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Bedload response to dam removal: Results from a 6-year particle tracking survey in the Leitzaran River (Basque Country)

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ABSTRACT

Dams, weirs and transverse barriers to rivers interrupt sediment continuity and reduce sediment supply downstream. In this regard, dam removal is an increasingly used river restoration measure to recover longitudinal connectivity of sediment, among many other river processes. In this work we present a 6-year (from 2016 to 2022) monitoring of bedload transport before, during and after the removal of the 7-meters high Olloki dam in the Leitzaran River (Basque Country). The removal process started in 2018 with the upper 3 m and was completed in 2019 with the remaining 4 m of the dam. To monitor bedload transport, we seeded RFID-tagged stones in three reaches: a control reach unaffected by the dam, a reach immediately upstream of the dam, and a reach downstream of the dam. We deployed 300 tagged stones each year (100 by reach), i.e., 1800 in total. We measured important mobilization and displacement of tracer stones (with maximum travel distances of ~8.8 km of tracers seeded upstream the Olloki dam) during an active hydrological year following the complete removal of the dam, with some tagged particles even travelling across a downstream weir. We also reported changes in the progression of tagged stones in the dam-affected reaches (upstream and downstream) with the removal, with further and faster dispersal of sediments once the dam was removed. In addition, in these reaches we estimated larger volumes of mobilized bedload in the three years following removal than in the previous years, especially in the upstream reach. In this regard, the relationship between bedload and cumulated energy suggests that less energy was expended in the upstream reach for mobilizing bedload once the removal of the dam was completed. Conversely, in the control reach no major changes were observed before and after the removal of the dam; this reach showed only an increase in sediment mobilization during the last hydrological year, which was the most hydrologically active of the whole monitoring period. In summary, our tracer observations document that travel distances and mobilization volumes are considerably increased with dam removal, especially once the dam was completely removed.

1. Introduction

The geomorphic dynamics of rivers depends on complex interactions between water flow, sediment fluxes and valley configuration, among other controls. In this regard, human activities can alter water and sediment flows and limit the space available for the river to freely flow during floods; thus representing a major disturbance to the geomorphic functioning of rivers in the "Anthropocene" (García et al., 2021). The 20th century has seen a wide variety of human impacts on rivers worldwide, but dams may have had the most significant impact in terms of the geomorphic dynamics of rivers. In fact, these human infrastructures constitute a barrier interrupting the longitudinal continuity of sediment fluxes (mainly in the case of the coarse bedload) and a modification of the flow regime. This is particularly noticeable for larger reservoirs (Brandt, 2000; Graf, 2005; Rollet et al., 2014; Major et al., 2017), but also applies to weirs depending on their height and the

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specific geomorphic setting (Sindelar et al., 2017; Peeters et al., 2020).

More than 53 % of the global land-to-ocean sediment flux is potentially trapped in reservoirs, with an estimated 4–5 Mt. trapped in about 28 % of the world's catchments (Vörösmarty et al., 2003; Syvitski et al., 2022). This trapping of sediment in reservoirs means a loss of storage capacity, functionality and a reduction of life-span for these infrastructures (Randle et al., 2021), but above all a deprivation of sediment necessary for a natural geomorphic and ecological functioning of the river downstream of the dam. This has consequences such as planform and bedform changes (Brandt, 2000), narrowing (Kondolf and Wolman, 1993; Kondolf, 1997; Downs and Piégay, 2019) or loss of habitats for some species (Walling, 2006). Sediment starvation and 'hungry waters' below dams (sensu Kondolf, 1997) can also trigger bed incision downstream, which has become the main 'disease' in many rivers reaches around the world, causing imbalances that endanger the infrastructure located in the channel and the land uses on the floodplain (due to the lowering of the water table). Incisions of up to 10 m have been reported in some reaches of the Bernesga, Gállego, Cervo or Secchia rivers (Ferrer-Boix et al., 2023), for instance. Sediment trapped in reservoirs can therefore be considered 'misplaced resources' (in the words of Kondolf et al., 2014), as these same sediments are unfortunately needed downstream of reservoirs to maintain river morphology and ecology and to replenish critical shoreline land.

In this context, there is an increasing societal awareness and demand to rehabilitate or improve bedload dynamics below dams to improve hydraulic conditions, river morphology, habitat complexity or spawning areas. In Europe, for example, the Water Framework Directive from 2000, calls for river restoration as a strategy to improve river functioning, explicitly mentioning the need to maintain river water, sediment and species continuity. In addition, the EU target is to restore 25,000 km of free-flowing rivers by 2030 (European Commission, 2020; Belletti et al., 2020), and the global Freshwater Challenge is to restore 300,000 km of degraded rivers by 2030 as part of the UN Decade of Ecosystems Restoration. Spanish national river strategy is also aligned with this purpose.

Several practices have been implemented aiming at increasing sediment availability below reservoirs, such as gravel augmentation (Pérez et al., 2015; Arnaud et al., 2017; Brousse et al., 2019; Brousse et al., 2021; Chardon et al., 2021; Van Looy and Kurstjens, 2022; Vázquez-Tarrío et al., 2023), sediment release from reservoirs (Wohl and Cenderelli, 2000; Kondolf et al., 2014), or weir or dam removal (Graf, 2003; Wilcox, 2014; Ibisate et al., 2016; Ritchie et al., 2018). In the last years many dam removals practices have been done worldwide. According to Dam Removal Information Portal, 1796 dams have been removed in US by 2023 (https://data.usgs.gov/drip-dashboard/) and other 6223 dams dismantled in Europe as per Dam Removal Europe (https://damremoval.eu/). Most of the removed dams are low-height barriers (Habel et al., 2020), and few of them higher than 30 m as is the case of dams removed in the rivers Sélune (Vezins dam), Elwha (Elwha and Glines Canyon dams), White Salmon (Condit dam) and Carmel river (San Clemente dam), with relevant monitoring programs (Wilcox et al., 2014; East et al., 2015; Randle et al., 2015; Warrick et al., 2015; Major et al., 2017; Fovet et al., 2023; East et al., 2023).

Overall, experiences with dam removal have demonstrated their potential to improve geomorphic conditions (in terms of reactivating sediment transport downstream dam, mitigating river incision, increasing channel's morphological diversity…) if implemented thoughtfully and in conjunction with comprehensive river management strategies. However, carefully considering of site-specific factors (Foley et al., 2017a) and potential environmental impacts is crucial to ensure the success and sustainability of such projects. This requires ambitious and sustained monitoring programs to assess the effects and/or success of the rehabilitation/restoration actions. In this regard, field monitoring of the geomorphic and sediment-transport response to dam removal provides precious and indispensable data for other complementary analysis on the topic such as flume experiments (Lisle et al., 1997, 2001; Cui et al., 2003; Ferrer-Boix et al., 2014, 2015) and numerical studies (Cantelli et al., 2004, 2007; Cui and Wilcox, 2008; Woodward et al., 2008; Downs et al., 2009; Cui et al., 2019). Field monitoring of river response to dam removal is typically based on topographic surveys, geomorphic change detection or particle tracking (Major et al., 2012; Ollero et al., 2014; East et al., 2015; Magirl et al., 2015; Ritchie et al., 2018; Gilet et al., 2021; Fovet et al., 2023; Mörtl et al., 2023).

According to Pizzuto (2002) and Graf (2005), time scales of river response to dam removal are uncertain, but they might be on the order of decades. However, most of the monitoring studies are much shorter and many do not have information on pre-removal conditions (Bellmore et al., 2017; Foley et al., 2017b), limiting our ability to completely understand river adjustments due to dam removal. Major et al. (2017) recommended that a successful monitoring program of dam removal should collect information of pre-removal conditions, reservoir sediment volume and characteristics, background sediment flux, reservoir erosion rates, downstream sediment transport, downstream channel morphological changes and long-term geomorphic adjustment. In addition to improving knowledge of geomorphological adjustments and sediment budgets, these measurements can provide data for numerical models designed to predict geomorphic responses to dam removal (Major et al., 2017).

Among the various techniques available for measuring sediment transport, perhaps one of the most potentially applicable in the context of dam removal is particle tracking, i.e., the use of tagged stones to trace the displacements of individual sediment particles over time. This technique has been largely used in fluvial geomorphology to understand links between sediment transport and channel morphology (e.g. Hassan and Bradley, 2017; Vázquez-Tarrío et al., 2019). This procedure allows tracking the displacement and dispersion of a sediment plume over time, which makes it particularly suitable for tracking the remobilization of the sediment pile stocked in a reservoir following dam removal. There are several experiences of gravel mobility tracking using tagged stones as tracers to assess gravel augmentation response (Arnaud et al., 2017; Chardon et al., 2021; Vázquez-Tarrío et al., 2023; Liebault et al., 2024) or dam removal (Gilet et al., 2021), but data are still scarce and there are no many long-term tracer studies available within the frame of assessing how gravel-bed rivers react to dam removal.

Following this argument, we present the results of a 6-year field survey (2016–2022) for the monitoring of the Olloki dam removal using particle tracking in the Leitzaran gravel-bed river. This sediment transport monitoring is part of a broader geomorphic monitoring of two dam removals in the Leitzaran River (Basque Country, Spain) and accomplished between 2013 and 2022. Our study provides data about the effect on sediment transport after the removal of the Olloki dam, and data of a long particle tracking survey (covering upstream, impounded and downstream reaches) and before, during and after dam removal, that helps to understand sediment dynamics during several years after the setting of a new base level. We detected a change in hydraulic response and sediment dispersal after dam removal, with different sediment transport responses in different reaches.

2. Study area

The Olloki dam is located on the Leitzaran River (Basque Country), a 42 km-tributary of Oria River that drains a 124 km^2 basin and flows into Cantabrian Sea in the northern Iberian Peninsula. The river in the study area flows across a narrow valley carved into Paleozoic outcrops. The channel is steep with a meandering pattern, and the bed morphology alternates between straight, plane-bed reaches and sequences of riffles and pools with alternate lateral and point bars. The area is forested with deciduous but also forest plantations with clearings practices (Fig. 1). The mean discharge of the Leitzaran River at the study site is 4.73 m^3/s, its mean unit stream power 19.7 W/m^2, bankfull discharge 67.8 m^3/s and its 2-yr, 5-yr and 10-yr return period discharges are 85.0, 126 and 153 m^3/s, respectively. Its bed material is mainly cobble and the median

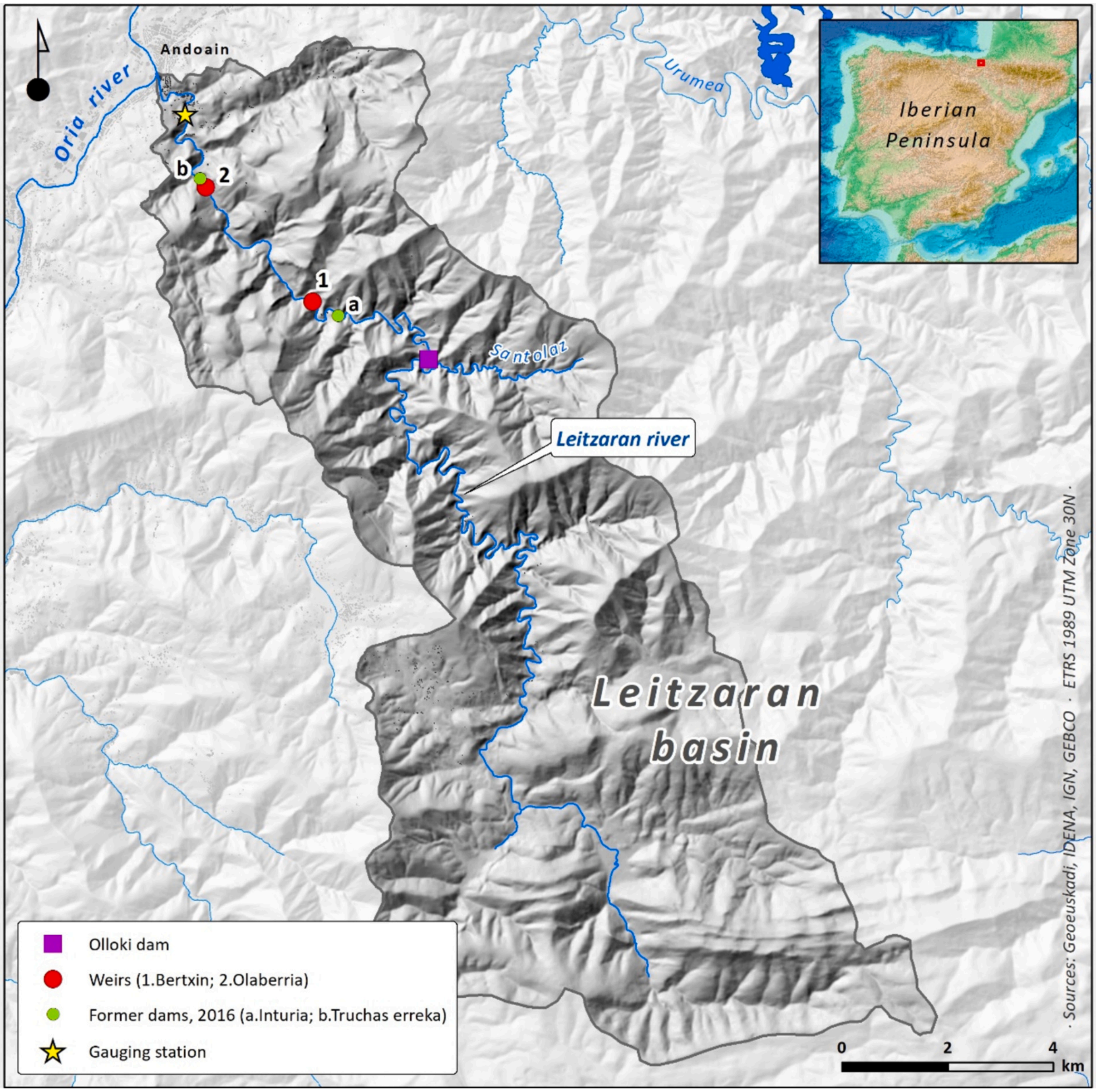

Fig. 1. Location of the studied area in Leitzaran River.

bed grain size has evolved over the studied period, ranging between 64 and 126 mm.

Two dams have already been removed in the framework of two European projects, a European Regional Development Fund (ERDF) project and a LIFE project that seek the recovery of longitudinal connectivity to improve Atlantic salmon habitats together with river geomorphology. These dams are: Inturia dam (12.5 m high), removed between 2013 and 2016 (Ibisate et al., 2016) and Otita (Truchas Erreka) (5 m high) in 2015, both downstream of Olloki dam. Inturia dam was constructed in 1913 for water regulation of a hydroelectrical station located downstream aimed to provide electricity to the tramway of San Sebastián city. Truchas Erreka was initially aimed for hydroelectrical production (from 1913 to 1977), and since 1977 it was used for supplying a fish farm. Nevertheless, there remain some transverse barriers (weirs) in the Leitzaran river, four upstream of Olloki dam and four others downstream of Olloki: Bertxin weir, of 5.8 m-hight, Olaberria weir, of 5.5 m-hight and two more near the confluence with the Oria River. Bertxin weir is filled with sediment (Ibisate et al., 2016).

The Leitzaran River has had since 1994 a gauging station that measures discharge every 10 min, located in the lower part of the river, near its confluence with the mainstream Oria River (the gauge station covers 110.01 km^2 of drainage area). Additionally, there is a weir upstream of the study area that derives water to a hydroelectric station located at the tail of the reservoir of Olaberria weir, located downstream (Fig. 1). This bypass has a maximum of only 3 m^3/s, which is not enough to affect the sediment transport capacity, less alone during flood events when sediment transport is expected to occur.

In this work, we focus on Olloki dam removal. This 7 m-height dam was built in 1762 for a forge and the definitive height of the dam was attained in 1929, when the Olloki hydropower plant was built (Cabezón, 2023). Therefore, the dam has almost a century of impoundment with its last height, but even 150 years more with a lower one. The reservoir upstream of the dam was 600 m long, ~25 m wide and filled (Fig. 2) with approximately 90,000 m^3 of sediment, mainly cobbles covered by a couple of meters of sand with few silts and clay (Ikerlur., 2015). The dam completely interrupted bedload transport, and only fine sediments travel across the dam during floods, which were the sediments that filled Inturia reservoir (Ibisate et al., 2016). Olloki dam was removed in two stages, by removing horizontal slats covering half width of the dam, as it can be seen in Fig. 2. The first 3 m slat was removed in September 2018

Fig. 2. Images showing the Olloki dam (photos taken from downstream to upstream) and the river immediately upstream (photos taken from upstream to downstream) and downstream the dam, before the removal (July 2017), partial removed (September 2018) and completely removed (July 2020) (photos taken from downstream to upstream).

and the second 4 m slat in September 2019 (Fig. 2).

3. Methodology

3.1. Experimental design

To understand how the Leitzaran river would react to the removal of the Olloki dam, we decided to set up a 'Before-After-Control-Impact' (BACI) experimental design and we monitored two impact reaches (upstream and downstream of the Olloki dam) and one control reach (upstream of the dam), both before and after dam removal. This kind of experimental designs are commonly applied in ecological monitoring studies for the quantification of environmental impacts (Underwood and Bennett, 1992; Roni et al., 2013; Smokorowski and Randall, 2017) and are becoming increasingly used in fluvial geomorphology (e.g., Marteau et al., 2022). After an initial field campaign in 2016 to characterize the study reaches and deploy the first tracers in the seeding sites, field monitoring extended from 2017 to 2022 and consisted in six fieldwork campaigns (one per year): two campaigns before starting the removal (summer 2017 and 2018); one in between the two removal phases (summer 2019); and three more once the removal was completed (summer 2020, 2021 and 2022).

We deployed RFID-tagged stones at three seeding sites, one in an unaffected reach of the river (by the dam) and the other two upstream and downstream of the dam (Fig. 3). The three seeding sites exhibited differences in bed slope and average grain size at the beginning of this research (Table 1). Control seeding site presented a generally natural hydrogeomorphological condition, without relevant alterations, so it could be under optimal conditions in terms of morpho-sedimentary dynamics. Conversely, upstream seeding site corresponds to the tail of the reservoir, and the downstream seeding site is located downstream of the dam, so geomorphic conditions in both reaches are affected by the dam.

From one seeding site to the next downstream, we defined a 'study reach'. We therefore defined three study reaches, hereafter referred to as 'control', 'upstream' and 'downstream', according to their location in relation to the Olloki dam (Fig. 3). That is being said, the 'control' reach starts in the most upstream seeding site and extends until the tail of the reservoir, where the upstream-dam seeding site was located. Then, the 'upstream' reach extends from the upstream-dam to the downstream-dam seeding site and includes the whole reservoir of the former dam. Finally, the 'downstream' reach starts at the downstream-dam seeding site and finishes in the Olaberria weir, where we found the lowermost travelling tagged stones.

The control reach is located ~2 km upstream the Olloki dam. It is a narrow (49-m-wide) riffle-pool reach, with a 0.0084 m/m bed slope. The upstream-impact reach is a 1.5-km length reach, located 450 m upstream the dam, but in the area influenced by backwater effects of the dam. It is a 41-m width reach with a ~ 0.08 % bed slope. The downstream-impact reach is located ~600 m downstream of the dam. It is a 30-m width riffle-pool reach, with a mean bed slope around 0.077 m/m. Table 1 summarizes the main characteristics of the three reaches.

A particle tracking field campaign was done on the three reaches using RFID technology and PIT-tags for 7 hydrological years, from the summer of 2016 (first seeding) to the summer of 2022 (last search of tracers).

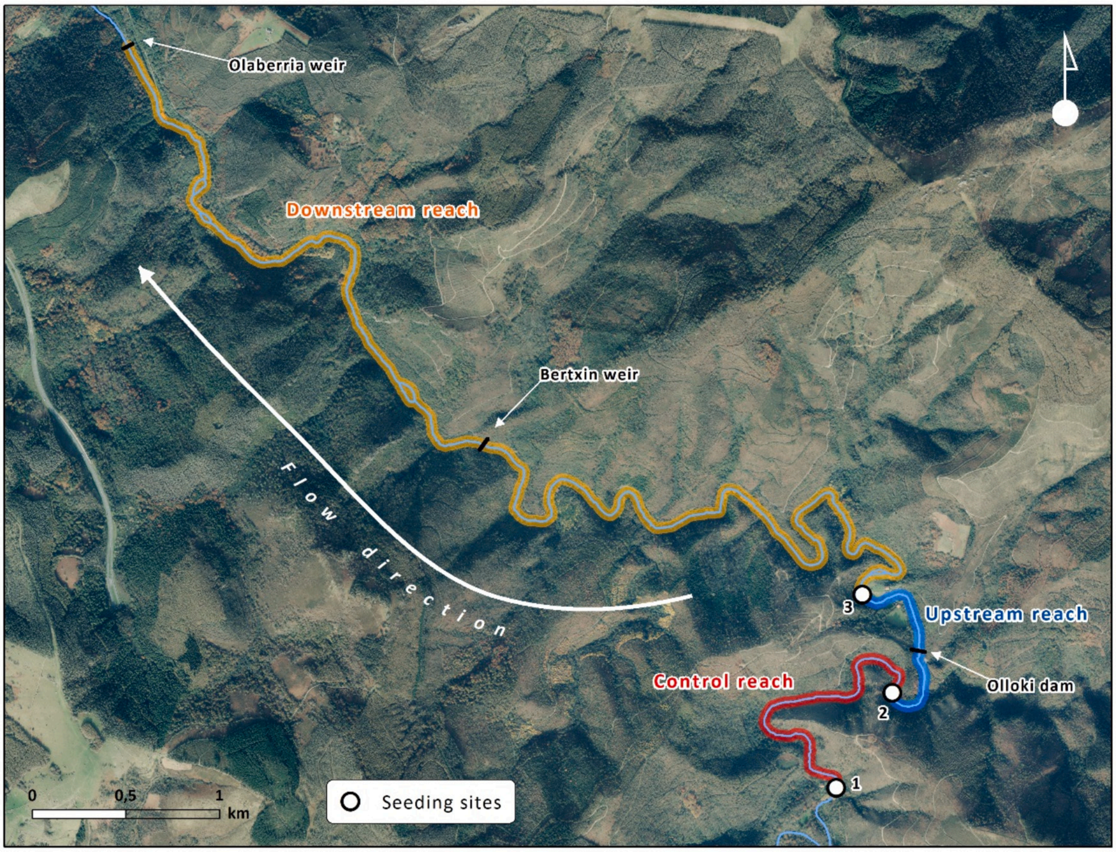

Fig. 3. Studied river reaches and seeding sites (1: Control, 2: Upstream, 3: Downstream).

Table 1
Characteristics of the studied reaches. Distance to the dam from seeding site, 0 represents the dam, negative distances correspond to upstream distance to the dam, whereas positive distances represent downstream distances to the dam.

Reaches	Length between seeding sites (m)	Cumulated lengths (m)	Bankfull width (m)	Distance to the dam from each seeding site (m)	Median grain size (mm)	Slope (m/m)	Drainage basin (km^2)
Control	1938	1938	49	−2224	$64 \geq Ø < 90.5$	0.0084	80.19
Upstream	1044	2980	41	−452	$64 \geq Ø < 90.5$	0.0008	81.91
Downstream	8020	11,002	30	595	$90.5 \geq Ø < 128$	0.077	91.23

3.2. Grain-size and topographic measurements

We characterized the grain size distribution of each reach using the Wolman pebble count method (Wolman, 1954) and an aluminum template (after Hey and Thorne, 1983) to measure particle diameter. Each year from 2016 to 2021, one Wolman sample (180 counted grains) was collected along "forced" sediment bars in each simple point.

The width, depth and the average bed slope of the cross-section where tracer stones were seeded at each of the three study reaches were measured using Leica TS02 and Leica TC-307 total stations. These measurements were repeated each year over the study period aiming at identifying possible geomorphic changes during the monitoring period.

3.3. Particle tracking

Each year, 100 clasts per reach were collected and drilled. Then, 23-mm RFID tags were inserted, and the hole was sealed with resin. We measured the three axes (a, b and c) of each particle, and we noted each tag identifying code. Finally, we painted the clasts with different colors for each site and year to facilitate their search in the field (Arnaud et al., 2017; Liebault et al., 2024). This workflow was repeated for the three selected reaches and for each study year from 2016 to 2021, i.e., 1800 tagged stones were seeded in total, 600 for each reach, that is, 100 per year and reach.

Tracer sizes were selected based on the median size of the bed sediment measured that year at each site. Then, tracer stones were selected to belong to the size class corresponding to the semi-phi interval including the median size, following the Wentworth scale, (Wentworth, 1922), and in the semi-phi size class above the median (Table 2). Due to the small size of the interval below the *D50* ($45.3 \geq Ø < 64$) in the control and upstream reaches (compared to the PIT-tag size, 23 mm) we decided to discard these intervals, as well as the lower interval of downstream reach, to be consistent and follow the same conditions in the three study reaches.

Table 2
Grain size intervals of each sample point. In black, the grain size intervals used for tagged stones in each river reach; in grey, those discarded.

ID	Wentworth interval		
	Below D50	D50	Above D50
Control	$45.3 \geq Ø < 64$	$64 \geq Ø < 90.5$	$90.5 \geq Ø < 128$
Upstream	$45.3 \geq Ø < 64$	$64 \geq Ø < 90.5$	$90.5 \geq Ø < 128$
Downstream	$64 \geq Ø < 90.5$	$90.5 \geq Ø < 128$	$128 \geq Ø < 256$

Tracers were deployed in each study reach forming a square over the surface of gravel bars and close to the bar-water boundary. Every year tracers were seeded in the same place (Fig. 4) at the beginning of each hydrological year (two broke and were lost when locating them on the seeding site). The tracer seeding position was geolocated with a GPS. Every summer, starting in 2017 and finishing in 2022, we searched and geolocated the found tracers helped with an Oregon RFID and Biomark tag readers. Two or three operators participated in each survey and the prospected area covered a channel surface defined by the control reach as upstream point, down to a lowermost boundary 500 m downstream of the last tracer found in each campaign. This surveying strategy was followed in all surveys except in the first one (2017), where the prospection was poorer due to limited time available for fieldwork and the surveyed area was up to ~250 m from the downstream seeding site.

During the field work, the exact location of each of the tracers found was measured with a trekking GPS during the three first years, and afterwards with the GPS integrated in the Biomark tag reader. Later, data were analyzed using GIS to obtain the spatial distribution of tracers along the river after each field campaign. Our GPS had planimetric errors close to 40 m at some points, due to the dense, tall tree cover and the steepness of the valley. We considered ~50 m as the precision of the tracer position to apply a palliative and conservative measure. Therefore, tracer positions were assigned to 50 m bins along the longitudinal channel profile. For this purpose, GIS software was used to draw a buffer polygon zone from the central axis of the Leitzaran riverbed, allowing a distance of 40 m on either side (i.e. a buffer of 80 m wide and 50 m long). Then, individual travel distances were computed with an error of ±25 m. The central axis of the channel in the study section was drawn at a scale of 1/1000 from the latest available orthoimagery.

3.4. Metrics for analyzing tracer data

Two different metrics were used to characterize the displacement of each single *i*-tracer: i. the distance travelled between two consecutive surveys (d_j); and ii. the cumulative distance travelled from the initial seeding location (L_j). Then, for each tracer survey, we estimated the mean value of these two metrics: $<d>$ and $<L>$:

$$\langle \mathrm{d} \rangle_{\mathrm{S_j}} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{i=n_{rf}}} \mathrm{X_{i,S_j}} - \mathrm{X_{i,S_{j-1}}}}{\mathrm{n_{rf}}}$$

$$\langle \mathrm{L} \rangle_{\mathrm{S_j}} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{i=n_{inf}}} \mathrm{L_{i,S_j}}}{\mathrm{n_{inf}}}$$

where S_j and S_{j-1} refer to two successive field surveys; n_{rf} is the number of tracers found in both surveys, and n_{inf} is the number of tracers for which its position is known (or is inferred) for a given survey; $X_{i,Sj}$ -$X_{i,\ Sj-1}$ is the difference in longitudinal tracer positions between S_j and S_{j-1} along the channel centerline; and L_i is the travel distance measured from initial tracer seeding position.

The first metric provides information of each tracer found in both two successive surveys and gives an idea of the average displacements of sediment particles during the survey period, while $<L>$ informs of all tracers found in each survey and provides insight on the progression of the centroid of the tracer plume (Arnaud et al., 2017). For the estimation of Li and $< L>$, following the recommendations of MacVicar and Papangelakis (2022), we included 'inferred' tracers into the analysis of our data, i.e., tracer stones missing in a survey but re-found close to their

Fig. 4. On the left shows seeding sites control, upstream, and downstream. On the right shows a tracer searching and a boulder and bedrock difficult to track reach downstream Bertxin weir.

previous position in a later prospection, so we could infer that they were immobile.

To characterize the hydraulic forcing, we used the cumulative excess energy or time-integrated excess (specific) stream power, based on previous literature documenting that mean travel distances of coarse sediment are well correlated with this parameter (Haschenburger, 2013; Papangelakis and Hassan, 2016; Papangelakis et al., 2022). Time-integrated excess (specific) stream power was calculated as:

$$\int (\omega - \omega_c)dt = \frac{\rho g S}{w} \int_{t_0}^{t_f} (Q_t - Q_c)dt$$

where ρ (kg/m^3 in SI units) is the density of water, g (m/s^2 in SI units) is the acceleration of gravity, S (m/m in SI units) is the bed slope at the beginning of each hydrological year, Q_t (m^3/s in SI units) is the water discharge at an instant t, Q_c (m^3/s in SI units) is the critical discharge, *w* is the bankfull channel width at the beginning of each hydrological year (m in SI units), and t_0 and t_f are the start and end of the mobilizing event.

To further assess the links between hydraulic forcing and tracer displacements, we also estimated the 'Energy Expenditure Index' (EEI) proposed by Vázquez-Tarrío et al. (2019) and Vázquez-Tarrío and Batalla (2019):

$$EEI = \frac{\int (\omega - \omega_c)dt}{\langle d \rangle}$$

where ω is the specific stream power and ω_c is the critical value of ω for incipient sediment motion.

This parameter is somehow related to the 'transport efficiency' concept of Bagnold and is in some way a proxy of the amount of energy needed to displace tracers per unit length (i.e., 1 m), which in a way quantifies the cross-sectional average energy required to displace the tracers.

3.5. Estimates of bulk bedload volumes

Several approaches have been proposed to estimate bedload volumes from particle tracking data (e.g., Haschenburger and Church, 1998; Liébault and Laronne, 2008; Mao et al., 2017). Here, bulk bedload volumes were estimated from the results of tracer experiments using the following expression proposed by Haschenburger and Church (1998):

$$i_b = {}^{\langle d \rangle}/_{t} \cdot w \cdot h \cdot (1-p) \cdot \rho \bullet f_m$$

where $<d>$ is the mean travel distance of tracers, *t* the time duration of the competent flow, *w* is the pre-removal bankfull width at the beginning of the hydrological year, *h* is the depth of the active layer (mobile sediment), *p* is the sediment porosity, *ρ* the mineral grain density (here assumed to be 2650 kg m^{-3}) and f_m is the mobile fraction of bed sediment.

The depth of the active layer was defined depending on the general bed mobility conditions of each year. When bedload transport was dominated by partial mobility (percent of mobile tracers <90 %), we took the D_{50} as mean depth of the active layer. For those periods where full mobility conditions were achieved (percent of mobile tracers >90 %), we estimated the depth of the active layer based on the equation for the scour depth proposed by Recking et al. (2023):

$$h = 1.4wS$$

Concerning the time duration of the competent flow, we consider the cumulated time above critical flow discharge for each study period. In this regard, during December 2017, 2017–2018 hydrological year, we observed in the field some very small movements, ±1 m or 1.5 m, and rearrangements of the tracers given between October and December 2017 in the control reach. Then, the peak discharge preceding this observation (~25–30 m^3/s) was assumed in this work as the critical discharge. Finally, the mobile fraction of bed sediment was estimated from tracer data as the ratio n_{mob}/n_{rec}, where n_{rec} is the number of the recovered tracers and n_{mob} are the number of moved tracers.

This bedload volume estimation was done for each year based only on the retrieved tracers that were introduced the year immediately before.

4. Results

4.1. Hydrology of the study period

From 2016 to 2022 there have been 22 floods whose peak discharges were above the critical flow rate (Fig. 5). The maximum recorded peak was 143.9 m^3/s and occurred between the 25th of November and 12th of December of 2021 (Table 3). The total number of days during which critical discharge has been exceeded at least once was 35 from 2016 to 2022.

The survey 2021/22 was the most 'active' year from a hydrological point of view, with the highest recorded floods (99.7 m^3/s maximum mean daily flow and 143.8 m^3/s peak flow – 7.9 yr return period–) during the whole monitoring period and more days above the critical flow (Table 3). Conversely, year 2020/21 was the 'quietest', with the lowest recorded peak discharge (39.1 m^3/s) and only 2 days with discharges above the critical threshold.

4.2. Grain size data

Table 4 shows the results of annual grain size measurements in the reaches. We observe a progressive fining of the grain size in the three reaches during the six years of the study. This fining was greater in the downstream reach. In general, downstream reach had the highest grain size values, while the upstream had the lowest values during all the campaigns, except for the last one, once the dam was completely removed, when the control reach had the highest values.

4.3. Tracer surveys: raw data

We recovered a remarkable number of the seeded tracers, but recoveries were variable depending on the year. Out of a total of 1798 tracers introduced in the three study reaches, we recovered 474 in 2022 at the end of the 6 years of field survey (Table 5). Many of the tagged stones were recovered several times during the different field campaigns.

The data presented in Table 5 document variable recovery rates, ranging from a relatively high recovery ratio of 51.3 % in 2018 to lower recoveries (26.4 %) in 2022. If we consider only the tracers that were found among those that were introduced in the previous year, the recovery ratios are higher in all field campaigns (Table 5). This may be because tracers did not have enough time to become buried and well-mixed in the riverbed, or to travel further down of the prospected area. Recovery ratios in general decreased as field campaigns progressed. The last survey period is the one in which we report a greater decrease in the number of tracers recovered (26.4 % of the total introduced). With all the surveyed years considered, the recovery in control reach was of 989 tracers, 363 in upstream reach and 977 in downstream reach (Table 5). The highest recovery rates were in control reach, considering that 8 tracers found in upstream reach were seeded in control reach and 328 of those tracers recovered in downstream reach migrated from upstream reach, and even 3 other tracers migrated from control reach. Some of the tracers were found in reaches other than the ones where they were seeded. The lowest recovery rates were in general in the upstream reach. Besides that, we never found 545 of the total seeded tracers. The painting of the particles was lost in many of the cases, so few of them were identified by their color.

The recovery rate of tracers in summer 2017 was very low compared to the other years (32 %). In addition, the measured displacements that year are limited to a very short reach and close to each seeding site

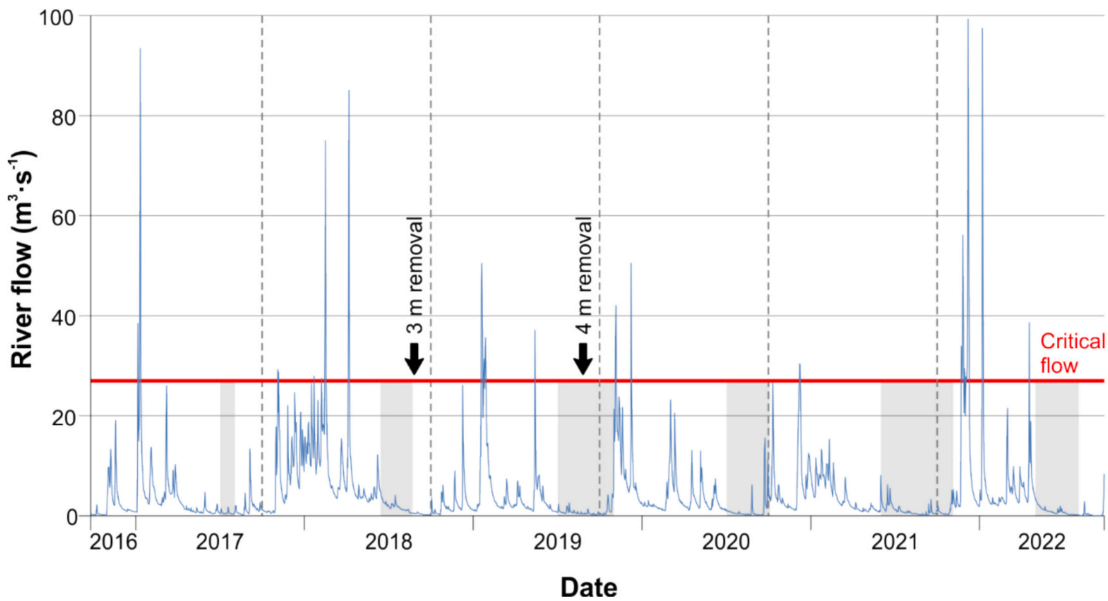

Fig. 5. Mean daily flow hydrograph of the whole monitoring period. Grey columns indicate the tracer tracking periods each year and the vertical dotted lines the beginning of each hydrological year (1-Oct to 30-Sep). Partial (3 m removal) and complete dam removal (4 m removal) moments are indicated.

Table 3
Hydrology data: days above critical flow and peak flows for each hydrological year.

Hydrological year	Days above critical discharge	Hours above critical discharge	Q max (m^3/s)	Dam removal phase
2016/17	4	120.9	110.2	Before removal
2017/18	7	267.5	109.9	Before removal
	First slat removal (3 m). Partial removal			
2018/19	7	251.3	70.6	3 m partial removal
	Second slat removal (4 m). Complete removal			
2019/20	3	101	69.9	Complete removal
2020/21	2	85.2	39.1	Complete removal
2021/22	12	404.3	143.9	Complete removal

Table 4
Grain size characteristics of each reach in each fieldwork campaign, in mm.

Reach	Decile	2016	2017	2018	2019	2020	2021
Control	D16	27	45	33	22	24	17
	D50	82	92	63	74	58	54
	D84	180	180	110	190	120	110
Upstream	D16	36	49	20	28	12	19
	D50	68	79	39	58	34	44
	D84	110	120	71	110	99	80
Downstream	D16	48	47	35	27	21	26
	D50	97	110	70	86	43	49
	D84	210	210	160	180	82	85

(Fig. 6). This is probably a bias resulting from the survey strategy followed during the tracer search, so the prospected area was probably shorter than the travel distance covered by the real movement of tracers. This could likely introduce noise in the interpretation and analysis of the data, so data from this first survey were therefore excluded from further analyses presented in this manuscript.

Fig. 6 shows the locations where tracers were retrieved during the different field campaigns. These locations already suggest an important mobilization of sediment during the 2017–2022 monitoring period. The distances and locations of the tracers evidence that some of them crossed weirs, as some particles appeared downstream of Bertxin in 2021 and 2022. In 2021 only one was identified downstream Bertxin weir, 5625 m downstream of the upstream seeding site where it was seeded in 2016. In 2022, we detected 5 tracers downstream Bertxin weir: at 8525 m downstream from its seeding site (seeded in 2019 in upstream site), at 7675 m (seeded in 2021-upstream), at 7425 m (seeded in 2016 in upstream site), at 4675 m (seeded in 2016 downstream) and at 5475 m (seeded in 2016 upstream) each of them. Three more arrived even to the reservoir of Olaberria (2 seeded in upstream reach in 2018–8925 m downstream the seeding site- and the third located at 8825 m from the upstream reach where it was seeded in 2021).

4.4. Analysis of tracer displacements

Globally, for the whole study reach, the analysis of the mean tracer displacements (d_i) shows: i. a progressive increase in the mean tracer displacements from the survey year 2017/2018 (before dam removal) to 2018/2019 (1st partial dam removal); ii. large tracer displacements were recorded once the dam was removed (survey year 2019/2020); iii. mean tracer displacements (298.6 m) are moderate during the year 2020/2021; and iv. large mean tracer displacements (1055.9 m) are recorded during the last monitoring year (2021/2022).

Focusing on the behavior of the tracers introduced in each reach, the downstream reach records the longest displacements in all monitoring years, as well as the highest displacements in the most hydrologically active years (Table 6). The shortest displacements are reported in either the control or in upstream reach, depending on the year. In 2017/2018, before the start of dam removal, the upstream reach had the lowest displacements, but after the 1st dam removal and after its completion, larger displacements were found in the upstream reach, higher than in the control reach. The last monitored year, 2021/2022 (3 years after dam removal was completed), recorded the largest displacements in the upstream and downstream reaches, while 2017/2018 was the year with the largest mean travel distances in the control reach.

We have also analyzed the potential influence of grain size on travel

Table 5
Recovery data by reach, identifying the seeding origin for each field campaign (in grey the number of tracers found just from those introduced the year before).

Seeding year	Seeding site	Location of found tracers	2017	2018	2019	2020	2021	2022
2016	CONTROL	CONTROL	62	55	46	28	49	43
		UP				1		2
		DOWN						2
	UP	UP	21	43	33	19	12	
		DOWN				15	32	13
	DOWN	DOWN	13	40	61	19	20	16
2017	CONTROL	CONTROL		49	35	40	60	29
		UP			1	1	2	2
	UP	UP		54	20	6	5	
		DOWN				28	29	13
	DOWN	DOWN		67	59	12	15	19
2018	CONTROL	CONTROL			49	46	62	44
		UP						1
	UP	UP			34	17	10	
		DOWN				29	27	21
	DOWN	DOWN			60	27	29	23
2019	CONTROL	CONTROL				46	70	43
		UP						2
		DOWN						1
	UP	UP				20	10	
		DOWN				38	40	13
	DOWN	DOWN				20	26	22
2020	CONTROL	CONTROL					10	44
		UP						1
	UP	UP					40	5
		DOWN						15
	DOWN	DOWN					79	7
2021	CONTROL	CONTROL						65
	UP	UP						1
		DOWN						15
	DOWN	DOWN						12
Recovered			**96**	**308**	**398**	**412**	**627**	**474**
% recovered			**32.0**	**51.3**	**44.3**	**34.4**	**41.9**	**26.4**
Recovered only from those seeded the year before			**96**	**170**	**143**	**124**	**129**	**93**
% idem			**32.0**	**56.7**	**47.8**	**41.3**	**43.1**	**31.0**
Seeded			**300**	**600**	**899**	**1199**	**1498**	**1798**

distances. For this purpose, it is not sufficient to plot distances against particle size, as this type of plot will be co-founded by the hydraulic effects associated with differences in hydraulic forcing in the data set. Therefore, it is first necessary to isolate the pure size effects from those due to different hydraulic conditions. In this respect, Church and Hassan (1992) proposed an approach to analyze the effects of grain size on travel distance, isolating them from the effects of hydraulics and particle arrangements. To do so, Church and Hassan (1992) suggested that observed tracer travel distances should be scaled with the mean travel distance of the bed median grain size ($L^* = L_J/L_{JD50}$)) and plotted against the ratio of the tracer size over the bed median grain size ($D^* = D_j/D_{Jd50}$). To estimate L_JD_{50}, we only used tracers from the semi-phi interval of the bed median size. Additionally, Church and Hassan (1992) used the median of the subsurface grain size distribution to estimate D*. Here the grain size data were scaled by the surface D50 area following Wilcock (1997) rather than the subsurface, so to fit the original form of the relationship found by Church and Hassan, the grain size was multiplied by a factor of 2.2, which is an average value for armour ratio in gravel-bed rivers (Vázquez-Tarrío et al., 2020). In Fig. 7, we have accomplished this analysis with our data. We do not observe any clear trend between particle travel distances and grain size, nor did we observe any difference before and after dam removal. Indeed, our tracer population was selected in a very narrow range of sizes and around the D50, so probably this is masking any potential trend.

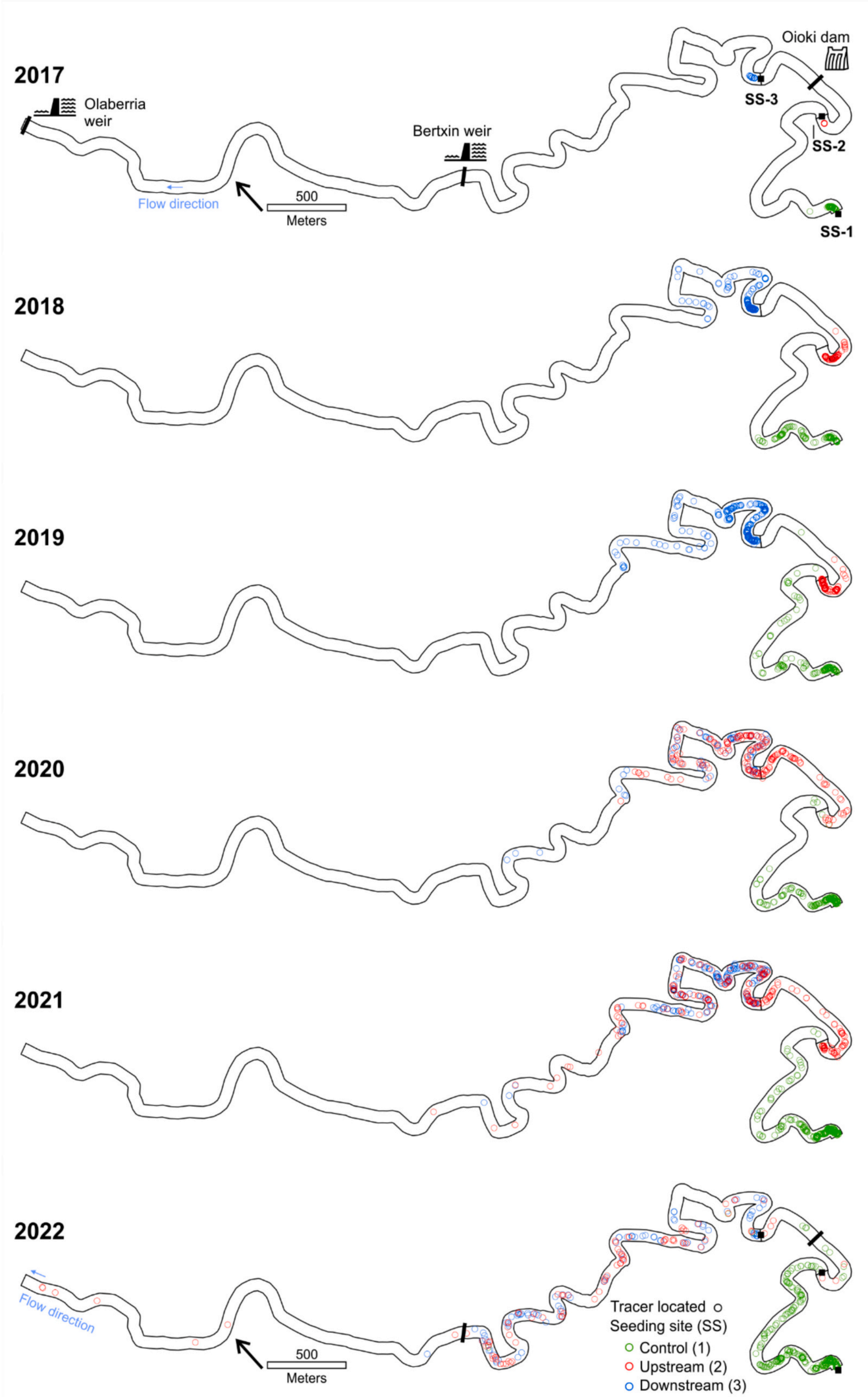

Fig. 6. Location of tracer stones at the end of each field campaign. Black squares represent seeding sites.

Table 6
Mean travel distance (m) reported each year for the tracers deployed the year before (d_i).

Tracking year (summer)	Hydrological year	Control	Upstream	Downstream	Total	Dam removal phase
2017	2016–2017	5.2	4.8	7.7	5.5	Before removal
2018	2017–2018	81.1	4.6	128.7	75.6	Before removal
First slat removal (3 m). Partial removal						
2019	2018–2019	24.5	52.2	158.3	87.2	3 m partial removal
Second slat removal (4 m). Complete removal						
2020	2019–2020	13.6	393.8	941.4	508.9	Complete removal
2021	2020–2021	2.5	53.8	460.1	298.6	Complete removal
2022	2021–2022	42.3	275.0	3525.0	1055.9	Complete removal

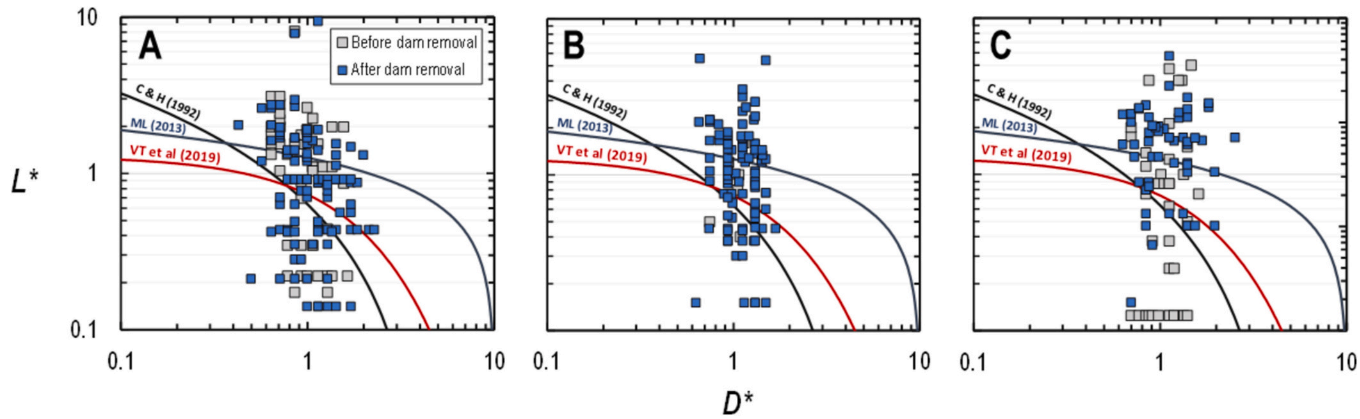

Fig. 7. Relation between the mean distance of travel of the median size class of surface sediment (L^*) and the ratio of the tracer size to the median size of the grain size distribution (D^*). C&H (1992) refers to Church and Hassan (1992), ML (2013) refers to Milan (2013) and VT et al. (2019) refers to Vázquez-Tarrío et al. (2019).

4.5. Progression of the tracer plume

We have compared the propagation of the tracer plume (L) in three years, one before dam removal, one after the partial removal and one after removal was completed (Fig. 8). That is, we compared the differences in tracer plume progression among 2017–2018, 2018–2019 and

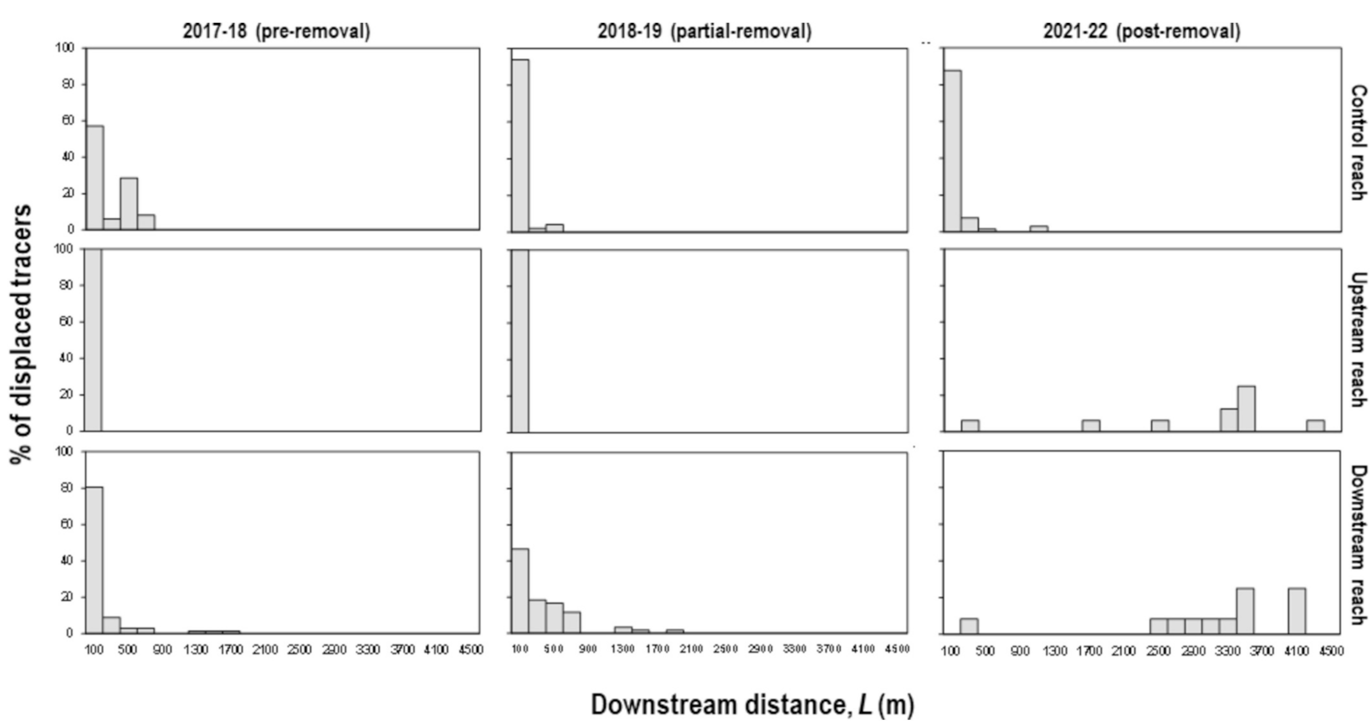

Fig. 8. Histogram of frequencies of tracer displacements for one pre-removal and one post-removal year. Upper: tracers seeded in the control reach. Middle: tracers seeded in the upstream reach. Down: tracers seeded in the downstream reach.

2021–2022. The first and third periods have similar discharge conditions and comparable high-flow durations (Table 3). In the control reach, there are no important differences between the pre-, partial- and post-removal periods: sediment moves in a relatively grouped fashion (Fig. 8). However, there were some differences in the dam-affected reaches (upstream and downstream). In the upstream reach there was barely no movement of the tracers (d < 100 m) before complete removal, whereas after complete dam removal there are rapid, large and dispersed displacements. In the downstream reach, prior to removal, the sediment transport pattern is more like the control reach, in the partial-removal year displacement is more dispersed and after complete removal the movement of the sediment pulse is fast and fragmented (Fig. 8) (Gaeuman et al., 2017; Chardon et al., 2021; Vázquez-Tarrío et al., 2023).

4.6. Links between tracer displacements and hydraulic forcing

In Fig. 9, we have plotted mean travel distances per reach and each study period (d) against the cumulative excess stream power. We have excluded the first tracking year results due to the short searching distance. Results show a weak but significant ($R^2 \sim 0.17$, p-value <0.05) and positive correlation. It is interesting to observe how the points corresponding to the post-removal surveys in the upstream reach plot in the upper envelope. This may indicate that similar ‘energy’ inputs are associated with larger displacements in this reach once the dam is removed, compared to the control and downstream reaches. This is likely to indicate an increase in bedload mobility following the removal of the dam.

In Fig. 10, we show the results of our analysis based on the Energy Expenditure Index (EEI). We analyzed this index by separating the data for each reach and removal phase (pre-removal, partial removal and post-removal). In the control reach the energy used for tracer displacement is constant throughout the monitoring period, with no differences between the different removal phases, pre-removal, partial removal and post-removal. The downstream reach requires more energy than the other reaches in the pre-removal and partial-removal phases, although the energy used decreases, dropping considerably in the post-removal phase with lower energy need than in the control reach. In the upstream reach, less energy is required for tracer displacement, and significantly decreases after the dam was completely removed.

A two-way ANOVA test analysis confirms the statistical significance of the differences for both the different reaches and the different removal phases (p-value <0.05). The reach and removal phase differ on the EEI ($p < 0.05$) and there is an interaction effect between reach and removal phase ($p < 0.05$).

4.7. Estimates of bedload transport volumes

We have estimated the mobilized bedload volumes for each year and reach, based on the displacements of the retrieved tracers introduced in the previous year (Table 7, Fig. 11). In the dam-affected reaches, the three years following dam removal are the ones that generally record larger volumes of mobilized sediment, very clearly differentiated from the previous years. This is even more drastic for the upstream reach. However, the control reach only shows a significant increase in the last hydrological year (2021/22), which had the highest number of days above the critical discharge.

However, to adequately compare bedload volumes between different survey periods and reaches, it is necessary to consider the ‘energy’ inputs into the system. We have therefore plotted estimated bedload volumes against cumulative stream power in Fig. 11. In both the control and downstream reaches there is a strong and positive power correlation between estimated volumes and stream power. However, the estimates for the upstream reach show a greater scattering. Again, in this reach, there seems to be an important difference in the relationship depending on the removal phase (pre- versus post-removal): less cumulative energy seems to mobilize larger bedload volumes once the dam is completely removed, in line with the analysis shown above.

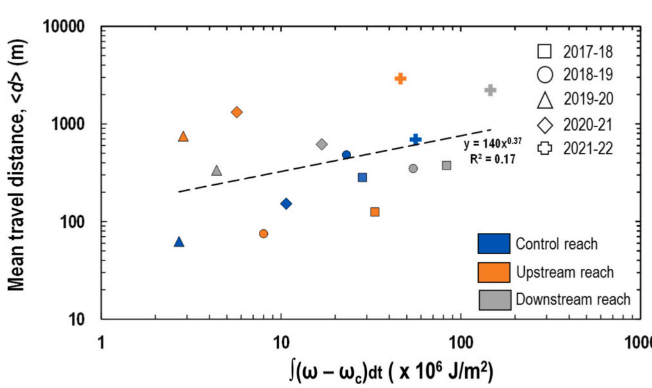

Fig. 9. Mean travel distance plotted versus cumulative stream power.

5. Discussion

5.1. Main findings of our tracer observations

The rate of tracer recovery was relatively important according to data compilation reported by Chapuis et al. (2014), Vázquez-Tarrío et al. (2019) or Liébault et al. (2024). Nevertheless, there is a decrease in the recovery rate as the field campaigns progressed; even though there are more tracers in the river and the number of recoveries were higher than the previous years, the rates decreased proportionally (Table 5). These results are similar to Liebault et al. (2012). We never found 545 seeded tracers, which account for 30.3 % of all of them. Some of the lost tracers could be buried deeper than the signal detection limit of the tracking reader or could have been travelled further downstream than the surveyed range. But also, they could be undetected by signal collision in clusters of tracers that could block each other signals, or constrained and hidden by sediments that do not move even if some nearby ones do (Church and Hassan, 1992; Liébault et al., 2012; Chapuis et al., 2014; Arnaud et al., 2015). The morphological characteristics of the river in some parts, large boulders, slope and presence of large wood debris, also made difficult tracer detection (Schneider et al., 2014; Liébault et al., 2024). All this can affect and bias the reported metrics of sediment displacement, even when recovery rates are high (MacVicar and Papangelakis, 2021).

Measured travel distances (Table 6) and the mobilization volumes (Table 7) registered are important according to the data compiled in the meta-analysis accomplished by Liébault et al. (2024). However, we should outline that the present sediment transport study has a bias related to the size of the sediment that we monitored, as we discarded the interval below the D50 due to the impossibility of inserting the 23 mm tags on them. This undoubtedly may have an influence on the results of displacement data, as well as the estimates of mobilized volume (Fovet et al., 2023), as we could not quantify lower size sediment movement. This supposed that the tracer size range we used was narrow, around D50, and it might be masked any trend between particle travel distances and grain size, or even any difference before and after dam removal.

The tracers that we found with the greatest travel distances were mostly seeded in the upstream seeding site, seeded in 2016, 2018, 2019 and 2021. The predominance of further migrating frontrunners from the upstream seeding site could be related to the increase in energy derived from the base level change in the upstream reach once the dam is removed. Consequently, an important volume of sediment provided by the erosion of the sediment stockpile accumulated within the reservoir became suddenly available, which is also looser sediment and less constrained (so it could move more easily). Most of these frontrunners

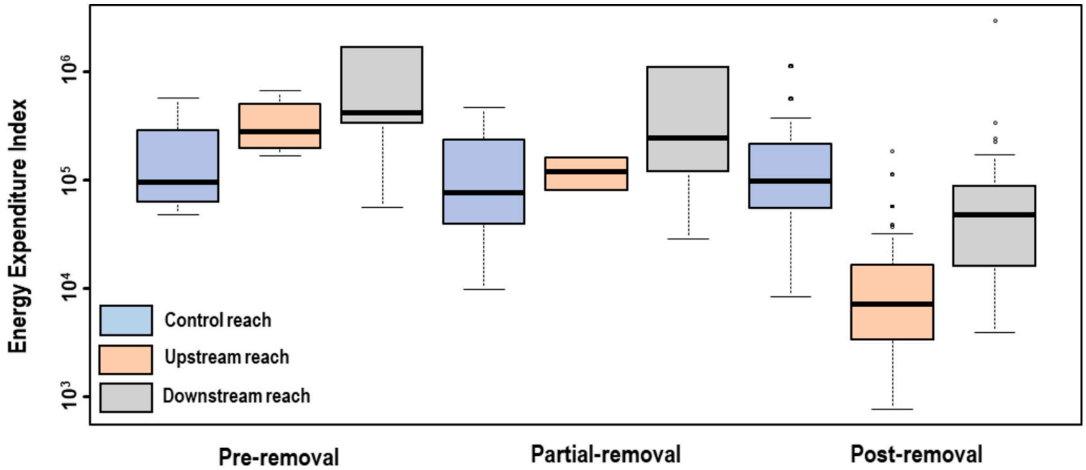

Fig. 10. Energy Expenditure Index during the different phases of the monitoring period. Boxplots in blue represent the control reach, in orange upstream reach and in grey downstream reach.

Table 7
Estimated volume of mobilized bedload (m^3) during the monitored hydrological years.

Hydrological year	Control	Upstream	Downstream	Dam removal phase
2017/2018	532	195	773	Before removal
2018/2019	351	15	395	Before removal
First slat removal (3 m). Partial removal				
2019/2020	106	1859	537	Partial removal
Second slat removal (4 m). Complete removal				
2020/2021	23	1262	246	Complete removal
2021/2022	1358	3987	4188	Complete removal

showed a significant displacement during the 2020/2021 hydrological year in relation to their position in 2019/2020, and notable displacements during 2021/2022 (Fig. 6).

We noticed that some found tracers crossed at least one of the weirs located downstream, such as Bertxin weir (Fig. 6). This was detected during the last field campaigns, 2021 and 2022, once the Olloki dam was completely removed. These tracers were seeded in different years, from 2016 to 2021. Bertxin weir is filled with sediment (Ibisate et al., 2016), so, although the flow velocity slows down, sediment transport occurs at flood times. This was also described by Csiki and Rhoads (2010), Major et al. (2012), Ibisate et al. (2013), Casserly et al. (2020) or Peeters et al. (2020) who named them as leaky barriers. In this regard, we did not find tracers seeded in the control reach downstream Bertxin weir; conversely, we found tracers mostly seeded in the upstream reach and only one seeded in the downstream reaches. This seems a bit counter-intuitive. One possible explanation is that tracers from the downstream reach could have experienced similar displacements as tracers from the other reaches, so they were lost because they travelled further than the prospected area, as previously reported (e.g., Liebault et al., 2012). Or it could be related to the specific morphological characteristics of a small reach of 1380 m of the river downstream Bertxin weir, with very coarse boulders (larger than 2 m of diameter) and deep pools difficult to survey (Fig. 4), where many tracers could be trapped and buried below detection limit, as it happened in Gilet et al. (2020). This agrees with previous works that point out at the role played by macro-bedforms and channel morphologies on sediment dispersion (Papangelakis and Hassan, 2016; Vázquez-Tarrío et al., 2019). However, the morphological configuration of this reach was not an obstacle for some tracers that travel across and beyond this part, i.e. those for which we reported the largest displacements. Another explanation could also be the local river morphology and the exposition to the flow of the seeded tracers to start the movement.

Travel distances are relatively high considering other studies with

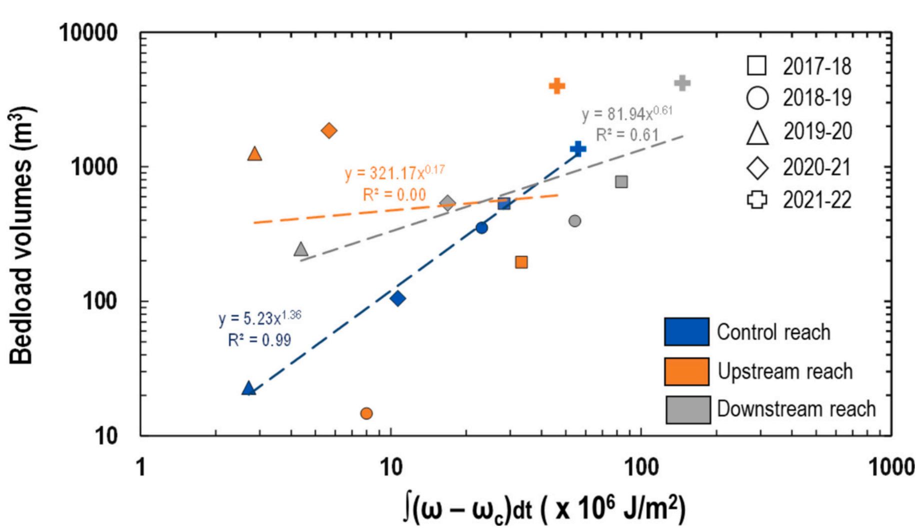

Fig. 11. Transported bed volumes and stream power relationship.

similar long monitoring periods, such as the Selune River, although the hydromorphological characteristics are very different (Fovet et al., 2023); or with the data compiled by Vázquez-Tarrío et al. (2019) and Liébault et al. (2024). In principle, we could think that this may be related to our experimental design: we made a new tracer injection each year, so many of the clasts in our tracer population were 'unconstrained' (sensu Vázquez-Tarrío et al., 2019), i.e. they had not enough time to mix well with the bed. Nevertheless, some of the further travelling front-runners had been seeded several years earlier: for example, in 2022 we found tracers seeded in 2016, 2018 and 2019 with travel distances of >5–7 km. This seems to indicate that tracers need times longer than 3–6 years to mix well with bed structures, which is consistent with some previous meta-analyses of tracer data (e.g. Vázquez-Tarrío et al., 2019).

5.2. Tracer displacements: can we isolate the effects related to dam removal from those linked to flow strength?

One of the aims of this monitoring program was to assess how sediment transport reacts to the removal of the dam and whether, or not, there are differences depending on the location of the seeding sites of the found tracers relative to it. Prior to removal, there were differences among the three reaches: no movement of tracers was detected in the upstream reach, whereas downstream and control reaches had similar patterns of sediment displacement; however, grain size is coarser in downstream reach and with more limited displacements. Once the dam was removed, sediment transport pattern continued unchanged in the control reach (as it could be expected) which means that travel distances in the control reach seems to be independent of the dam removal, whereas it changed in the upstream and downstream reaches in a coherent fashion (Fig. 10); i.e., both reaches show an increase in the displacement and a similar pattern of dispersion of the tracer plume (Fig. 8). This contrasts with the results of Gilet et al. (2021), who did not find differences in the downstream reach.

Our analysis of the required energy to move tracers showed some interesting differences according to the position relative to the dam: the upstream reach showed a more conspicuous reaction to the removal of the dam and travel distances were higher for a similar hydraulic forcing than in the rest of the reaches (Fig. 9), which may indicate that similar 'energy' inputs are associated with larger displacements in this reach, compared to the control and downstream reaches. This is likely to indicate an increase in energy slopes following dam removal. Similarly, the results from the Energy Expenditure Index (EEI) show a clear difference among the different reaches related to the different removal phases (pre-removal, partial-removal and post-removal) (Fig. 10). Control reach has no change along all the periods, downstream reach requires more energy than the other reaches in pre-removal and partial-removal situations, but it decreases much more in post-removal situation needing less energy than control reach; and upstream reach requires significantly less energy once the dam is completely removed. The largest energy expenditures recorded in the downstream reach before the removal is completed could be linked to a more stable and coarser streambed below the dam. This would be coherent with previous literature on the impacts of dams, showing bed stabilization and increased armouring downstream dams, due to a reduction in sediment supply (Kondolf, 1997). However, this situation changes once the removal is completed and fed with the material coming from upstream reach.

On the other hand, the decrease in the energy required to move particles in the upstream reach, following dam removal, may be partially related to the fact that the removal of the dam supposed an increase of the bed slope in the upstream reach, due to the abrupt lowering of the base level following the removal of the dam, but also due to the narrowing of the channel with the incision of the sediment stockpile (Doyle et al., 2003; Ibisate et al., 2016). In addition, the release of sediment from the reservoir stockpile after the removal of the dam created a thin 'alluvial' layer in the reach immediately downstream of the dam; the associated change in relief may also have facilitated bedload propagation. In other words, before the dam was removed, this reach was mainly a bedrock reach with different deep pools in which sediment could be trapped. After the removal of the dam, the sudden arrival of sediment from the reservoir stockpile filled many of these pools and created an incipient homogeneous and less rough semi-alluvial riverbed, which probably facilitated the propagation of previous coarse sediment.

Moreover, mobilization of sediment also increased in the upstream reach once the dam was removed; whereas in control and downstream reaches only increased in the last monitoring year (Table 7), which was the one with higher and longer flows. The response to dam removal of the upstream reach is more remarkable if we consider that the 2019−2020 and 2020−2021 hydrological years were quite modest (Table 3). Therefore, it seems that the mobilized volume is specially related to the dam effects in the reach where more changes are reported. This is again probably associated with degradation of the sediment stockpile following base-level lowering and upward erosion. So, in those years following dam removal, the mobilization of sediment is more a question of availability and change of river conditions, opening of the barrier and base level change than a response to high flows, as it was noticed by Gilet et al. (2021). Nevertheless, the effects of flows are not negligible. Indeed, the 2021−2022 hydrological year was very relevant with the highest floods during the studied period and more days above the critical flow (Table 3), which was associated to the largest sediment transport volumes, especially in the downstream reach (Fig. 11).

Finally, our results also show that travel distances are linked to flow duration (as, for example, Vázquez-Tarrío and Batalla, 2019 or Schneider et al., 2019), Fig. 9, which partially explain the large estimates of bedload volumes (Table 7, Fig. 11) and high travel distances (Table 6, Fig. 6) recorded in the last monitoring year (2021−2022), with higher number of days above the critical discharge compared to the rest of the study period (Table 3). However, it should be taken into account that the field identification of the critical discharge was only done in the control reach, so it could vary in the different reaches; or even internally in each reach, depending on their morphological conditions and with temporal changes.

5.3. Sediment-transport monitoring following dam removal: how long is enough?

The monitoring time length of this study (6 years) with two surveys before the removal of the dam, one during the removal process, and three after the complete removal provided information about sediment transport during a large period and for different hydrological conditions in a context of dam removal. This type of information is necessary to properly understand the restoration process (Fovet et al., 2023), although it would be interesting to have even longer monitoring to adequately assess the adjustment of the river to the new base level conditions. One question that remains open is how long would it take to the upstream and downstream reaches to achieve a new dynamic equilibrium. But also, for how long bedload transport would continue to be conditioned by the position of the reach in relation to the location of the former Olloki dam, i.e., for how long a 'signal' associated with the dam and the dam removal process could be detected in the sediment-transport data. Ultimately, the answers to these questions are important in deciding how long field monitoring should continue for a full evaluation of dam removal.

5.4. Particle tracking as an effective tool to assess the effects of dam removal

Practices such as dam removal or sediment re-injection are becoming increasingly common to restore geomorphological conditions and sediment transport dynamics downstream of dams. However, this kind of measures are still largely at an experimental stage and several questions can be raised as to how they must be implemented. For example, i. do these works have a real and identifiable effect on sediment transport conditions? ii. is the response to such works determined by the geomorphological and hydrological characteristics of the site? We believe that long-term monitoring may be the best strategy to answer these questions (Bradley, 2017; Gilet et al., 2021). And in this sense, particle tracking may be a very useful tool for this type of monitoring (Peeters et al., 2020; Gilet et al., 2021; Fovet et al., 2023). In addition, as case studies with similar and different hydrogeomorphological conditions become available, comparisons and meta-analysis will become increasingly possible.

In our study case, monitoring coarse sediment transport before, during and after the removal of Olloki dam in the Leitzaran River helped us to understand the following questions: i. First, did sediment transport change in response to the removal of the dam? The response from our monitoring was affirmative, as long as we could detect a change in sediment propagation after dam removal. ii. Second, was the response of sediment transport to dam removal different depending on the position relative to the dam? Again, the answer was affirmative: we observed different behavior in the upstream and downstream reaches; the upstream reach had a more pronounced response to dam removal. Iii. Finally, is it possible to isolate the effects of hydrology from the effects of dam removal from particle tracking data? In this regard, we tested some metrics (such as the EEI index) that allowed us to distinguish the hydrological/hydraulic effects from the consequences of dam removal.

6. Conclusions

In this paper we present the results of 6 years of monitoring a dam removal in the Leitzaran River (Basque country). Bedload transport was monitored before, during and after the dam removal using ~1800 RFID tagged stones. To adequately analyze the potential effects of dam removal on sediment transport, we monitored two reaches immediately upstream and downstream of the dam, and compared them to a reference control reach unaffected by the dam and dam removal.

Our particle tracking data show a change in the patterns of particle displacement and the volumes of mobilized sediment for the dam-influenced reaches (upstream and downstream the dam), whereas the unaffected control reach did not show changes linked to the removal process. We registered very high travel distances of ~8.8 km of tracers seeded upstream the Olloki dam. Upstream reach registered largest travel distances once the removal was completed with similar energy inputs linked to increase slope due to lowering of base level, looser material and narrowing of the channel with the incision of the sediment stockpile. Downstream reach required more energy than any before and even partial removal phases requiring less energy than any once it is completely removed. Mobilization of sediment volume also increased in the upstream reach, probably linked with degradation of the sediment stockpile following base-level lowering and upward erosion. So, in those years following dam removal, the mobilization of sediment is more a question of availability and change of river conditions, opening of the barrier and base level change than a response to high flows. However, the effect of flows is also important: Three years after the dam being removed, bedload transport was enhanced following an active hydrology in the three reaches, but especially in the two dam-affected river reaches, as the 2021−22 hydrological year showed.

In summary, our results confirm that i. particle tracking monitoring with the interpretation of different metrics was useful to assess the response of sediment transport to dam removal in each river reach; and ii. travel distances and mobilization volumes are considerably increased with dam removal (specially once the dam was completely removed). And suggest iii. the need of monitoring data prior to restoration actions, such as dam removal, to achieve a valuable assessment of the results of these actions; and iv., long enough post-action monitoring periods that include different hydrological conditions and allow time for the system to respond and adapt to the restoration action.

CRediT authorship contribution statement

A. Ibisate: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **H. García:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **D. Vázquez-Tarrío:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **I. Sánchez-Pinto:** Validation, Methodology, Investigation. **X. Herrero:** Validation, Investigation, Data curation. **A. Sáenz de Olazagoitia:** Visualization, Validation, Methodology, Investigation, Data curation. **A. Ollero:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2024.109542.

Data availability

We have uploaded the dataset

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Databases

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