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RESEARCH ARTICLE

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Channel forms and vegetation adjustment to damming in a Mediterranean gravel-bed river (Serpis River, Spain)

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Abstract

This paper focuses on the analysis of changes observed in channel morphology in the Serpis River (Alicante, Spain), a gravel-bed river dammed since 1958. The paper analyses flow series and several aerial images, prior and subsequent to dam construction, to analyse changes in channel morphology and vegetation colonisation using Geographical Information Systems (GIS) techniques. Results show a concatenation of morphological changes throughout an adjustment sequence (60 years), which started with the transformation from wandering to single thread channel pattern, was followed by a slow vegetation encroachment, and culminated with the stabilization of channel migration. The role of vegetation (particularly Salicaceae species) has been critical in controlling floods' effectiveness, reducing river mobility and shifting, and consolidating a channel planform model adapted to the post-dam flow conditions.

KEYWORDS

channel forms, channel mobility, evolutionary trajectory, hydrological changes, river damming, Salicaceae species, vegetation encroachment

1 | INTRODUCTION

Nowadays, there is a wide consensus on the three main alterations caused by reservoirs in rivers (Braatne, Rood, Goater, & Blair, 2008; Brandt, 2000; Rood, Braatne, & Goater, 2010). First, worldwide gauging data have registered how reservoirs alter the timing of high and low flows (Graf, 2006; Kondolf & Batalla, 2005; Schmidt & Wilcock, 2008), weakening the connection between river flow and headwaters run-off and affecting downstream river forms and ecosystems. Second, reservoirs retain sediments causing channel incision and narrowing, bed armouring, and other channel degradation forms (Surian & Rinaldi, 2003; Brierley & Fryiers, 2005; Rollet, Piégay, Dufour, Bornette, & Persat, 2014). Finally, changes to flow regime and sediment supply affect vegetation evolutionary patterns due to the narrow interaction between vegetation and hydrogeomorphology (González del Tánago, Martínez-Fernández, & García de Jalón, 2016; Gurnell et al., 2015; Picco, Mao, Rainato, & Lenzi, 2014; Picco, Sitzia, Mao, Comiti, & Lenzi, 2016; Solari, Van Oorschot, Hendriks, Rinaldi, & Vargas-Luna, 2015; Surian et al., 2015).

The analysis of the changes induced by reservoirs in river evolution has to consider three issues. First, it can be developed through the comparison of downstream versus upstream reaches, regulated rivers versus nonregulated, or pre- versus post-dam periods. According to Braatne et al. (2008), although the combination of the three methods is the best option, the pre- versus post-dam approach provides the most reliable results. This approach is endorsed by several works that have explored historical river channel adjustment processes after damming (Surian, 1999; Magdaleno, Anastasio Fernández, & Merino, 2014; Scorpio et al., 2015; Scorpio & Roskoff, 2016; Martínez-Fernández, González del Tánago, Maroto, & García de Jalón, 2016; Arnaud et al., 2015).

Second, the analysis of dam effects is normally complicated by the difficulty of isolating this factor from other human actions. The intense anthropisation of riverine ecosystems entails the frequent combination of different human impacts in the same river basin, such as gravel mining, channelization, weirs and check dams, and among others (Moretto et al., 2014; Ollero, Ibisate, Granado, & de Asua, 2015; Preciso, Salemi, & Billi, 2012; Sanchis-Ibor, Segura-Beltrán, & Almonacid-Caballer, 2017).

Finally, landscape configuration is a key factor in determining the hydrogeomorphic impact of flow regulation. Petts and Gurnell (2005) have identified varied geomorphic responses after damming in different rivers of North America, Europe, and Australia. More recently, Reid, Brieerley, McFarlane, Coleman, and Trowsdale (2013) have highlighted how the impact of a dam can also differ markedly in different landscape settings of the same river. This diversity of responses makes further research necessary on adjustment processes under different flow conditions and in different riparian environments.

We analyse here the case of the Serpis River, a small Mediterranean gravel-bed river located in Spain, following these considerations. Despite the relatively abundant works on the effects of dams in large and medium Mediterranean or Alpine rivers, short coastal Mediterranean rivers have not won the attention of researchers. Moreover, the Serpis River documentation allows the comparison of pre- versus post-dam conditions throughout 70 years, and the lack of other significant human impacts permits isolation of the effects of the dam on the river forms.

Thus, the aims of this paper are the following: (a) to reconstruct channel changes during the last 70 years; (b) to identify cause–effect connections between channel changes, vegetation, and changes in river flow; and (c) to calculate and to identify the timing of different morphological parameters in the sequence of river adjustment.

2 | STUDY AREA

The Serpis River is located between the Alacant and València provinces, in Eastern Spain. It is 75 km long and drains a 752 km^2 basin. The river valley is flanked by calcareous karstified mountains, with three different sectors: the upper valley of Alcoi, a depression covered by Miocene marine marls; the Estret de l'Infern, a narrow limestone gorge; and the Pleistocene alluvial fan of Gandia, between this gorge and the Mediterranean Sea (Garófano-Gómez et al., 2011).

The river basin is under the influence of a Mediterranean climate, with the mean annual rainfall ranging from 494 mm at the headwaters (Alcoi) to 677 mm at the river mouth (Gandia). Mean yearly river flow is 1.3 m^3/s, but flash floods are recurrent, reaching mean daily flow maximum historical values of 800.2 m^3/s (in 1922 in Vilallonga gauging station). The Beniarrés Dam (30 hm^3) has regulated the headwater flows since 1958 for flood prevention and irrigation purposes. The reservoir has stored a sediment volume estimated to be 3,831,000 m^3 between 1958 and 1997 (Cobo, 2008). Forest fires have been recurrent in the medium and low part of the basin since 1970.

The study area (103 ha) is located between the Beniarrés dam and the CV-701 bridge, beside the village of L'Orxa (Figure 1). It is 6.4 km long, and it has a confined section between 60 and 270 m wide, excavated on Pleistocene terraces. The longitudinal slope of the thalweg is quite regular, with a mean value of 5.8$^{o}/_{oo}$. The L'Encantada Ravine (27.3 km^2) and the Vessant de la Carrasca Ravine (14.4 km^2) are the only relevant tributaries at the study area. No human activities altering sediment or flow regime had taken place in the study area during the study period, although gravel mining is documented upstream Beniarrés reservoir since 1977.

3 | MATERIALS AND METHODS

3.1 | Assessment of land use changes

We mapped land use changes in the drainage basin of the study area located immediately downstream the dam in 1956 and 2009 from aerial photographs and orthophotos (Table 1). We defined seven land use types for classification: (a) urban areas; (b) forested areas (>50% of forest strata coverage); (c) shrub areas; (d) sparsely vegetated areas; (e) bare rock areas; (f) annual crops; and (g) cultivated trees. Vegetation class identification was manual.

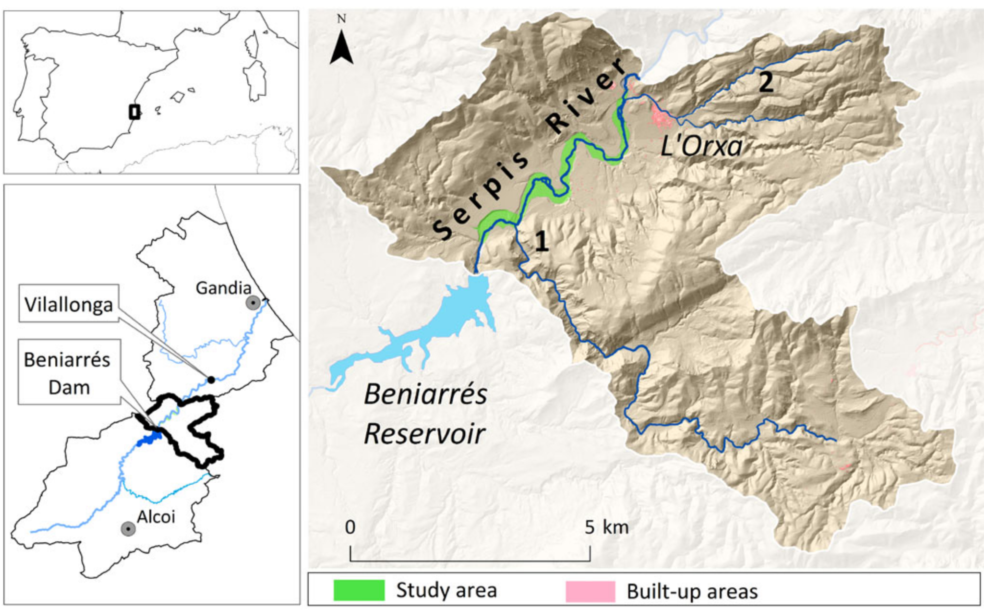

FIGURE 1 Sketch of location of the study area. Number 1 for L'Encantada Ravine and 2 for Vessant de la Carrasca Ravine [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Characteristics of the images used, and mean river flow when the images were taken

Date	Type	Scale	Agency	Pixel size (m)	Mean RMS Error (m)	Mean Monthly flow (m^3/s)
March 1945	Aerial photograph	1/43,000	Ministry of Defence (CECAF)	1	1.6	7.1
April 1956	Aerial photograph	1/33,333	Ministry of Defence (CECAF)	1.15	1.46	-
January 1977	Aerial photograph	1/18,000	Ministry of Agriculture (IRYDA)	0.66	1.13	0
July 1989	Aerial photograph	1/25,000	Generalitat Valenciana	0.55	1.17	5.2
July 1994	Aerial photograph	1/25,000	Generalitat Valenciana	1	1.74	4.7
August 2000	Ortophoto	1/20,000	Valencian Institute of Cartography (ICV)	0.50		2
July 2004	Ortophoto	1/20,000	Valencian Institute of Cartography (ICV)	0.44		3.4
June 2012	Ortophoto	1/50,000	National Center of Geographic Information (CNIG)	0.25		2.2
June 2017	Ortophoto		Galileo Geosystems	0.09		0.6

3.2 | Assessment of hydrological changes

Information on flow conditions and flood series was obtained from the Beniarrés Reservoir and Vilallonga Gauging Station (Figure 1). The Beniarrés Dam registers all the water released daily by the reservoir immediately upstream of the study reach, and Vilallonga is a gauging station located 12 km downstream of the study area. Their drainage basins are 465 and 547 km^2, respectively, so flow measurements are expected to be slightly higher in Vilallonga.

Both series of mean daily flows cover different periods. Vilallonga has three periods with data: 1916–1931, 1943–1953, and 1998–2017. The first two periods show the natural river flow, before the reservoir construction. The Beniarrés Dam series registers the outflow dam data and covers the period 1958–2017. Since 1989, 5-min data from online dam inflow and outflow has been used for real-time flood management.

On the basis of these data, the magnitude, peak, and frequency of floods and annual discharge have been analysed. The annual discharge has been calculated using the average daily flow of the hydrological year (1st October–31st September).

3.3 | Assessment of channel changes

River channel changes between 1945 and 2017 have been assessed through interpretation of aerial photographs. Images dating from 1945, 1956, 1977, 1989, and 1994 (Table 1) were scanned at a resolution 400 dpi and georectified through a second order polynomial through ArcGIS TM version 9.3 (ESRI, Redlands, California, 2009). In order to reduce distortions in rectification as much as possible, the images of 1945 and 1956 were fragmented into several pieces and rectified separately. The Spanish Geographical Institute (CNIG, 2009) orthoimages were used as a base layer for georeferencing aerial photographs. Images taken from a drone in June 2017 that were used to generate the most recent orthoimage.

Channel forms were manually classified in order to identify changes in river morphology. We distinguished between the following: (a) flowing channels; (b) unvegetated gravel bars; (c) barely vegetated areas, deposits covered by grasses, and scattered shrubs (<5%); (d) mixed vegetated areas, covered by shrubs and scattered trees (<5%); (e) tall vegetation, compact masses of trees; and (f) agricultural lands. The scale of mapping (1:2,000) allowed distinguishing patches of 20 m^2 or greater size. The evolution of the channel forms was measured calculating the prevailing trajectories of change, following the method described in Sanchis-Ibor et al. (2017). Between each pair of aerial photographs, we measured the percentage of the area with changes reflecting (a) channel narrowing or vegetation encroachment; (b) the changes showing channel widening or floodplain destruction processes; and (c) the stable forms.

In order to assess the changes in the gravel channel in terms of the number of branches, we used ArcGIS TM version 9.3 to calculate the channel count index (BI_{T3}; Egozi & Ashmore, 2008). It consists of the mean number of channel segments (N_L) intersected by cross-sections (X_S) of the river. For this calculation, Egozi and Ashmore (2008) suggest using a distance between cross-sections equal to or less than channel width, and for this purpose, channel width can be measured using the ratio channel area/reach length (156 m in this case). Consequently, measurements were taken in 40 cross-sections separated by 156 m.

Channel width was also estimated in these 40 cross-sections for each one of the aerial photographs used. This measure, referred to as flowing channel width, is determined by the water surface extent at the moment that the aerial photographs were taken. It is a reliable source of information for the post-dam period, because the river flow is almost constant. However, during the natural regime period, this measure could be more variable (see mean monthly flow of each aerial picture in Table 1). The active channel (AC) area is more reliable to assess the pre- and post- dam channel changes. It was calculated as the area occupied by the flowing channel and bare gravel bars in the mentioned cross-sections.

River mobility was estimated by comparing the area occupied by the flowing channel in different periods. We calculated the coincident area of the flowing channel between two different aerial images, or preserved channel area (P_a); the river channel area abandoned between these 2 years (A_a), and the new channel area occupied at the end of the period (N_a; see Figure 2). In order to reduce the bias associated with the flowing channel width in each period, we calculated a channel migration index (CMI) as the result of the addition of the total extent of N_a plus A_a, divided by the P_a. We also calculated the mobility zone width (M_w; Figure 2) of the flowing channel between each pair of aerial photographs in the 40 mentioned cross-sections. We obtained this width by calculating the distance between the two

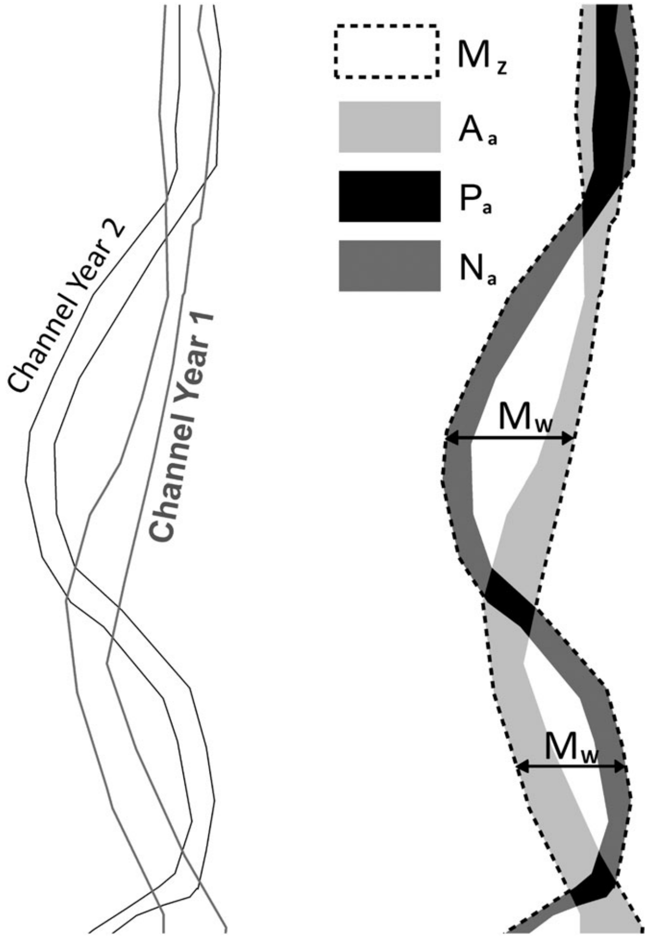

FIGURE 2 Chanel migration indicators. Preserved channel area (P_a); abandoned channel area (A_a); and the new channel area occupied at the end of the period (N_a). Mobility zone (M_z) and mobility zone width (M_w) of the flowing channel between each pair of aerial photographs

external borders of the flowing channel, after overlapping the position of the flowing channel in two aerial photographs (merging them in a unique shapefile).

Finally, a vegetation inventory based on field works was completed in the spring of 2016 covering the river corridor of the study reach, to validate units mapping and to provide a better understanding of flow–vegetation interaction. Trees, shrubs, and grass species were identified and statistically classified into eight different vegetation associations that were mapped.

4 | RESULTS

4.1 | Land cover changes in the drainage basin of the study area

The analysis of the land cover changes in the drainage basin of the study area between 1956 and 2009 does not reveal significant changes in terms of effects on sediment yield. Abandonment of agricultural land has been significant. Herbaceous and tree crops occupied 25.7% of the area in 1956, but only 8.4% in 2009. This process has stimulated the colonisation of grasses and shrubs of the abandoned crop fields, whose values increased from 15.9% to 26.1% and from 30.9% to 36%, respectively.

However, this spontaneous expansion of the Mediterranean garrigue was simultaneous to a deforestation process, mainly caused by forest fires (Figure 3). Forest cover, which represented 23.6% of the drainage basin in 1956, has decreased to 13.7% in 2009, unlike the regional trend, where the afforestation is usual in this period. Moreover, the bare rock area, exclusively located in the gravel bars of the river corridor in 1956 (2.1%), was only mapped in a mountainous area (2.7%) in 2009.

4.2 | Hydrological changes

Flow data analysis shows significant changes throughout the 20th century, in terms of discharge, flood frequency, and flood magnitude. Mean annual discharge markedly decreased in Vilallonga before and after the construction of the Beniarrés Dam, from 87.6 hm^3 (1917–1953) to 39.2 hm^3 (1998–2017). Beniarrés Dam data also show lower values than the pre-dam period: 29.7 hm^3 for the complete period

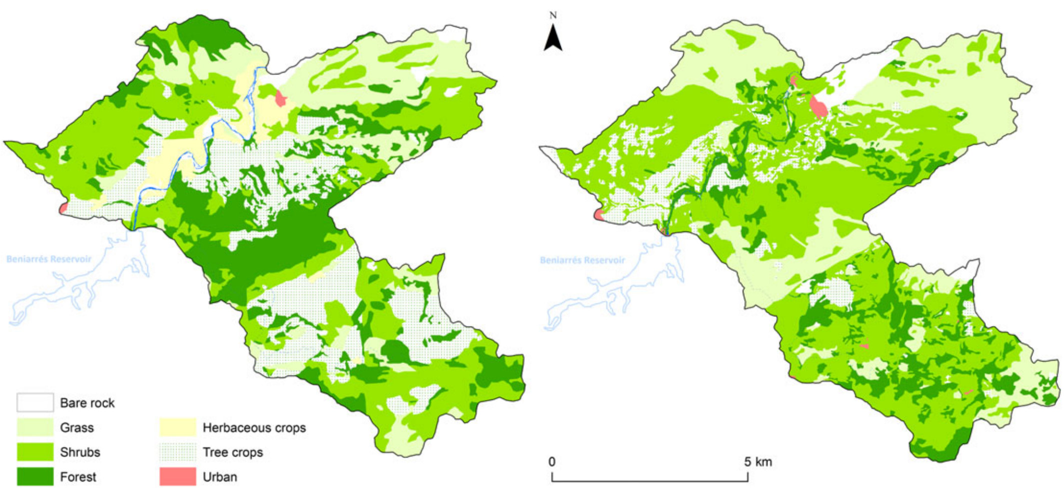

FIGURE 3 Land cover changes in the drainage basin of the study area between 1956 and 2009 [Colour figure can be viewed at wileyonlinelibrary.com]

(1957–2017) and 27.71 hm^3 for the shorter period comparable with Vilallonga series (1998–2017).

The number and magnitude of flood events have also changed after the construction of the reservoir (Table 2). Vilallonga pre-dam flood series registered 29 flood events, with an average of 1.16 events per year. After dam construction, this average decreased to 0.47 events per year (1998–2017). The Beniarrés Dam series shows a greater reduction, with 19 flood events in 59 years and an average of 0.28 events per year between 1958 and 1998 and 0.42 in the period coincident with Vilallonga (1998–2017). No flood events higher than 40 hm^3 were registered in either of the observatories after dam construction.

The maximum annual flow has also clearly decreased (Figure 4). In 1922, Vilallonga Gauging Station registered 800 m^3/s, the highest value of the study period, and a second peak was recorded in 1946 (643 m^3/s). Another four flood events registered values higher than 200 m^3/s in the decades of 1920 and 1940. However, after dam construction, the maximum value that Vilallonga has reached is 111 m^3/s (19th January 2017), and Beniarrés' maximum annual flow has never been higher than the 106 m^3/s registered in 1974.

During the first two decades after reservoir construction, the river alternated between short dry and wet periods, with only two relevant floods (>50 m^3/s), in 1964 (70 m^3/s) and the aforementioned event of 1974 (106 m^3/s). This flood took place immediately after another significant flood event, 60 m^3/s in 1973, the third most relevant between 1957 and 1977.

The wettest period took place between 1986 and 1993. The capacity of flood abatement was limited in Beniarrés due to an unusually rainy period, and five flood events higher than 50 m^3/s took place in 8 years. After 1993, the Serpis basin went through a severe drought, which is the longest dry period of the series, until 2004. In December 2004, another relevant flood event took place (92 m^3/s), followed by other minor events between 2007 and 2013. The floods of winter 2016–2017 recorded the maximum value of the post-dam period (Figure 4).

4.3 | Changes in Serpis River corridor

4.3.1 | Evolution of channel forms and pattern

Important planform changes have taken place over the study period (Figure 5). Before Beniarrés' construction, most of the river corridor was occupied by unvegetated bars (49.4% in 1945 and 52.5% in 1956). There were no patches of tall vegetation, and the barely vegetated plus the mixed vegetated areas did not exceed 30 ha. The river landscape was dominated by gravels, and some of the scarce agricultural lands (7.1% in 1945 and 6.2% in 1956) were devastated and partially covered by gravels (Figures 5 and 6). Gravel bars areas were slightly larger in 1956 than in 1945, but mainly because in 1945, the water flowing was more abundant at the moment the aerial picture was taken (Table 1, Figure 5).

TABLE 2 Number of flood events in Beniarrés and Vilallonga series

	Flood events (Mm^3)							Total	Events/Year*
	5–10	10-20	20–30	30–40	40–50	50–100	>100		
1916–1956 Vilallonga	13	2	6	1	1	3	3	29	1.16
1958–1997 Beniarrés	5	3	2	1				11	0.28
1998–2017 Beniarrés	6	1	1					8	0.42
1998–2017 Vilallonga	2	4		1		2		9	0.47

*Considering only years with available data.

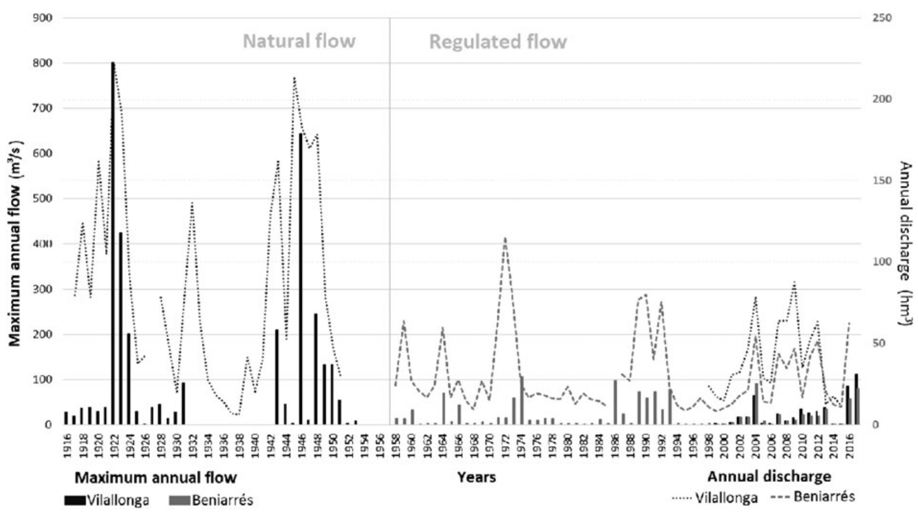

FIGURE 4 Maximum annual flow and annual discharge of Serpis River in Vilallonga and Beniarrés during the study period

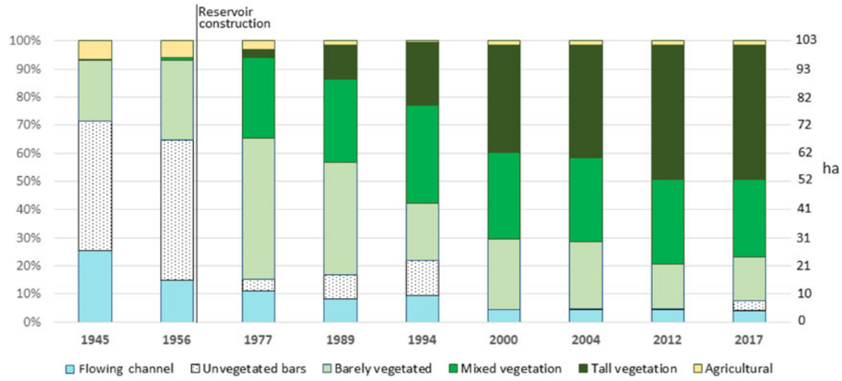

FIGURE 5 Changes on the channel pattern throughout the study period [Colour figure can be viewed at wileyonlinelibrary.com]

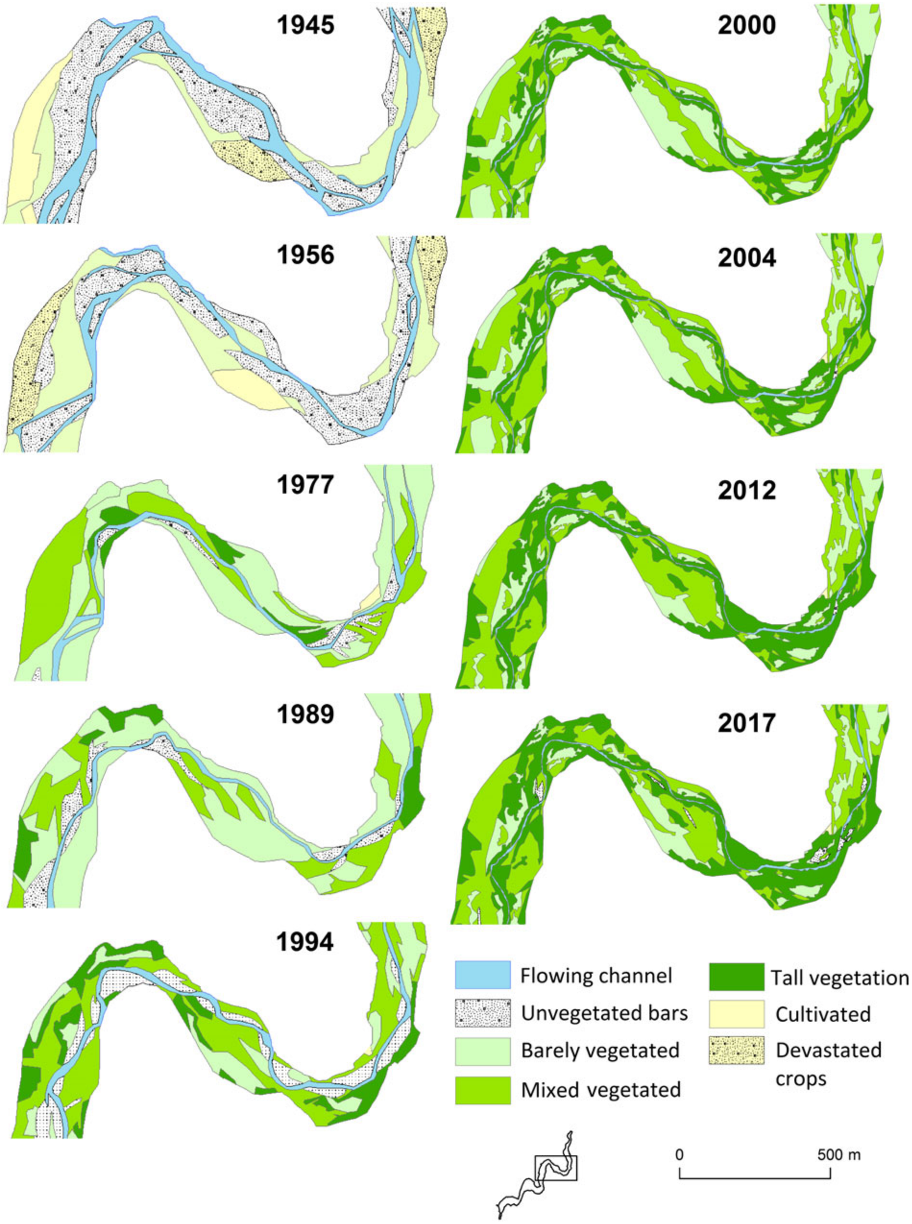

FIGURE 6 Changes on the channel pattern throughout the study period in a representative reach of the study area [Colour figure can be viewed at wileyonlinelibrary.com]

After dam construction, vegetation started to colonise most of the river corridor. In 1977, gravel bars had decreased to 4.4%, and the barely vegetated areas were the larger river form, occupying 53.5%. Between 1977 and 1994, gravel bars slightly increased to 13.4%, but the total vegetated areas (close to 80% of the river corridor) remained almost constant (Figures 5 and 6). However, among the vegetated forms, tall vegetation increased considerably from 3.1% to 20.6%, whereas barely vegetated areas decreased to 20.6%. Mixed vegetated areas behaved as a transitional form, increasing by 10.3% between 1977 and 1994.

During the period 2000–2017, the vegetated areas covered more than 90% of the river corridor. A gallery forest grew along the flowing channel, making the river water almost imperceptible in the aerial pictures in some reaches (Figure 6). According to the vegetation inventory and the aerial pictures, this gallery forest is dominated by *Salix atrocinera*, with some scattered groups or individuals of *Salix purpurea*, *Salix eleagnos*, *Arundo donax*, and *Populus nigra*.

Important masses of shrubs and trees were consolidated over the old gravel bars. Tall vegetation areas (mainly *P. nigra* and also *Pinus halepensis and Salicaceae species*) occupied 41.2% in 2000 and 50.4% in 2017, whereas shrubs remained almost stable (31.9% in 2000 and 28.8% in 2017) and barely vegetated areas decreased from 26.8% to 16.5%. Gravel bars almost disappeared (less than 0.5% between 2000 and 2012) and only reached 3.8% after the winter floods of 2016–2017. Plantations in the original agricultural lands of the study reach facilitated dissemination of *P. nigra*.

Throughout the whole study period (Table 3), the flowing channel width decreased by 80%, and the active channel area decreased by 89.3%. Three clear stages appear in this decreasing trend in both indexes:

- Pre-dam period. Between 1945 and 1956, there was a significant reduction of the flowing channel width but only a slight decrease of the active channel area. This different behaviour of the flowing channel and the active channel is most likely due to the difference in the river flow between the two aerial pictures.
- Between reservoir construction (1958) and 1994. In 1977, both indexes show values considerably inferior to the pre-dam period but from this date onwards remain almost stable, with a slight increase in 1994, particularly in the active channel area.
- After 1994. Both indicators show minimum values, with decreasing or almost stable values at the end of the period.

4.3.2 | Changes in the channel pattern and channel mobility

Simultaneously to the channel narrowing process, the river rapidly abandoned its wandering pattern to adopt a single-channel morphology (Table 3 and Figure 7). In 1945, river bifurcations were frequent, and water flowing underneath the lateral gravel bars repeatedly fed cross-bar channels, which joined the main current after a short stretch. The BI_{T3} index was the highest of the studied period (1.97). This typical wandering pattern appears to have slightly decreased in 1956. From 1977 onwards, for the entire post-dam period, the river shows a typical single channel pattern, with BI_{T3} between 1.15 and 1.

TABLE 3 Flowing channel width, active channel area, and channel count index between 1945 and 2017

	Flowing channel width (m)	Active channel area (ha)	Channel count index (BI_{T3})
1945	42.7	73.9	1.97
1956	24.5	67	1.45
1977	16.7	15.7	1.15
1989	14.3	17.4	1
1994	17	22.9	1.03
2000	8.5	4.7	1.13
2004	7.9	4.8	1.05
2012	7.1	4.8	1.03
2017	8.5	7.9	1.1

Channel mobility also follows a decreasing trajectory (Figures 7, 8, and 9). The flowing channel freely moved over the river corridor before dam construction but also over the periods 1956–1977 and 1977–1989. Only after 1989, mobility was restricted to a narrower area, and finally after 2000, the channel seems almost fossilized. The CMI shows maximum values in the period 1956–1994 (Figure 9), despite the importance of the reduction of the mobility zone width (Figure 8). The CMI is also high before dam construction but almost irrelevant after 2000.

5 | DISCUSSION

Short Mediterranean rivers are subjected to and adapted to enormous flow fluctuations. Damming is a radical alteration of their natural regime, which forces these systems to adjust through processes that take place over several decades. These processes occur through the interaction of different factors, with various rhythms and some concatenated effects. The results of this research allow assessment of the complete trajectory of fluvial metamorphosis following reservoir construction, according to the model developed by Petts and Gurnell (2005).

The *natural regime state* is clearly reflected over the period 1945–1958, in which the Serpis River presented an aggradational pattern, as devastated agricultural plots show. Two large floods took place at the beginning of this period (Vilallonga recorded 643 m^3/s in 1946 and 244.3 m^3/s in 1948), followed by a short dry period between 1952 and 1956. The river, well connected to the headwater sediment sources, had a wider active channel, with larger gravel bars, a typical wandering pattern, and significant mobility, surely stimulated by the floods of 1946 and 1948. Serpis' forms and dynamics were very similar to other gravel-bed rivers in the region, in which, in the absence of direct human impacts, a slight grass colonisation of gravel bars is observed during the same period (Calle, Alho, & Benito, 2017; Sanchis-Ibor et al., 2017; Segura-Beltrán & Sanchis-Ibor, 2013). This slight reduction of the active channel can be attributed to the short dry period 1952–1956, because herbaceous colonisation takes place rapidly in these environments in absence of floods (Hooke, 2015; Sanchis-Ibor et al., 2017).

The *transient state* took place in the Serpis River between 1958 and 2000 (Figure 10). The lack of aerial pictures between 1956 and 1977 does not allow the identification of a reaction phase, but the prolonged adjustment phase is easily recognizable. Over the period 1958–2000, the river forms completely changed, although it is possible to identify various rhythms of transformation in the different morphological parameters. The first one to significantly change was the number of channel branches. In 1977, the river had already adopted a clear single-channel pattern, which did not experience significant variations in the following decades, according to the BI_{T3} (Table 3). Flow regulation seems to be responsible for this rapid change. The

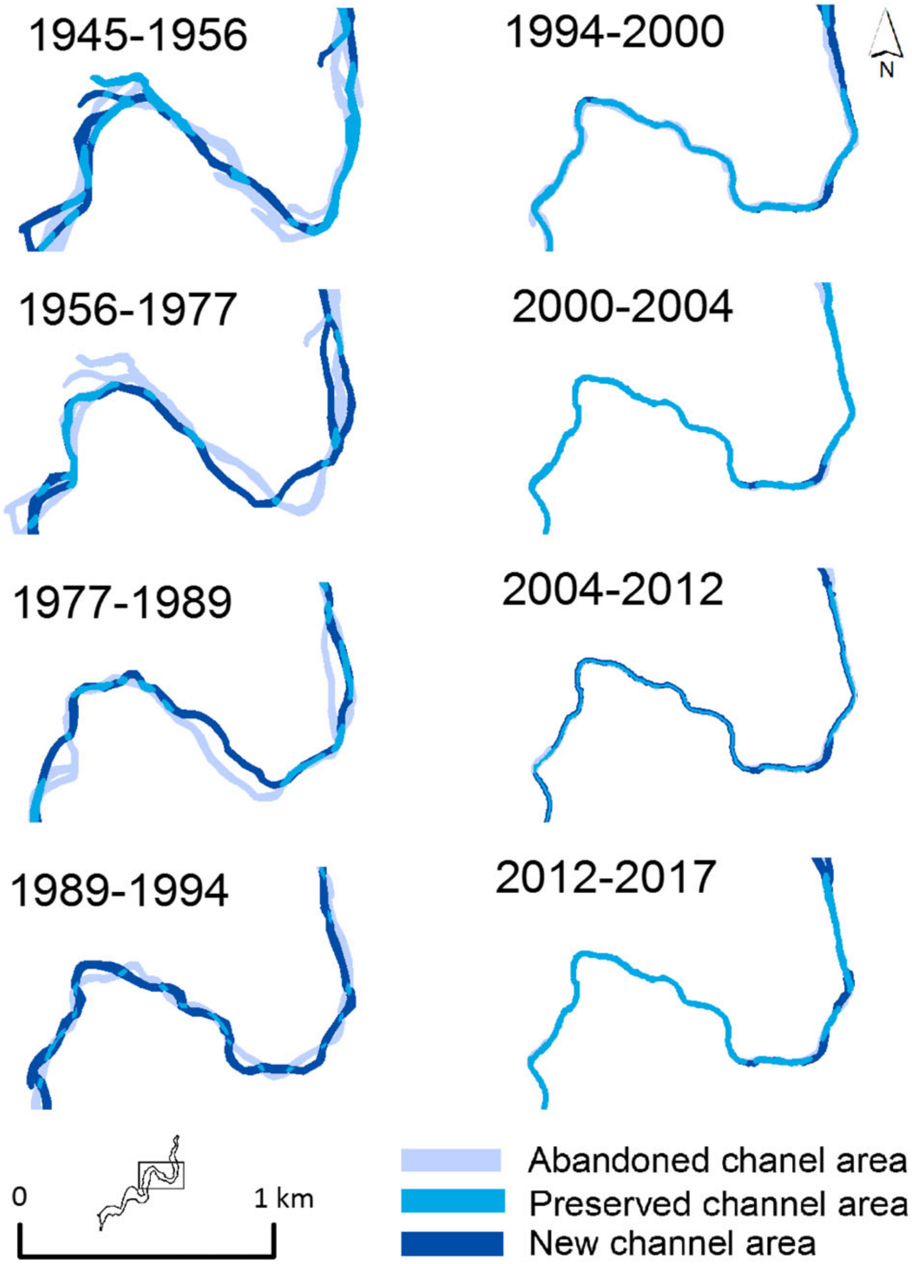

FIGURE 7 Channel migration between each pair of aerial photographs, showing channel stabilization after 2000 [Colour figure can be viewed at wileyonlinelibrary.com]

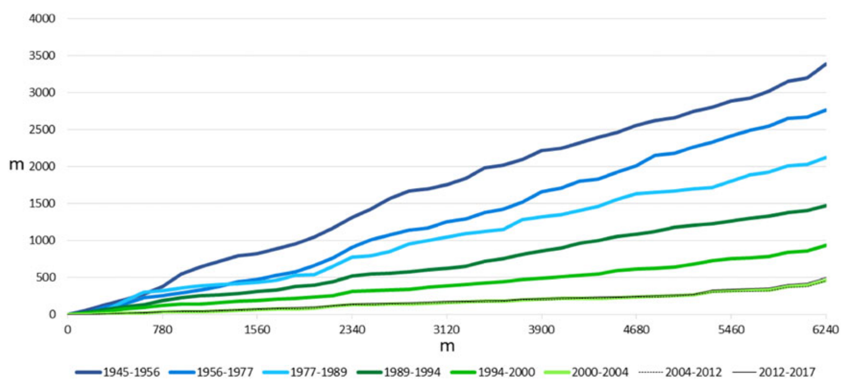

FIGURE 8 Accumulated width of the mobility zone (m) [Colour figure can be viewed at wileyonlinelibrary.com]

base flow became lower and much more regular, and the main channel was enough to absorb it all, leaving secondary branches dry and rapidly colonized by vegetation.

Vegetation encroachment followed a slower but constant trend throughout the study period. This is particularly relevant in tall vegetation, which is the category with a higher areal increase and with less

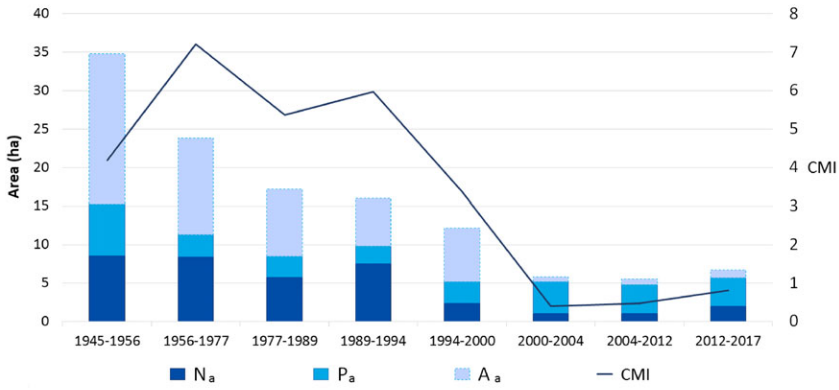

FIGURE 9 Quantification of the channel migration and channel mobility index results. Parameters as reported in Figure 2 [Colour figure can be viewed at wileyonlinelibrary.com]

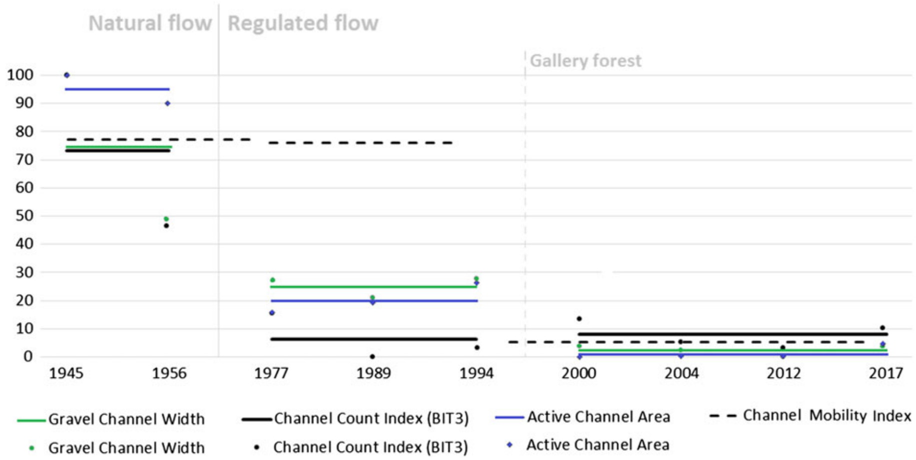

FIGURE 10 Mean (lines) and absolute values (points) of the main indicators calculated for each of the three stages of the adjustment sequence. Channel migration index (CMI) is represented as a line because is calculated with two dates [Colour figure can be viewed at wileyonlinelibrary.com]

reversion trends (Figures 5 and 6). Once trees consolidate in any area, active channel-widening changes are more difficult. However, the active channel area moderately increased in 1989 and 1994 (Table 3), as a consequence of the large flood of 1986 (98.5 m^3/s, Figure 4) and the subsequent rainy period of 1989–1993. Vegetation encroachment was then temporally compatible with a moderated increase of the unvegetated gravel bars, because some barely vegetated areas absorbed the impact of the floods (ephemerally enlarging the active channel) and also allowed the development of shrubs and trees in the areas further away from the flowing channel.

Decrease in river mobility was the latest transformation to be completed in this metamorphosis. Mobility indicators decreased with a certain delay with regard to other river planform change indicators (Figure 10), due to the fact that they were directly concatenated to tall vegetation colonisation. The extension of the area in which the river migrates (M_w) constantly decreased throughout the study period, in parallel to tall vegetation development. However, within this shrinking area, the river still maintained significant mobility until 1994, as reflected in the CMI, which proves to be a simple but effective tool to assess mobility in this sort of rivers. New channel stretches were created and others abandoned throughout this period, moved by the recurrent although abated floods, in parallel to the moderated growth of gravel bars.

After 2000, the Serpis River had completed the adjustment process to the regulated flow conditions. During this adjusted regime state, all the channel planform change indicators showed minimum values (Figure 10). The end of the relaxation period was determined by the development of a forest gallery, mainly formed by *S. atrocinera*. These vegetation communities were not yet present (or did not have adult form) in the 1994 aerial photograph but appeared clearly consolidated in the 2000 image, after a long period without floods (1993–2001) that could have favoured vegetation development at the flowing channel banks. In another river of the region affected by damming, the Mijares River, Garófano-Gómez et al. (2013) observed a period of the same duration (40 years) between reservoir construction and the completion of the process of encroachment of dense woody vegetation, whereas Martínez-Fernández et al. (2016) have identified a similar stage of stability between 2000 and 2015 in Northwestern Spain.

The forest gallery has covered and stabilized almost all the gravel bars, reducing the active channel to a minimum extension. But the most direct consequence of the consolidation of this forest gallery is the fossilization of the flowing channel, which has not showed significant migration during the last two decades (Figures 7 and 10). This is particularly relevant if we consider that at the end of this period, during winter of 2016–2017, the Serpis River registered an important flood event (80.2 m^3/s, the fourth in magnitude of the post-dam period) and other two significant floods (57.5 and 55.7 m^3/s).

The 2016–2017 flood event shows a change in the effectiveness of floods during this metamorphosis. Throughout the adjustment process, the pioneer development of riparian vegetation was not enough to protect the river forms from channel planform changes. Similar events (1986, 1989, 1991, and 1993; all of them below 100 m^3/s) caused gravel channel enlargement and significant river mobility in this period. However, during the adjusted regime state, not even the three events of winter 2016–2017 caused significant alterations of the river forms. Similar observations have been made by Picco, Comiti, Mao, Tonona, and Lenzi (2017) in the Piave River, but the Serpis case reports an even lower effectiveness of large magnitude floods. In the Mediterranean basins, dams have a dual use (irrigation/urban supply and flood control), and the management of floods is conditioned by urban and agricultural pressures to storage water. On 22nd December 2016, with Beniarrés reservoir almost empty, rainfall (621 mm in 4 days at l'Orxa) caused a maximum daily inflow value of 171 m^3/s, but the maximum daily outflow was only 57.5 m^3/s. On 19th January 2017, full, and with no abatement capacity, Beniarrés registered 80.2 m^3/s outflow (79.5 m^3/s inflow) and 55.7 m^3/s (48.4 m^3/s inflow) on 16th March 2017. Between the first two events, flow was never more than 20 m^3/s. The lack of effectiveness of these floods shows two effects: the variable abatement capacity of reservoirs and the vegetation capacity to stabilize river forms.

The 2016–2017 events did not result in relevant morphological changes, except for a slight increase in unvegetated areas, caused by small gravel lobes formed in those areas where the river abandoned the single-channel during the flood. The dense vegetated barrier prevented the river flow from mobilizing the sediments stored in the former gravel-bed channel, and only the sediments supplied by the Barranc de l'Encantada were able to build new small deposits (which in absence of subsequent floods are now being rapidly colonized by herbs). This stabilization contrasts with the recent stage of widening that has been identified in some Italian rivers by Scorpio et al. (2015). The development of the forest gallery seems to be the critical variable that differentiates the Serpis case from the Italian rivers (Crati and Trigno) that have completed their adjustment sequence. This fact highlights the critical role of vegetation in the evolution of river forms.

6 | CONCLUSIONS

Reservoir construction causes a drastic alteration of river flow parameters, which modifies river evolution and landforms. Under these regulated hydrologic conditions, significant changes take place in the river channel planform, as a result of multiple interactions between flow, sediments, and vegetation. Most of these interactions cannot be completely monitored over long periods of time, but by following basic parameters such as daily flows, vegetation, and channel form patches, it is possible to reconstruct the fluvial readjustment processes.

This study, through a pre- versus post-dam approach, permits isolation of the impact of river damming from other human disturbances in a small Mediterranean basin, the Serpis River. The results shown allow us to confirm damming as the main driver of channel planform change in the last 60 years. The main findings are the following: (a) the adjustment process of this short and irregular river follows the same metamorphosis changes as defined by Petts and Gurnell (2005), with a four decade long transient state, and a high magnitude morphological response (89% reduction of the active channel, change from wandering to single thread pattern, and total loss of mobility); (b) the Serpis case shows a clear concatenation of morphological changes, which started with the adoption of the single thread channel, was followed by a slow vegetation encroachment, and culminated with the stabilization of channel migration; (c) the CMI proves to be a simple and effective indicator to assess the mobility trends in wandering and single-thread channels; and (d) since 2000, the gallery forest has fossilized the flowing channel, whose forms have remained stable, even after the impact of large floods.

The first change (adoption of the single thread channel) can be attributed to the decrease in the base flow. The second (vegetation encroachment) is a direct effect of flood abatement. The third is a corollary of this abatement and vegetation encroachment processes. The effectiveness of floods has been progressively reduced by vegetation encroachment processes, particularly tall vegetation development. Events that were capable of moving the channel during the transient state are now unable to stimulate channel migration. Under these conditions, fluvial restoration actions such as flushing flows cannot be effective.

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