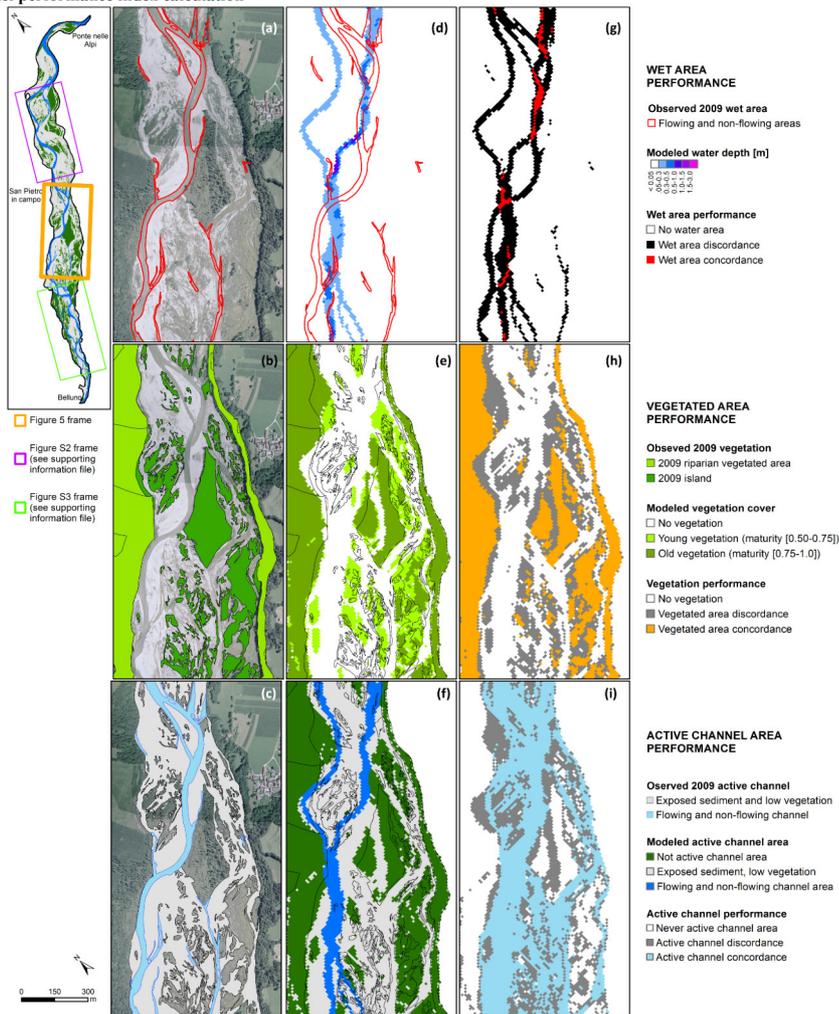


Figure 6. (a) 2009 real channel, (b) 2009 modeled channel used as starting point for the scenario runs; (c-f) Scenarios 1-4 results at the end of the runs (2034)

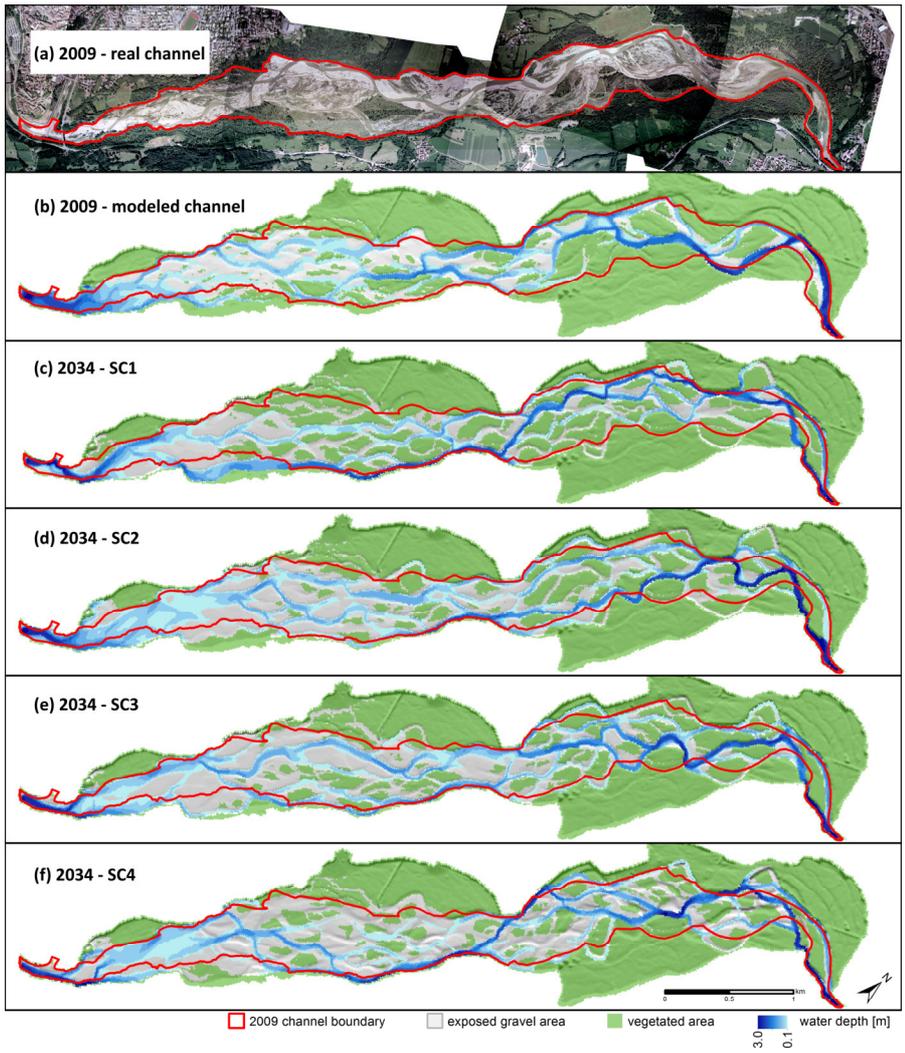
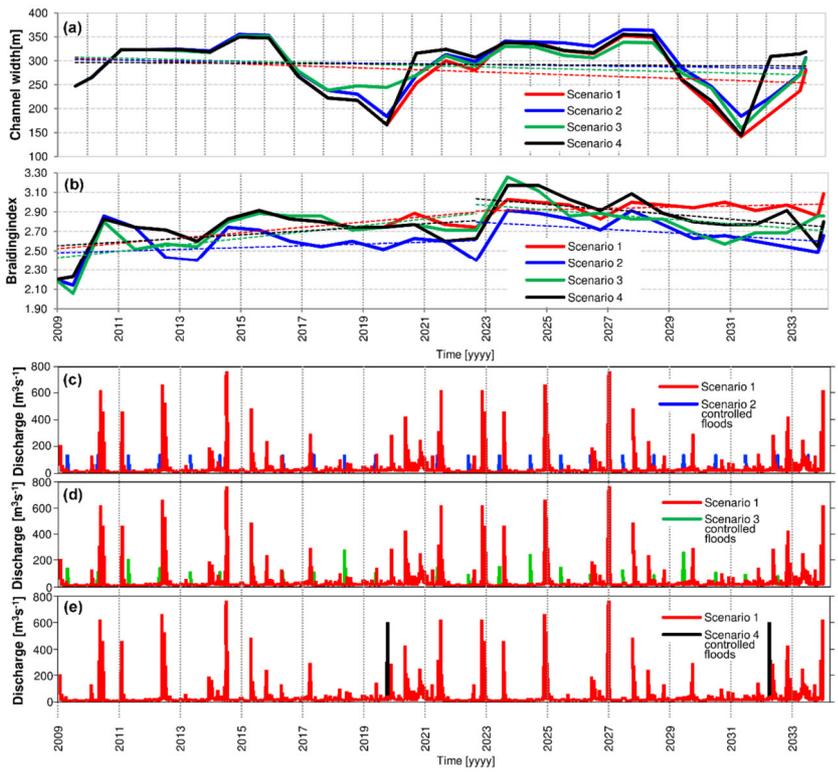


Figure 7. Scenario results expressed in terms of channel width (a) and braiding index (b) variations, coupled to the simulated upstream inflow series with controlled flood releases: (c) scenario 1 and 2, (d) scenario 3, (e) scenario 4



1225 **Table 1. Summary of the data used for the historical adjustment analysis and modelling activity**

Type	Source	Data	Main characteristics	Location
Aerial photos	Autorità di Bacino delle Alpi Orientali	July 5th 2003	Resolution: 30 cm	The whole study reach
	Department of Geosciences, University of Padova	August 5th 2009	Resolution: 15 cm	The whole study reach
Cross section survey	Autorità di Bacino delle Alpi Orientali	2003	DGPS topographic survey.	See Fig. 1
	Department of Geosciences, University of Padova	March 2009	RTK DGPS topographic survey	See Fig. 1
DEM / DSM	Autorità di Bacino delle Alpi Orientali	July 5th 2003	LiDAR DEM / DSM, grid dimension: 2 m	The whole study reach
Bed grain size measurements	[Tomasi, 2009]	July 2008	6 samples. Volumetric method. Sampled depth 0.5 m	See Fig. 1

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Table 2. Main hydrological characteristics of the four scenarios

Scenario	Controlled flood releases frequency	Maximum controlled flood peaks [m ³ s ⁻¹]	Controlled flood peaks range [m ³ s ⁻¹]	Recurrence interval maximum controlled flood [year]	Controlled flood duration [days]	Cumulative volume released per flood [Mm ³]	Cumulative volume released per scenario [Mm ³]
SC1 [baseline scenario]	No releases	No releases	No releases	-	-	0	0
SC2	One per year	135	Constant	1.08	5	58.32	1.46x10 ³
SC3	One per year	276	[80 - 276]	1.4	5	58.18	1.45x10 ³
SC4	In case of average channel width narrowing under 200 m (2 times in 34 years)	600	Constant	5	1	51.84	1.04x10 ²

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Table 3. Description of the CAESAR-LISFLOOD model calibrated factors

Factor ^a	Investigated range		Calibration setting
	Min	Max	
Lateral erosion rate [-]	0.002	600	30
Maximum erosion limit [m]	0.001	0.075	0.01
Active layer thickness [m]	0.004	0.28	0.04
Number of passes for edge smoothing filter [-]	30	200	150
Water depth above which erosion can happen [m]	0.01	0.15	0.15
Bed load solid transport formula ^b	0	1	1
Vegetation critic shear [Nm ⁻²]	0.7	180	0.9
Vegetation maturity [year]	0.06	20	4
Courant number [-]	0.1	0.7	0.2
Input/output difference allowed [m ³ s ⁻¹]	1	5	5
In-channel lateral erosion rate [Nm ⁻²]	1	30	10
Slope for edge cells ^d [-]	-	-	0.005
Sediment proportion recirculated ^d [-]	-	-	1

^a All factors are configurable using the graphical user interface

^b 0 - Einstein (1950) formula; 1 - Wilcock and Crowe (2003) formula

^c Factor not included in the old CAESAR model version

^d Factor not calibrated

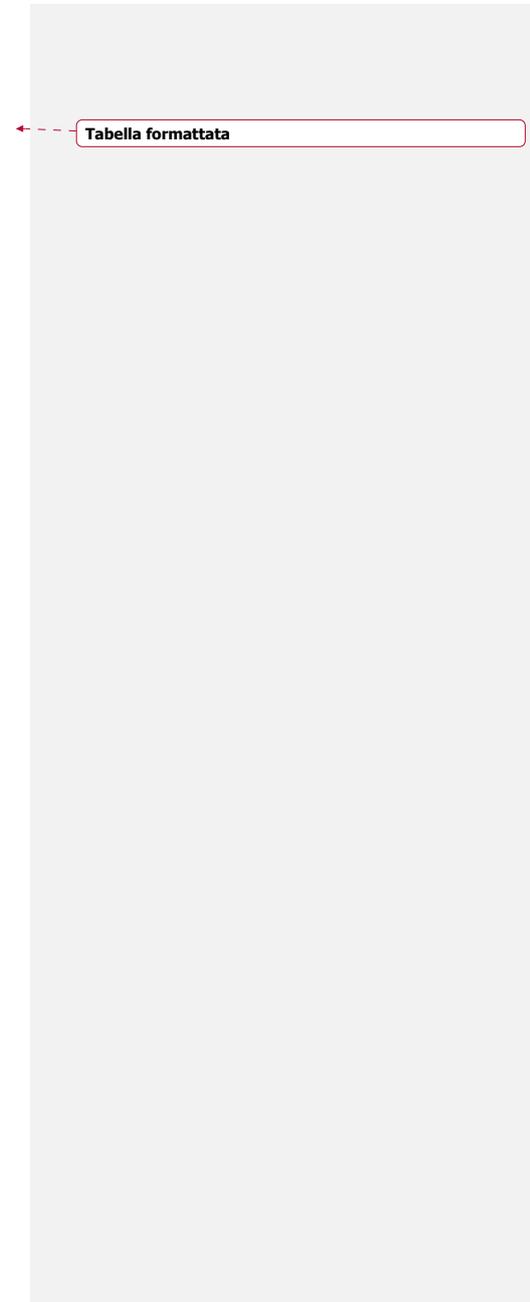


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Table 4. Results of CAESAR-LISFLOOD calibration

	Observed active channel 2009 [rasterized data - 10x10 m]	CAESAR-LISFLOOD result
Active channel width [m]	241	247
Active channel width change in 2003- 2009 period [m]	- 35	- 29
Wet are width [m]	51	66
Braiding Index [channel counted]	1.69	1.71
Performance active channel [%]		54.2 %
Performance vegetated area [%]		69.7%
Performance wet area [%]		15.7%

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