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

General Response to reviewers

Dear Editor,
We thank the reviewers for their thoughtful and useful comments. All comments are 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.
Regards

Nicola Surian

April 30, 2020

Response to reviewer 1 (Anonymous)

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.

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 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 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.

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
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).

(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.

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.

(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.

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
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 m$^3$/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).

Figure 1. This new run shows the effects of a large flood (peak value = 1600 m$^3$/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.

(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?

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).

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 Ziliani, Nicola Surian, Gianluca Botter, Luca Mao

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

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

Abstract. Most Alpine rivers have undergone strong alteration of 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 through the reintroduction of channel-forming discharges. The aim of this work is to assess the morphological changes induced in the Piave River (Italy) by two different controlled flood strategies, the first characterized by a single artificial flood per year and the second by higher magnitude, but less frequent, floods. The work was carried out 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 modelling allowed the assessment of morphological changes for four long-term scenarios (2009-2034). The scenarios were defined 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 controlled flood scenarios to a baseline scenario (i.e., no controlled floods) it turned out that artificial floods had little effect on channel morphology. The highest channel widening (13.5%) resulted from the release strategy with high-magnitude floods, while the other strategies produced lower widening (8.6%). Negligible change was observed in terms of braiding intensity. Results pointed out that controlled floods may not represent an effective solution for morphological recovery in braided rivers with strongly impacted 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 flow 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 ecological (Collier, 2002; Céréghino 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...
Nowadays, dam construction is now considered a viable strategy to support the increasing 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 volumes greater than 0.5 km$^3$ 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 the magnitude and temporal trends in alterations of river flow regimes induced by hydraulic infrastructure (Richter et al., 1996; Richter et al., 1997; Martinez Santa-María et al., 2008; Yin et al., 2015). As well, extensive sediment monitoring efforts 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 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 on sediment fluxes have been assessed on reaches directly impacted by damming (Graf, 1980; Williams and Wolman, 1984; Gaeuman 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 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, reduced braiding intensity, and coarsening of bed sediment. Since the 1970s, growing attention has been paid to 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 or removing dams to reproduce some aspects of the natural regimes (flow and sediment), via increasing or recovering seasonal baseflow, 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 releases (Melis, 2011; Olden et al., 2014). In other cases, the management strategies have focused directly on recovering morphological features through dam removal (Poulos et al., 2014; O’Connor et al., 2015), or mechanically removing vegetation (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 the costs of these programs, decision-makers are increasingly requesting the scientific
community to develop appropriate tools to identify and control the factors that cause channel alterations, and (ii) to assess the effectiveness of management programs. Environmental agencies in several countries require dam operations to respect release protocols in an attempt to mitigate adverse impacts on downstream ecosystems (Schmidt and Wilcock, 2008; Olden and Naiman, 2010; Watts et al., 2011; Konrad et al., 2012). Although successful empirical experiences do exist (Souchon et al., 2008; Konrad et al., 2011), robust predictive tools and models are urgently needed to predict channel responses to dam operations and interruption of the longitudinal river continuum (Bliedner 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 be achieved 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 numerical models, either Computational Fluid Dynamic (CFD) models or Reduced Complexity Models (RCMs) (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 apply an 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 applied to a 7-km-long braided reach of the Piave River (Italy), one of the most heavily and historically regulated river systems in Italy.

We applied the CAESAR – LISFLOOD model (hereafter C-L) to assess the morphological effects related to two different kinds of flow regime management strategies: the first is characterized by yearly controlled floods with peaks able to transport sediments, while the second with less frequent higher magnitude floods (i.e., floods with 5-year recurrence interval) 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 “renaturalization” 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 natural scenario 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 than the maximum volume stocked in the reservoirs existing upstream of the studied reach.

This paper aims to address 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) to assess 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, and the hydrological model, (Botter et al., 2010; Coulthard et al., 2013), and the criteria adopted for 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 alterations, (iii) the CAESAR-LISFLOOD calibration, and (iv) the simulations of three different Controlled Floods (CFs) 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 northeastern Italy, and 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 approximately 1,350 mm. Significant annual variations in the Annual rainfall amount have been measured and were noted over the 20th century, but without any statistically relevant trends (Surian, 1999).

Like most of the Italian Alpine 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 Piave basin has experienced a rapid increase in anthropogenic exploitation, with the construction of a series of dams and reservoirs between the 1930s and 60s. There are now 13 major reservoirs (Botter et al., 2010) built along the main stem and some tributaries. A complex regulation scheme exists in place for details see Surian, 1999; Botter et al., 2010) designed to maximize production of hydroelectric power and the provision of 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 has also experienced strong changes due to land use modifications. Especially since the 1950s, the development of industry and tourism boosted the abandonment of traditional agricultural cropping activities 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 reducing sediment fluxes since the 1960s. Furthermore, human pressure on the river channel dynamics has also resulted from construction of bank protection structures and torrent control works. As a result of these bank protection works, 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 studied 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 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, being 241 m on average, while the fluvial corridor width, defined by the presence of Holocene fluvial terraces, ranges between 106 and 1,110 m, being 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 studied reach has undergone notable lateral adjustments (narrowing up to 66%), but no significant changes in channel pattern. In terms of bed-level changes, two phases have been identified: 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 studied reach. River channel, islands, flowing channels and bank protection structures were digitized using the available aerial photos and terrain models covering the studied reach (i.e., 2003, 2009 - Table 1). The analysis was carried out using ArcGIS 10.2. The braiding index was calculated using the average number of branches across the river (Ashmore, 1991; Egozi and Ashmore, 2008). The historical analysis carried out by Comiti et al. (2011), which covered the period 1805 – 2006, 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 the aerial photos 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 obtain bed elevation, the water depth was estimated through the application of 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. 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 calibrated by direct
measurements 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.

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 (\(D_{50} \sim 24.5 \text{ mm}, D_{15} \sim 2 \text{ mm}, D_{84} \sim 77 \text{ mm}\)) with nine size classes, as required by the C-L morphodynamic model.

### 3.2 Analysis of the hydrologic regime of the Piave River

A variety of 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 (Villi and Bacchi, 2001; Botter et al., 2010; Comiti et al., 2011), such analysis has been hampered by (i) the unavailability of a long-term flow data series, and (ii) the difficulty in distinguishing between natural and artificial 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 m\(^3\)s\(^{-1}\).

Furthermore, their analysis showed that the discharge with a recurrence interval of 2 years was not statistically different if calculated separately for pre- and post-regulation periods (1954 was used as the separation date between the periods). However, higher frequency peak discharges of the more frequent events (RI ≤ 1.5 year) showed a reduction after 1954.

Similar outcomes have also been reported in Picco et al. (2016). Botter et al. (2010) offered a more detailed analysis of the impact of regulation on river regimes, where a physically-based modelling approach was applied to assess the alterations in the streamflow regime observed in various cross sections of the drainage network downstream of dams and weirs. The authors 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 to smaller, unregulated sub-catchments (that allowed verifying the capability of the model to reproduce the natural streamflow regime), the authors applied the model also to several regulated sections of the Piave River, including Soverzene (about 5 km upstream from Ponte nelle Alpi, Fig. 1), in order to evaluate the natural flow regime in regulated cross-sections and, based on the difference, the effect of regulation on the statistical 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 as 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 the which are modelled as a marked Poisson process with mean depth \(\alpha\) and mean frequency \(\lambda\). The parameter \(\alpha\) identifies the average intensity of
daily rainfall events, while \( \lambda \) is the frequency of flow-producing events, which is smaller 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, are embedded in \( \lambda \). Additionally, in this framework, streamflow recessions between flow pulses are assumed to 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 \( \lambda/k \) and scale parameter \( \alpha k \). 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 presence of snow dynamics 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 Schaefli 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 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 obtain guidelines for devising meaningful strategies of the flow regime management. In particular, the daily streamflow series used in this study has been recorded from 1995 to 2009 at Belluno gauging station located at the downstream section of the studied reach (Fig. 1). The highest flood event peaks observed in the reference periods (1996, 2000 and 2002) were checked and modified combining data from Belluno and discharge measurements at the Soverzene weir (Braidot, 2003).

### 3.3 The CAESAR-LISFLOOD model

Over the last 20 years the application of hydro-morphodynamic physically-based numerical models (generally known as Computational Fluid Dynamic models, CFD) has mainly been focused on laboratory-idealized channel configurations at the laboratory scale (Wu et al., 2000; Defina, 2003; Rüther and Olsen, 2005; Abad et al., 2008) or referred to in the morphological 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 range of application of these models reflects 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 scales. This limitation has driven to develop the development of alternative two-dimensional alternative models that 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 reduced-complexity models (RCM – Murray, 2007; Nicholas et al., 2006; Nicholas et al., 2012). These models have a common solution to the problem of which is the adoption of simplified hydrodynamic and sediment transport equations derived from the abstractions of the governing physics.
A major advantage of RCMs is their computational efficiency, allowing to simulate 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 these models has received relatively little attention (Nicholas, 2009; Nicholas, 2013b; Ziliani et al., 2013), and there have been only a few studies that deal with the high sensitivity of these models to the grid resolution of the computational domain (Doeschl-Wilson and Ashmore, 2005; Doeschl et al., 2006; Nicholas and Quine, 2007). Despite the progress made in several works (Nicholas, 2009; Nicholas, 2013a), there are still few applications to 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) 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 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 model. Ziliani et al. (2013) submitted CAESAR to a rigorous and objective performance evaluation procedure, and showed that (i) CAESAR can be a very powerful tool for modeling spatial and temporal scales supported by 2D–3D CFD models, (ii) it can be very useful for setting “what-if scenario” strategies over meso- and meso-temporal scales, and (iii) it provides reliable bedload sediment budget estimations. From a morphological point of view, Ziliani et al. (2013) have shown that CAESAR is able to reproduce the average change in channel width, but performs poorly in reproducing the braided in-channel pattern 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 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 C-L model has not been fully evaluated referring to real case study data. The embedded erosion and deposition modules have been tested at reach (Feeney et al., 2020) and deposition modules have been tested at 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 geometric 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 Weil, 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 uncertainty proportionally to the increased complexity of the modeled processes 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) include all the limitations inherent in calibration of this type of model, and (ii) are mainly based on field and remote sensing data (Nicholas, 2010). There are currently no standard international methods for the calibration and validation of fluvial morphodynamic models (Mosselman, 2012), and those previously proposed are typically designed for hydrodynamic CFD models (ASME, 1993; Lane et al., 2005). Furthermore, the calibration of RCMs has to be performed keeping in mind that a calibrated RCM model can be empirically adequate (Van Fraassen, 1980) and its validation is 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 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 Zilli 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.
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 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 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 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

In rivers, Water management of historically regulated, water management, rivers, may be oriented to restoring the flow regime to close to the prior that before impact conditions, typically aiming to reactivate at reactivating physical processes linked to specific components of the flow regime (Wohl, 2011). Nevertheless, existing priorities in uses of the water 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 volume of water released for partial restoration goals. Olden et al. (2014) provided a systematic review of flood experiments to evaluate globally the success of this practice in flow regime management. They considered 113 flood experiments in 20 countries were reviewed revealing and found that only 11% of the case studies were aimed directly at morphological effects and about 80% of the experiments involved only low magnitude flow events. Most experimental flow releases in these were focussed on a biological variables (primarily fishes), aquatic organisms (Konrad et al., 2011) and re-establishing vegetation (Shafroth et al., 2010), rather than on abiotic factors (e.g., channel morphology) (Wohl et al., 2015b). The so-called “environmental flows” and “Green Hydro” are concepts widely accepted even though the concepts that refer mainly to quantity, timing, duration, frequency and quality of water releases,
as required to sustain freshwater, estuarine and near-shore ecosystems, according to social interests (Acreman and Ferguson, 2010; Rivas et al., 2017).

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

Controlled floods and removing vegetation actions are expensive and potentially expensive can preclude other positive feedback effects. It is therefore worthwhile to preliminary evaluate and test other positive feedback effects. It is therefore worthwhile to preliminary evaluate and test these kinds of actions into account the morphological effects of different channel-forming discharges (Surian et al., 2009). As emphasized by Rathburn et al. (2009), flow releases from dams must exceed a series of thresholds to be morphologically effective. Four discharge thresholds of increasing intensity should be identified in a morphological recovery/conservation plan, each capable of activating a specific morphological process: (i) the mobilization of interstitial sediment essential for the hyporheic exchange; (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 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 available flow availability, assuming the natural flow regime as a reference. In this work, the scenarios of flow regime management defined in reference to three flood threshold levels that partially match those proposed by Rathburn et al. (2009): (i) the full in-channel transport discharge assumed to be able to mobilize the sediment; (ii) the bankfull discharge to maintain the natural bedforms; and (iii) the overbank discharge to affect the main lateral units by inundation. A field study conducted in the reach using painted sediments similar to those used in Mao and Surian (2016) and Mao et al. (2017) allowed to estimate the first reference threshold at about 80 m$^3$s$^{-1}$ (RI $\leq$ 1 year, full transport discharge able to mobilize sediment, 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 m$^3$ s$^{-1}$, and corresponds to a 2.5 years RI, consistent with other literature references in the literature (Leopold, 1994). Only data > 1,000 m$^3$ s$^{-1}$ floods were identified asableto be capable of completely inundating the oldest island and overflowing locally into the recent fluvial terraces.

Four simulation scenarios, each were considered, all covering the same 25-year-long period (2009-2034), were explored (Table 2). The first scenario (i.e., the baseline scenario, SC1) corresponds to the current condition, characterized by a strongly altered flow regime. In this case, the discharge series measured at the Belluno gauge station has been repeated twice. Scenarios 2 (SC2) and 3 (SC3) were both set up as a flow regime strategy characterized by one CF per year. In SC2, the yearly CF in SC2 had a constant value of 135 m$^3$ s$^{-1}$ (RI = 1.08 years). This value has been calculated as the average of the maximum annual floods observed in 1995-2009. This was higher than the reference threshold discharge, i.e. the full in-channel transport discharge (80 m$^3$ s$^{-1}$). In SC3, the yearly CF values for SC3 were randomly selected above the threshold discharge using the natural streamflow pdf estimated by the model (minimum value = 80 m$^3$ s$^{-1}$, maximum value = 276 m$^3$ s$^{-1}$, RI = 1.4 years). In this case, the average value of all the CF values was found to be equal to the SC2 yearly CF discharge for SC2, assuming values included in the [80 – 276] m$^3$ s$^{-1}$ range. 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 with the released peaks is increased from 0.025 (observed altered regime) to 0.04, being the natural reference value 0.14. Scenario 4 (SC4) was planned to represent a different management strategy, consisting 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 by a one-year step downstream the SC4 simulation, only two CFs were released, one in 2020 and the other in 2032, respectively. The released discharge was fixed equal to 600 m$^3$ s$^{-1}$ (RI 5 years), ranging between the second and the third reference threshold discharges discussed above, so that it was surely able to maintain the channel and undoubtedly be capable of maintaining in-channel bedforms dynamics, while completely avoiding any hydraulic risk, damages and damages in the overbank units (i.e., recent terraces), locally occupied by secondary roads and cultivated fields.

All of the CFs have here been released in November, avoiding to occur during winter while overlapping floods were avoided. All the scenarios made use of the same model setting, which was obtained in the calibration phase; using the 2009 calibration dataset in raster format as the initial boundary conditions (i.e., bed elevation, vegetation cover, grain size and 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 than the maximum seeded volume in the reservoirs existing upstream from the studied reach (90.8 Mm$^3$). SC2 and SC3 required similar volumes of about 58 Mm$^3$ of water, corresponding to about 1.45x10$^7$ Mm$^3$ to cover the whole entire scenarios.
period. SC4 represents the cheapest scenario because it needed 51.8 Mm³ per year and 104 Mm³ globally, one order of magnitude lower 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 of San Pietro in Campo, where the river is naturally more confined (Fig. 1). The reach was divided into two sub-reaches to better describe the morphological adjustments over the 1800-2009 period. The trends in average width are similar for both sub-reaches, 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 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, 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 (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 the flood in 2002, the river 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 studied reach over the last 200 years. While widening during phase III was likely due to the termination of in-channel gravel mining (Comiti et al., 2011), the most recent phase of narrowing (phase IV) was likely due to the absence of major floods (see also Fig. 2).

4.2 Flow regime alterations

The comparison 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 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 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 m³/s 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 at improving the current flow-regime should be implemented as needed, (ii) this strategy should compensate the expected low
morphological dynamism of the river caused by the decreased occurrence of discharges able to mobilize sediments and hence producing significant morphological changes in the studied reach. It is worth noting that the hydrological model underestimates the frequency of the highest flows (i.e., discharges larger than 300 m$^3$/s) because all the non-linearities of the hydrological response (e.g., the presence of different flow components such as surface runoff) are neglected in this version of the model (Busso et al., 2015). As a consequence, the probability associated with the highest flows in regulated conditions is larger than the corresponding value estimated by the stochastic model for the natural setting. However, this limitation, however, does not have any significant consequences 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 in Ziliani et al. (2013) and Coulthard et al. (2013) have been taken as a reference to achieve the C-L calibration. According to the results of the sensitivity analysis in Ziliani et al. (2013), the lateral erosion rate and maximum erosion limit have been assumed as 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 "trial-and-error" calibration strategy (i.e., 175 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 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 is (i) the vegetation performance index ($F_{\text{veg}}$), (ii) the wet area performance index ($F_{\text{wet}}$) and (iii) the active channel performance index ($F_{\text{c}}$). In addition, several planimetric features were 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 material" file) show a very good performance (performance class as defined in Henriksen et al., 2003; Allen et al., 2007) for both the vegetation cover ($F_{\text{veg}} = 69.7\%$) and the active channel area ($F_{\text{c}} = 54.2\%$). Output values of the active channel width and braiding index values confirmed these results. The difference between the real and modelled 2009 active channel width (6 m) is less than the input DEM cell size (10 m), and the modelled braiding index value (1.71) is very close to the real value (1.69). The model performance is poor only in reproducing the flowing channel position ($F_{\text{w}} = 15.7\%$), which partially confirms the results presented in Ziliani et al. (2013).

In order to integrate the morphological performance evaluations, we carried out an estimation of the mean annual bed load sediment yield at the downstream end of the reach and along the whole 2003-2009 period. The modelled annual to integrate morphological performance evaluations. Average modelled bed load sediment yield resulted of about in the 2003-2009 period was around 21.5 x 10$^3$ m$^3$/yr. The yield varies significantly along the reach (up to 30%) taking into account with higher yearly values in the sub-reach upstream San Pietro in Campo. Significant differences exist between the maximum and minimum annual values. The 2006 minimum corresponds to an
average annual sediment yield of is about 260 m$^3$ yr$^{-1}$ versus the 2008 maximum of about 53.3 x 10$^3$ m$^3$ yr$^{-1}$.

Such 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).

4.4 Channel response to flow regime management strategies: scenario results

Channel adjustments induced by each of 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 greater than in SC1 (the baseline scenario). On average, during the whole scenario period, SC2 and SC4 produced comparable channel widening of about 13.5% at the end of the simulated period. The maximum annual widening was observed in SC4 (~ 120 m in 2033), followed by SC3 (~ 77 m in 2020) and SC2 (~ 43 m in 2032 - Fig. 7).

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 an average of 6-7 years and has an 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 m$^3$s$^{-1}$ (RI ~ 1.9 years) occur, channel width follows a quasi-steady trend and is greater than 300 m. Instead, channel width decreased during the following periods (2017-2021 and 2029-2031) affected by lower magnitude floods (200 m$^3$s$^{-1}$ maximum peak value), channel width shows decreasing trajectories. Over the whole 25 years, SC1 provided 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% greater than width in the baseline scenario.

The braiding index indices of Scenarios 2-4 were similar to or lower than that of SC1. SC4 revealed the most similar scenario closest to that of SC1, with an average BI in-time averaged value equal to 2.78, only which was slightly lower than that of SC1 (1.5%). During SC2 we measured a significant decreasing trend in SC2 but in the BI values compared to SC1 (-7.3%, 0.21 BI unit – Fig. 7), although these differences were small. The behaviour of trajectories, braiding intensity shows different behaviour in comparison to channel width, as in that there are no clear oscillations phases but was one period (from 2009 to 2023) with any 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 did not show an inverse trend after 2023, while SC2 scenario has a very anomalous trend showing a consistently
lower BI value steadily lower than the other CF scenarios, while SC3 and SC4 show a good agreement in the and very similar BI mean values.

5. Discussion

5.1 Geomorphic effectiveness of controlled floods

Comparing the several insights can be obtained from comparing future scenarios to the historical evolutionary trajectory (Fig. 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 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 scenario) 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 Section 4.1) seems to follow an oscillatory evolution with half the frequency of the oscillation modelled between 2009 and 2034, (iv) there is a good correlation between the variation of channel width and the flow regime reproduced in the future scenarios, whereas this is not always the case in the past evolution. This point is exemplified by the rather major 2002 flood event, which did not re-widen the river at the levels of 1999 (about 342 m), despite being relevant and significant in terms of magnitude (13-year RI). Indeed, the width the following year (2003) was approximately 289 m, about 15% less than in 1999. This suggests that the study reach, after a period (phases I and II in Fig. 3) of morphological instability characterized by a prevalent narrowing tendency, has reached a new equilibrium configuration characterized by periodic oscillations in channel width. Similar 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 intercomparison of our four simulations shows that a few high magnitude floods provide slightly better morphological recovery/conservation than small yearly floods, and at a significantly lower operational cost. Therefore, SC4 should be preferred to SC2 and SC3 from a purely morphodynamic point of view. Nevertheless, results suggest that none of the CF scenarios are able to significantly change long-term channel width and braiding intensity trends, CF releases have no significant morphological benefits and do not represent a solution for the rehabilitation of braided rivers that suffered strong and historical impacts in terms of flow and sediment supply regimes. It is worth noting that the selected CPs 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 results partially confirm the outcomes of Hicks et al. (2003) referring to 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 condition. The cost of CFs is probably smaller than that of alternative strategies focused on increasing sediment supply, such as sediment augmentation, because flood releases commonly can be performed without redesign of reservoir structures. Nevertheless, reintroduction of flood flows implies “loss” of stored resources for other purposes (e.g., hydroelectric production, and supply of drinking or irrigation water). 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), this kind of strategy should be 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 flow and sediment regimes: (i) none of the tested controlled flood strategies was able to 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 evolutionary trajectory similar to that induced by the controlled 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.

### 5.2 Assessment of CAESAR-LISFLOOD performance

In Ziliani et al. (2013) the authors concluded that the main factors causing the poor morphological response of CAESAR are: (i) the DEM cell size, which has been pointed out 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 period removal, and therefore the 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 refinement included in the LISFLOOD-FP module (one of the most recent and advanced Reduced Complexity Hydraulic Model schemes), (ii) the adoption of input data of higher quality (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, including the pioneering and complex 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. $D_{50}$ changed from 24.9 mm to 22.7, 24.3, 22.7, 24.3, 22.7 mm).
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 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 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 the calculation of bedload transport.

The C-L model may be considered a useful tool in the search of an effective combination of simplicity and physical realism in the context of reduced-complexity modeling, overcoming some of the previous problems associated with earlier simplified hydrodynamic simplification issues. The encouraging results achieved in this case study seem to justify the effort faced in such further development of this RCM. Although, the physical realism of flow and morphodynamic rules can remain unsolved at small scales (i.e., below the DEM cell dimension), the improvements of the C-L model response at reach scales compared to the older CAESAR model is evident.

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 flood strategies. The simulated future scenarios (with a duration of 25 years) show that: (i) none of the CF strategies can provide significant long-term morphological benefits and is able to reverse the ongoing channel width trend; (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 yearly low-magnitude floods (i.e. SC2 and SC3), also at 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. The study confirms the suitability of the RCMs for modelling future long-term scenarios at spatial and temporal scales still hardly supported by 2D-3D CFD morphodynamic models. From the morphological point of view, the C-L model has proven to be able to reproduce the capability of reproducing variations in channel width variation, preserving the complexity of morphological braiding complexes, including the vegetation dynamics, and to estimate reasonably the average bed load sediment yield. The model performance assessment shows significant improvements of the C-L model in comparison with previous CAESAR model versions (Ziliani et al. 2013). The application of 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 useful indications for management of braided rivers at mesoscales.

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).

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
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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Figure 1. (a) Study reach location. (b) Water infrastructure system in the Piave Basin
Figure 2. (a) June 1st, 1995 - December 31st, 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.
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 digitized 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
| 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            |
| Scenario | Controlled flood releases frequency | Maximum controlled flood peaks [m³/s] | Controlled flood peaks range [m³/s] | Recurrence interval maximum controlled flood [year] | Controlled flood duration [days] | Cumulative volume released per flood [Mm³] | Cumulative volume released per scenario [Mm³] |
|----------|-----------------------------------|--------------------------------------|----------------------------------|-----------------------------------------------|-----------------------------|------------------------------------------|---------------------------------------------|
| SC1 [baseline scenario] | No releases | No releases | No releases | - | - | 0 | 0 |
| SC2 | One per year | 135 | Constant | 1.08 | 5 | 58.32 | 1.46x10³ |
| SC3 | One per year | 276 | [80 - 276] | 1.4 | 5 | 58.18 | 1.45x10³ |
| SC4 | In case of average channel width narrowing under 200 m (2 times in 34 years) | 600 | Constant | 5 | 1 | 51.84 | 1.04x10² |

Table 2. Main hydrological characteristics of the four scenarios
Table 3. Description of the CAESAR-LISFLOOD model calibrated factors

| Factor *                        | Investigated range | Calibration setting |
|---------------------------------|--------------------|---------------------|
|                                 | Min    | Max    |                      |
| Lateral erosion rate [-]        | 0.002  | 600    | 30                  |
| Maximum erosion limit [m]       | 0.001  | 0.75   | 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 $^c$ [-]   | -      | -     | 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
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 %                 |