HyMoCARES Project
WPT3. EFFECTS OF HYDROMORPHOLOGICAL MANAGEMENT AND RESTORATION MEASURES
D.T3.3.1 Technical note on the evaluation of physical and ecological effects of river restoration works

Case study: Buëch and Upper Drac rivers, France

Project: HyMoCARES
Work package: WPT3. Effects of hydromorphological management and restoration measures
Activity: A.T3.2-3.Evaluating physical and ecological effects of management/restoration works
Deliverable: D.T3.3.1. Technical notes on the evaluation of physical and ecological effects of river restoration works
Status: final version
Date: 14/10/2019
Authors: Frédéric Liébault (Irstea Grenoble), Mélanie Bertrand (Irstea Grenoble), Guillaume Brousse (Irstea Grenoble and Univ. Paris 7), Romain Gaucher (CD05), Isabelle Chouquet (CD05), Baptiste Marteau (CNRS Lyon), Laurent Borgniet (Irstea Grenoble)
Revision: PP10 and PP4
Approval: PP10 Irstea

This project is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme

www.alpine-space.eu/hymocares

CONTENTS

1 Introduction

This technical report presents a synthetic analysis of the main physical and ecological effects of the two monitored river restoration projects in the French Alps investigated during the HyMoCARES project: (1) the Buëch and (2) the Upper-Drac restoration projects. It includes the contributions from Irstea Grenoble and Conseil Départemental des Hautes-Alpes.

The Buëch is a gravel-bed braided river draining the Southern French Prealps. The 2.2-km study reach is located close to the city of Serres, downstream from the EDF dam of Saint-Sauveur. This river is characterized by a general context of sediment supply decrease from the catchment, induced by the cumulative effects of (i) climate changes following the end of the Little Ice Age, (ii) spontaneous reforestation following rural depopulation, and (iii) torrent-control works during the 1860-1915 period. In addition to gravel mining, the bedload transport continuity has been strongly impacted by the construction of the Saint-Sauveur dam in 1992. Three flood gates allow some sediment continuity during floods, but most of the coarse sediments are trapped in the reservoir. As early as 1993, only few months after the dam commissioning, the formation of an entrenched single-thread channel in the former braided corridor downstream from the dam was observed (channel narrowing and channel degradation). The incision of the channel is known to be locally controlled by bedrock outcrops, and by the formation of a coarse surface layer, interpreted as exhumed proglacial deposits from the Last Glacial Maximum (LGM) (Gautier, 1994).

The restoration project of the degraded reach downstream from the dam includes an important operation of artificial gravel replenishment of 44 000 m^3, implemented in September 2016 and funded and supervised by the power plant company EDF. Replenished gravels were directly dredged from the alluvial fan of the Buëch forming into the proximal part of the St Sauveur reservoir. Gravels were deposited along a 400-m reach downstream from the dam, by the creation of two gravel berms on each side of the main channel. To facilitate the remobilization of the left-side berm, a trench was cut into the deposit. The general objective of the restoration project is to improve the hydrogeomorphic conditions of the degraded reach downstream from the dam, by an artificial increase of the coarse sediment supply to the reach, without any other intervention. Expected restoration effects are: (1) the reversing of the channel incision trend,

(2) the increasing of habitat heterogeneity, and (3) the improvement of the ecological status of the river.

The Upper Drac is a gravel-bed braided river draining the Southern French Prealps. The study reach extends from the Champsaur leisure center to the village of St-Bonnet-en-Champsaur (3.7 km). Of particular importance is the presence of lacustrine deposits in the valley floor, related to the obstruction of the valley by the Séveraisse Glacier during Würmian phases of glacier recession. Like most of alpine braided rivers in France, the Drac has been highly impacted by intensive gravel mining since the late 1960s and this activity stops only very recently (2012). The Upper Drac is not impacted by any dam, and it is marginally affected by embankments. Alterations of the channel morphology and sediment transport may have been amplified by the general context of sediment supply mentioned above.

These human alterations of the sediment regime resulted in important channel responses, like active channel narrowing and channel degradation, as attested by the historical long profile of 1913 (Laval and Guilmin, 2014). A shift from a braided to a wandering pattern can be clearly observed along several reaches, including the study reach. Near St-Bonnet, the incision reaches 2 to 4 m, and propagates upstream. This incision rapidly cut through the relatively thin alluvial layer, and starts to scour LGM lacustrine clay deposits. Once this clay layer has been reached, the incision dramatically accelerates, and a 4 to 5 m deep canyon-like channel formed along the Upper Drac. This dramatic accelerated channel incision has several consequences: (i) destabilization of the banks, with a direct threat for the artificial pond of the Champsaur leisure center; (ii) lowering of the water table and subsequent alteration of the riparian forest; (iii) alteration of aquatic habitats related to the loss of gravel substrate and to the expanding clay outcrops.

The restoration project of the degraded reach near St-Bonnet was implemented between November 2013 and April 2014 and consisted in the creation of a new wide and shallow channel using more than 450 000 m^3 of coarse sediment from adjacent alluvial terraces (390 000 m^3) and other complementary sources (60 000 m^3). This is an operation of channel widening using a designed 100-m wide rectangular cross-section, associated with a general rise of the bed-level. A 1.65 m high grade-control weir was built at the downstream end of the restored reach, with a fish pass. These works were funded and supervised by the French Water Agency, the local basin authority (Communauté de Communes du Champsaur), the Hautes-Alpes department, the Région Rhône-Alpes, and EU (total cost of ~5 millions of euros). The general objective of the restoration project is to recreate a braided channel corridor. Expected restoration effects are: (1) the spontaneous recreation of a braided channel, (2) the increasing of habitat heterogeneity, and (3) the improvement of the ecological status of the river.

More information about the two restoration projects can be found in the following reports from the HyMoCARES project (D.T3.1.1):

- Technical note about the monitoring of hydromorphological restoration of the Buëch River (Hautes-Alpes, France) from Irstea Grenoble and Conseil Départemental des Hautes-Alpes
- Technical note about the monitoring of hydromorphological restoration of the Upper-Drac River (Hautes-Alpes, France) from Irstea Grenoble and Conseil Départemental des Hautes-Alpes

2 Monitoring approach

According to the comprehensive classification of restoration monitoring designs presented in Roni *et al* (2013), the physical and ecological monitoring designs of the Buëch and Drac rivers can be classified as a BACI design (Before and After Control Impact), since pre-restoration data are generally available, and since a control site is generally used to evaluate the restoration effects (Fig. 1). However, this has not been possible for every investigated components of the river hydromorphology or ecology (Table 1). For example, the investigation of habitat heterogeneity based on high-resolution imagery was only possible for the restored reach, without any pre-restoration data (Intensive Post Treatment design, referred as IPT).

In the case of the Buëch River, the reference site for isolating the morphological effects of sediment replenishment is the reach located downstream of the frontrunner population of RFID tracers, which gave a good approximation of the maximum propagation of the sediment wave induced by gravel reinjection. In the case of the Upper-Drac River, the reference site is the Chabottes plain, a braided river reach located upstream of the restored reach.

Tab. 1. Types of monitoring designs for the different biophysical components investigated in the monitoring of the restored reaches of the Buëch and Upper Drac rivers

Biophysical monitoring components	**Types of monitoring design**
Channel morphology	BACI
Bedload transport	IPT
Physio-chemical water quality	BACI
Water temperature	IPT
Active channel habitat heterogeneity	IPT
Riparian vegetation	BACI
Macroinvertebrates	BACI
Fish	BA

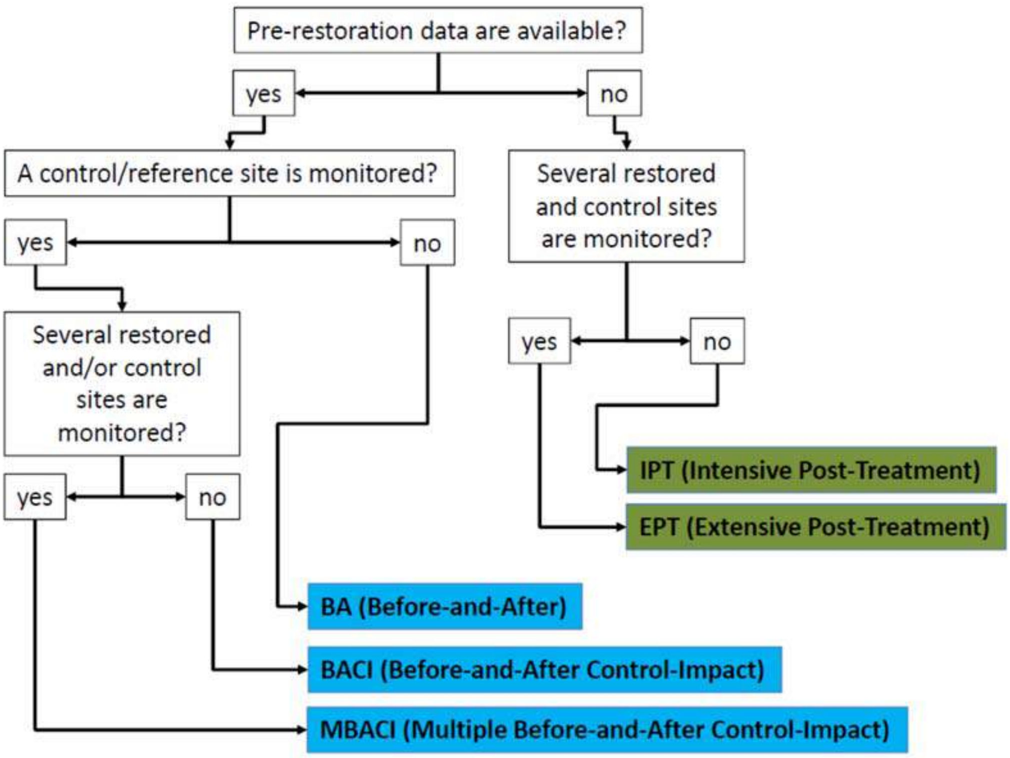

Fig. 1. Simplified chart for the determination of the type of monitoring design used to evaluate the effects of restoration projects (inspired from Roni *et al.*, 2013)

2.1 Physical monitoring

For both case studies, the physical monitoring combines (i) repetitive high-resolution topographic surveys of the restored reach, (ii) a bedload tracing program using active ultra-high frequency RFID technology, and (iii) ancillary field surveys for specific data analysis (e.g. bedload transport computation).

Repetitive topographic surveys of the restored reach (DEMs) are overlayed to produce change detection maps. These DEMs are derived from 3D point clouds (3D points to TIN and to DEM) from airborne LiDAR surveys and from the processing of UAV high resolution images with SfM photogrammetric technics. Prior to this subtraction step, a crucial step of realignment has been conducted in order to fix the systematic error due to point cloud georeferencing, and to have a more accurate sediment budget. After this step, DEMs have been produced into CloudCompare software and the rasters subtracted within ArcGIS©. Topographic differencing based on airborne LiDAR surveys was only possible on dry areas of active channels, since the infrared LiDAR technology cannot capture the bathymetry of wet areas.

Sets of active UHF-RFID tags (inserted into artificial gravels of similar size and density of natural gravels) have been deployed to characterize the residence time of gravels in the restored reach, and to evaluate their virtual velocity. Distances of travel are computed by comparing the position of the tags between field detections.

Some ancillary fieldwork surveys have been made (associated with UAV and active tags detection field campaigns) to record validation data of water depth and ground control points coordinates with a dGPS, and some surficial grain-size distribution (GSD) characterization. GSD data have been notably used to compute time-integrated bedload transport using the BedloadWeb tool (https://www.bedloadweb.com).

2.1.1 Buëch case study

Topographic surveys of the Buëch restored reach before and after the sediment replenishment operation are presented in Table 2. Only some of these surveys have been used to capture changes. The analysis of the morphological effects of sediment replenishment is based on the differencing of the November and December 2016 LiDAR surveys. The November 2016 survey has been done right after the setting of artificial gravel berms, and it can be considered as a pre-restoration topographic dataset. The 2015 survey has been only used to control the effective volume of the artificial berms. The analysis of habitat heterogeneity following sediment replenishment is based on summer 2017 and 2018 UAV surveys.

Tab. 2. Topographic surveys of the Buëch River downstream of the Saint-Sauveur dam, before and after sediment replenishment; in red: topographic surveys used to evaluate the morphological effects of sediment replenishment; in blue: topographic surveys used to evaluate active channel habitat heterogeneity changes following sediment replenishment

Date of the survey	Type of survey	Data source	Before (B) After (A) restoration Spatial coverage
15/01/2015	Airborne LiDAR	EDF/Sintegra	B (Serres-Montrond, 6 km)
04/11/2016	Airborne LiDAR	EDF/Sintegra	A (Serres-Eyguians, 11 km)
22/12/2016	Airborne LiDAR	EDF/Sintegra	A (Serres-Eyguians, 11 km)
10-11/07/2017 24/08/2017	UAV-SfM*	Irstea	A (St. Sauveur-Montrond, 2 km)
04-05/09/2018	UAV-SfM**	Irstea	A (St. Sauveur-Montrond, 2 km)
16/11/2018	Airborne LiDAR	EDF/Sintegra	A (Serres-Eyguians, 11 km)

* using RGB and IR cameras
** using RGB camera

A set of 148 active tags inserted in artificial gravels has been deployed upstream of the dam to evaluate the sediment transparency, and to constrain the travel distance of the reinjected gravels downstream of the dam.

2.1.2 Upper Drac case study

Topographic surveys of the Upper Drac restored reach before and after the sediment replenishment operation are presented in Table 3. The morphological monitoring of the restoration integrates the whole topographic dataset based on LiDAR and dGPS surveys. The analysis of active channel habitat heterogeneity is based on the two UAV surveys done in summer 2017 and 2018.

Like for the Buëch, a set of 161 tags has been inserted in artificial gravels and deployed in the braided Chabottes plain upstream of the restoration site, to evaluate the bedload transit time from this major sediment source and the restored reach.

Tab. 3. Topographic surveys of the Upper Drac River near Saint-Bonnet-en-Champsaur, before and after the restoration project; in red: topographic surveys used to evaluate the morphological effects of sediment replenishment; in blue: topographic surveys used to evaluate active channel habitat heterogeneity changes following sediment replenishment

Date of the survey	Type of survey	Data source	Before (B) After (A) restoration Spatial coverage
08/02/2011	Airborne LiDAR	CD05/Sintegra	B (Ricoux-Sautet, 35 km)
15-28/10/2013	Airborne LiDAR	CLEDA/Vinci	B (St. Bonnet, 3.5 km)
11-17/04/2014	dGPS survey	CLEDA/Vinci	A (St. Bonnet, 3.5 km)
10/09/2015	Airborne LiDAR	CD05/Sintegra	A (Ricoux-Sautet, 35 km)
22/09/2016	Airborne LiDAR	CD05/Sintegra	A (St. Bonnet, 3.5 km)
04-05/09/2017	UAV-SfM*	Irstea	A (St. Bonnet, 3.5 km)
18-20/09/2018 26-27/09/2018 04/10/2018	UAV-SfM**	Irstea	A (St. Bonnet, 3.5 km)
18/10/2018	Airborne LiDAR	CLEDA/OPSIA	A (Orcières/Les Borels-Sautet, 45 km)

* using RGB and IR cameras
** using RGB camera

2.2 Ecological monitoring

An overview of the ecological monitoring protocol implemented by the Département des Hautes-Alpes (CD05) is presented here. Monitoring is a key component of adaptive management, especially in the context of restoration works. So, the protocol design is based on the existing knowledge of aquatic ecosystems and it follows a multi-disciplinary approach (Navarro *et al.*, 2012).

Following recommendations from AFB (ex Onema) and French Water Agencies (Navarro *et al.*, 2012), the CD05 monitoring protocol includes 3 interconnected biological compartments (macroinvertebrates, fishes, and riparian ecosystems). Starting with those 3 working conditions, the frame of the monitoring protocol is detailed below.

2.2.1 Hydro-biological monitoring

The hydro-biological monitoring concerns fish and benthic invertebrate fauna. For the benthic invertebrate fauna, two protocols have been combined through time, in order to cover all biological cycles:

- ✓ the Water Framework Directive application to evaluate the water quality by quoting the indicator group of invertebrates;

- ✓ the semi-qualitative methodology on the lotic habitat to qualitatively evaluate invertebrates (as a complement of the WFD protocol.

The monitoring of fish populations is based on data from repetitive electric fishing surveys.

2.2.2 The physical chemistry monitoring

To have a precise image of the chemical and physical properties of the river's water quality, a set of parameters have been investigated using discrete water sampling during the project (Table 4). Those parameters are classically used to characterize the water quality of biological monitoring stations. Each water sampling have been systematically associated with a discharge gauging using water velocity measurements.

Tab. 4. List of monitored physical chemistry parameters

Physical parameters	Chemical parameters
temperature	ammonium Nitrogen
conductivity	nitrites
pH	nitrates
dissolved diatomic oxygen	orthophosphates
diatomic oxygen saturation rate	total phosphorus
biological oxygen demand at 20°C	organic carbon
Suspended sediment concentration	*Escherichia Coli*
	intestinal enterococci

2.2.3 Investigating riparian environments and water temperatures

The diachronic analysis of SPOT satellite images over the period 2014-2017 and a field campaign in 2018 made it possible to map and study the evolution of the different functional units of the fluvial corridor (water, bare alluvium, pioneer phase, herbaceous phase, shrub phase, forest phase, riparian area exploited, riparian zone occupied). This work was done in the restored areas and test areas downstream of the restored areas (Gramond, 2018).

Airborne infrared thermal surveys of long stream reaches including restored sites and reference reaches were conducted during summer 2018 to investigate the longitudinal patterns of surficial water temperatures of the active channel aquatic units (Marteau and Piégay, 2018). These one-shot data surveys were used to inform groundwater – surface water exchanges along the restored reaches.

3 Physical effects

3.1 Buëch case study

Hydrological conditions after sediment replenishment

Few weeks after the replenishment operation, a large and long-duration Mediterranean autumn flood occurred in the Buëch River (Fig. 2), with a recurrence interval estimated at 5 years at the Serres gauging station. This flood was characterized by a long sluicing from EDF (Fig. 2B). The three flow peaks have been in total hydraulic transparency (Fig. 2C). In the replenishment reach at the peak flow (265 m^3 s^{-1}, the 22/11/2016 at 11:00 AM), the right-bank berm was submerged, the trench cut into the left-bank berm was in bankfull conditions, and the left-bank berms were not submerged (Fig. 2D). The total bedload transport volume during the flood was estimated at 12 000 m^3 from hydraulic computation using the Recking formulae with the Bedloadweb tool (Fig. 2B).

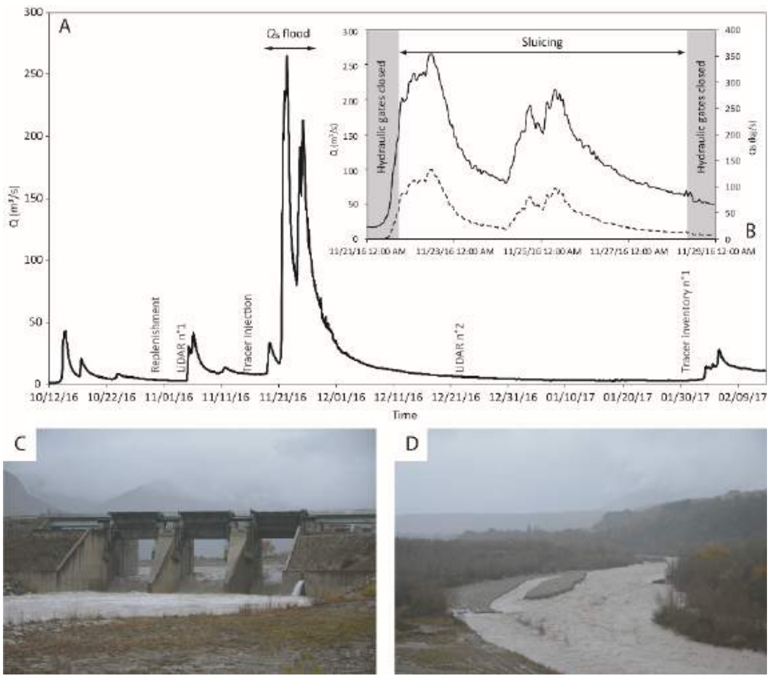

Fig. 2. Buëch River hydrology during the investigated period. A: Discharge record at the Serres gauging station; B: Focus on flood discharge (dark line) and computed bedload transport (dashed line); C: View of the sluicing operation during the Q5 flood in November 2016; D: View of the replenishment site at the time of the peak flow; view looking downstream (Brousse *et al.*, in press)

Bedload tracing

We obtained a 71% recovery rate of RFID tracers (n=105). Almost all of the recovered tracers were displaced during the period (n=100). Many tracers crossed the dam (19.6%; n=29) whereas others not (51.4%; n=76). Most of them stopped their course in the alluvial fan (32.9%; n=58). Mobile tracer travel distances range from 12 to 3406 m, with a mean value of 1020 m. All the investigated grain sizes have been mobilized during the flood, and no grain-size effect on transport distances was observed. Frontrunners deposited downstream the confluence with the Torrent de Channe, in a reach where bedload sheets with avalanche faces were observed just after the flood. The cumulative frequency of transport distances shows that 50% of the tracers travelled a distance greater than 900 m, and that a rapid decline of tracer frequency occurs at a transport distance of around 1700 m.

Sediment remobilization in the replenishment site

In the replenishment reach, the topographic differencing between the LiDAR surveys of November and December 2016 shows a gross erosion of 25 450 m^3 and a gross deposition of 7600 m^3 (Fig. 3A and 3B). This negative sediment balance is clearly driven by berm erosion: 52% of the initial berm volume has been eroded during the flood. The replenishment reach shows a much higher morphological activity in the right-side of the channel, where most of the flow was concentrated. Erosion was very important for the right-bank berm (6450 m^3), referred as BU1 in Fig. 3B. The left-bank berm in direct contact with the active channel (BU2C in Fig. 3B) has been also strongly eroded (14 100 m^3). Only 1550 m^3 of erosion was observed for the berm on the left-side of the trench (referred as BU2A in Fig. 3B). Bank erosion of a low-terrace accounted for the remaining 2800 m^3 of sediment loss. A deposit of 800 m^3 was observed along the trench, showing that bedload transport was active in this artificial secondary channel. The remaining 6800 m^3 of deposition are homogeneously distributed over the low-flow channel of the replenishment reach, which exhibits a 0.5 m aggradation after the flood. This clearly shows that a significant bedload volume crosses the dam during the flood.

Morphological change in the downstream reach

Downstream the replenishment reach, the longitudinal distribution of active channel bed-level changes shows a much higher morphological activity in the first few km downstream the dam, up to a distance of c.a. 3.5 km, and a lower activity further downstream (Fig. 4). This is a first observation suggesting a strong channel response to sediment replenishment. Along the first 3.5 km downstream the dam, three successive singular reaches can be easily isolated, which alternate in aggradation and degradation. The first one corresponds to a 2-km aggraded reach down to Montrond (positive net sediment budget of 20 700 m^3); the second one corresponds to a 0.45-km degraded reach; the third one corresponds to the next 0.75-km aggraded reach.

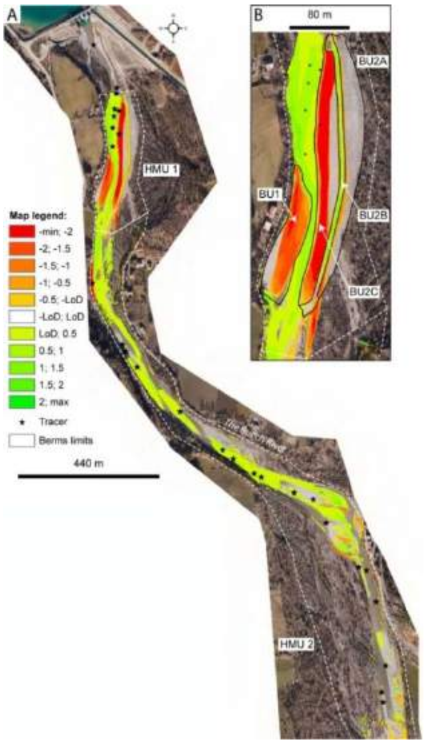

Fig. 3. Channel change detection map following the November 2016 flood in the Buëch River downstream of the St. Sauveur dam. A: DoD after LoD subtraction then exclusion; the white dashed lines represent the surface covered by LiDAR data; B: Zoom on the replenishment reach (Brousse *et al.*, in press)

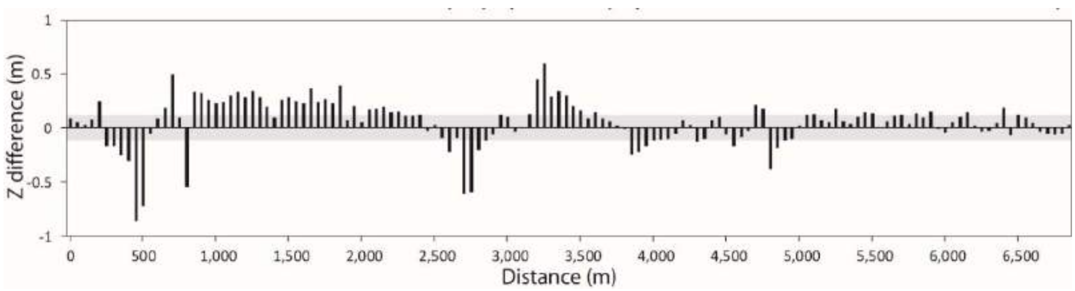

Fig. 4. Buëch River bed-level change downstream of the St. Sauveur dam following the November 2016 flood, based on the mean elevation of the active channel; grey surface corresponds to the level of detection (0.13 m) (Brousse *et al.*, in press)

Assessment of the downstream propagation of replenished gravels

The classic sediment balance equation (O=I-ΔS, with O, the sediment output, I, the sediment input, and ΔS, the net storage change) and the cumulative distribution of tracer transport distances were combined for assessing the downstream propagation of the sediment wave induced by the sediment replenishment operation. By considering sediment loss of the replenishment reach, it appears that 25 450 m^3 of gravels have been supplied to the downstream reach of the Buëch River, mainly by lateral erosion of artificial berms (22 650 m^3). A first way to evaluate the minimum distance at which this volume has been entirely diffused is to look at the cumulative sediment deposition curve downstream of the replenishment reach. This curve shows that the minimum diffusion reach has a length of 2.3 km (Fig. 5). By applying the cumulative frequency distribution of tracer transport distances to the volume of sediment loss in the replenishment reach, it is possible to obtain a theoretical curve of the sediment wave deposition. This curve nicely fits to the observed cumulative channel deposition along the first 2.3 km downstream of the replenishment reach (Fig. 5). It is likely that this distance of 2.3 km corresponds to the maximum propagation of the sediment wave induced by gravel replenishment. This also means that this distance is likely the appropriate spatial scale to consider for applying a reach-scale sediment balance equation which is not too much biased by sediment throughput.

The application of the sediment balance equation along the reach where significant net deposition is observed provides a way to reconstruct sediment transfers of the Buëch downstream of the dam during the November 2016 flood (Fig. 6). The only term of the equation that has been constrained is the storage change along the reach (net deposition of 20 700 m^3). By considering bedload transport computation using the flood hydrograph at the downstream end of this reach (12 000 m^3), it is possible to evaluate bedload inputs at 32 700 m^3. Inputs are divided into (i) berm erosion (22 650 m^3), (ii) bank erosion (2800 m^3), and (iii) the back-calculated bedload passing through the dam (7250 m^3). Since a deposited volume of 7600 m^3 is observed along the replenishment reach, it should be added to the 7250 m^3 that passed through to dam, giving a total bedload transport crossing the sluice gates during the flood of 14 850 m^3. This value corresponds to 35% of the mean annual bedload yield upstream of the dam and 74% of the mean bedload yield downstream of the dam.

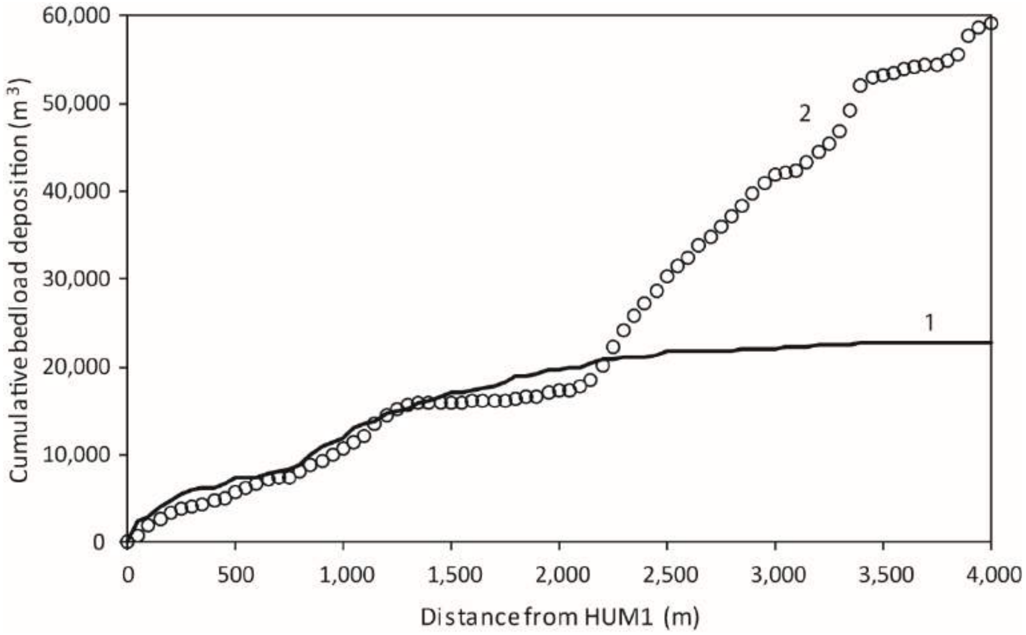

Fig. 5. Cumulative bedload deposition downstream of the replenishment reach (HUM1); 1: Reconstruction of bedload deposition from tracer CDF; 2: Observed deposition using sequential LiDAR surveys (Brousse *et al.*, in press)

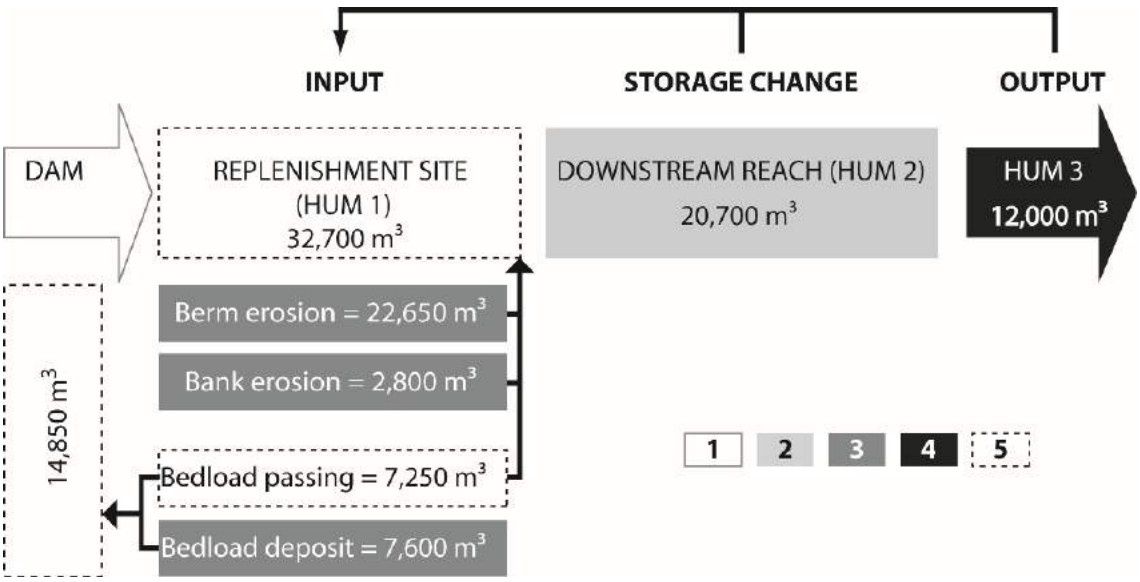

Fig. 6. Buëch River sediment balance of the November 2016 flood; 1: unknown volume; 2: DoD after LoD subtraction then exclusion; 3: bedload calculation; 4: back-calculated volume (Brousse *et al.*, in press)

A key issue to consider for the planning of sediment replenishment operations in river channels is the pattern of gravel redistribution downstream of the injection site during flow events. The case of the Buëch River offers a well-documented field experiment where the combination of topographic resurvey covering a long channel reach (c.a. 7 km) and bedload tracing successfully helps to isolate the morphological signature of an artificially-induced sediment wave. The bed-level evolution and 2D change detection map from sequential LiDAR data both reveal a dominant pattern of channel aggradation along a 2.5 km reach downstream of the dam. Further downstream, another sediment deposition zone is observed at a distance of 3.5 km, but this distal aggraded reach is likely not related to the sediment replenishment operation. The cumulative frequency of bedload transport distances observed during the flood indeed shows that 90% of the tracers deposited at a distance lower than 2 km. When this cumulative frequency is used to redistribute the effective bedload supply from the replenishment reach, which has been well-constrained by sequential LiDAR data, it is possible to reproduce the observed cumulative deposition curve up to a distance of around 2 km downstream of the replenishment reach. Data from RFID tracers clearly help to detect the propagation front of the artificial gravel wave. It should however not be forgotten that the frequency curve of tracers only integrates the coarse fraction of the bedload GSD, and it is possible that the right-tail of the distribution is not correctly represented by the observations. This is also supported by the fact that tracers have been deployed upstream the dam, and that their virtual velocity may have been reduced by the dam effect. A seeding of tracers in the artificial berms would have been better for reconstructing the deposition pattern of the replenished sediment. It is also recognized that a change detection integrating the wet portions of the active channel would have been better for reconstructing the flood sediment balance. However, the fact that the regulated discharge downstream the dam was strictly the same during the two LiDAR surveys shows that bed-level evolutions obtained for both the active channel and the low-flow channel can be considered as unbiased.

Sediment replenishment effect on physical habitat heterogeneity

The images acquired with the UAV were processed within a photogrammetric software to produce high resolution (~5 cm) DEMs and orthophotos. A specific procedure was developed to correct on the DEM the effects of air/water interface refraction and improve water depth accuracy.

A simple typology of physical habitats was derived from the main physical features, extracted from the analysis of DEMs and orthophotos. The relative elevation to the water level was computed within a GIS from a rasterization of a TIN of the water surface which was obtained from elevations of the nodes of the water polygon limits. This relative elevation to the water surface was obtained by subtracting interpolation of water level to the DEM (previously corrected of the effects of refraction). Relative DEM was discretized into 6 classes which represent various conditions: (1) lower than -0.35 m, the deepest aquatic units found in the stretch; (2) between -0.35 m and -0.1 m, shallow aquatic units which can be numerous within braided channels; (3) between -0.1 m and 0.1 m, the transition habitats which are frequently inundated; (4) between 0.1 m and 0.35 m, the terrestrial habitats less frequently inundated; (5) between 0.35 m and 1.2 m, the terrestrial habitats inundated for larger floods; and (6) above 1.2 m, the higher terrestrial habitats of the active channel.

The presence of vegetation on gravel bars was detected with a simple threshold on the red value of the orthophotos (below 60 for 2017 and below 95 for 2018) and it was discretized in two classes (presence/absence). Unvegetated gravel bars were classified according to the dominant surficial sediment size, considering only two types: fine-grained gravel bars (mostly composed of medium to very-coarse coarse gravels of the Wentworth scale, from 8 to 64 mm), and coarse-grained gravel bars (mostly composed of small to large pebbles of the Wentworth scale, from 64 to 256 mm). This classification was done by an expert-based interpretation of HR orthophotos.

Relative elevation, vegetation and grain size classes were combined into 12 classes: 3 classes of aquatic habitats with various water depths, 3 classes of unvegetated fine-grained gravel bars with various relative elevations, 3 classes of coarse-grained gravel bars with various relative elevations, and 3 classes of vegetated gravel bars with various relative elevations.

This methodology was apply for 2017 and 2018 campaigns where the discharge of the Buëch was at low flow and nearly identical for both campaigns (Fig. 7a and b). The extent was limited to the maximal spatial coverage available for both dates within the active channel. We identified changing habitat conditions between 2017 and 2018 (Fig. 8). This represents a large proportion of the restored reach (63%), with a concentration of changes in the areas within or close to the low-flow channel. In descending order of importance of change, the changes between a terrestrial type to another terrestrial type are the most frequent (51% of the observed changes), then the changes between an aquatic type to another aquatic type (19%), then the changes between an aquatic type to a terrestrial type (17%) and finally the changes between a terrestrial type to an aquatic type (13%). This means that there are more changes in terms of exposed bar habitat conditions, in terms of grain size and of vegetation coverage than changes in terms of morphology of the channels bed or than changes occurring near the water level. This indicates that the morphological structure of the active channel has not been highly modified during the period. The frequency distributions of habitat types (Fig. 9) shows more equally distributed types for 2018 than for 2017. Habitats (considering terrestrial and aquatic habitats together) are more diversified, even if this increasing heterogeneity is not related to an increase of the number of water channels, but directly related to modifications of the bed morphology. All the vegetated classes have increased between 2017 and 2018, and this confirms the first observations on the proportion of changes by habitat types.

At the reach scale we calculated a Shannon index (Eq. 1) of diversity of aquatic and terrestrial habitats considered both together and separately (Table 5).

Eq. 1 $$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

Where S is the number of types and p_i the frequency of each type.

This Shannon index is often used in ecology to assess the changes in species abundance and richness. Here it shows that between 2017 and 2018, the diversity increased slightly when considering all the habitat types together: the frequency of rare habitats increased and conversely the frequency of common habitats decreased in order to maximize the frequency of all habitats together. It is noticeable that the diversity of aquatic habitats decreased between 2017 and 2018; this is visible on the orthophotos (Fig. 7 a and c) where the geometry of the active channel and the number of channel simplified. Conversely the diversity of terrestrial habitats increased as the water level changed, the grain sized spatially changes and the vegetation developed on the highest less frequently inundated bars.

Tab. 5. Evolution of the diversity of habitat types between 2017 and 2018 assessed with the Shannon index calculated for aquatic and terrestrial habitat types

Shannon index	2017	2018
All habitats	2.97	3.04
Aquatic habitats	0.87	0.77
Terrestrial habitats	2.32	2.62

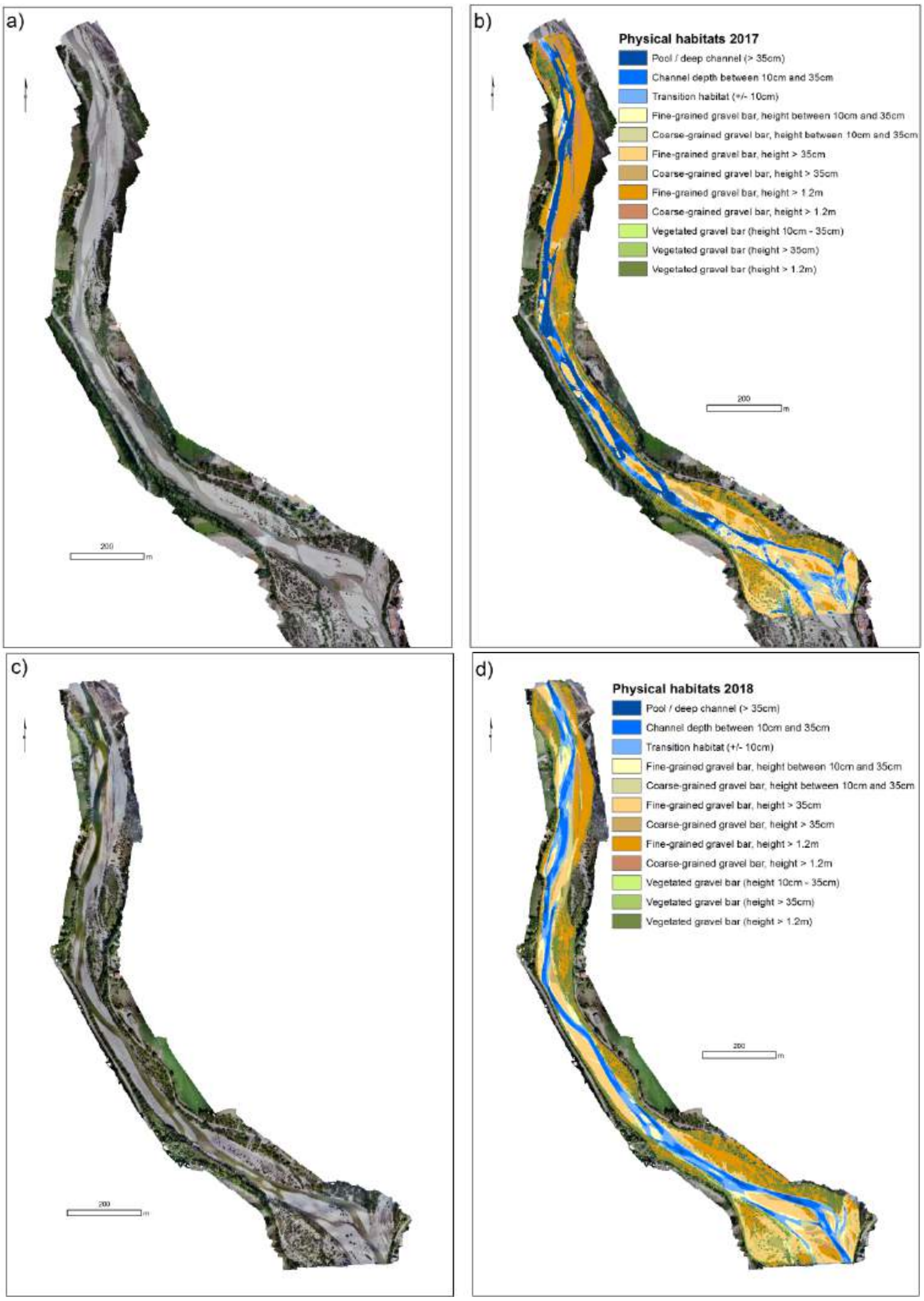

Fig. 7. Buëch River physical habitats. a) 2017 orthophotos; b) 2017 map of physical habitats; c) 2018 orthophotos; d) 2018 map of physical habitats.

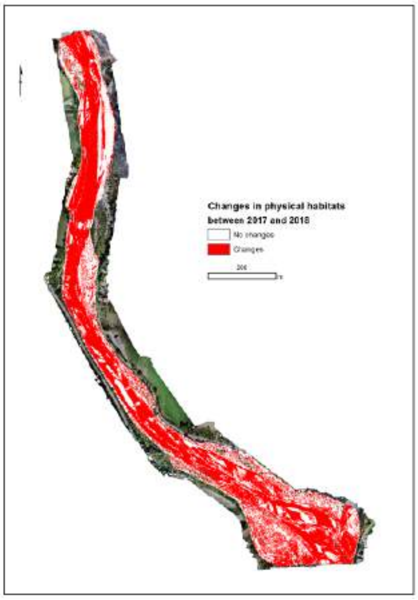

Fig. 8. Location of changes in physical habitats along the Buëch restored reach between 2017 and 2018.

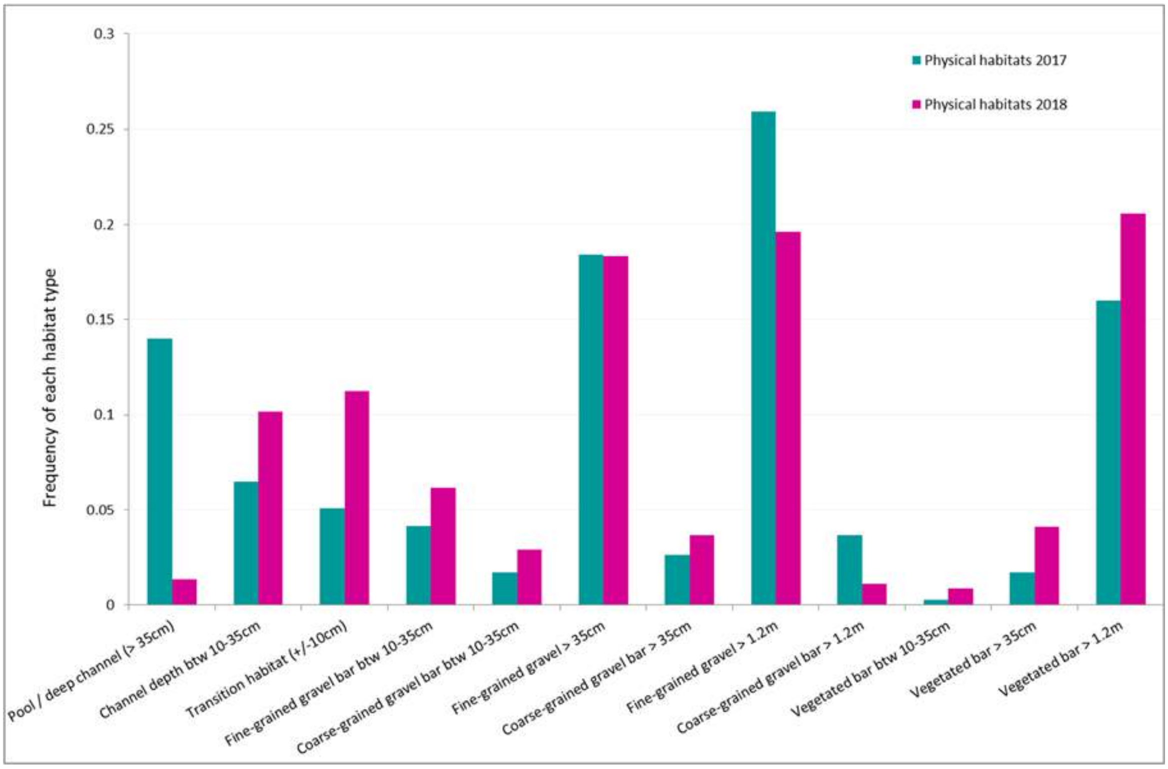

Fig. 9. Frequencies of physical habitat types at the Buëch restored reach scale, for 2017 and 2018 low flows.

3.2 Upper Drac case study

Morphological trajectory of the restored reach

The hydrological sequence of the Upper Drac since the restoration works has only showed some low intensity snowmelt or autumn rainfall-induced flow events (Fig. 10). The only event exceeding the 2-yr daily flood discharge is the November 2014 peak discharge (88 m^3 s^{-1}). The November 2016 flood, which has been particularly intense in the Buëch (5-yr return period), has been much lower in the Upper Drac. Bankfull discharge conditions along the restored reach have not yet been observed until now.

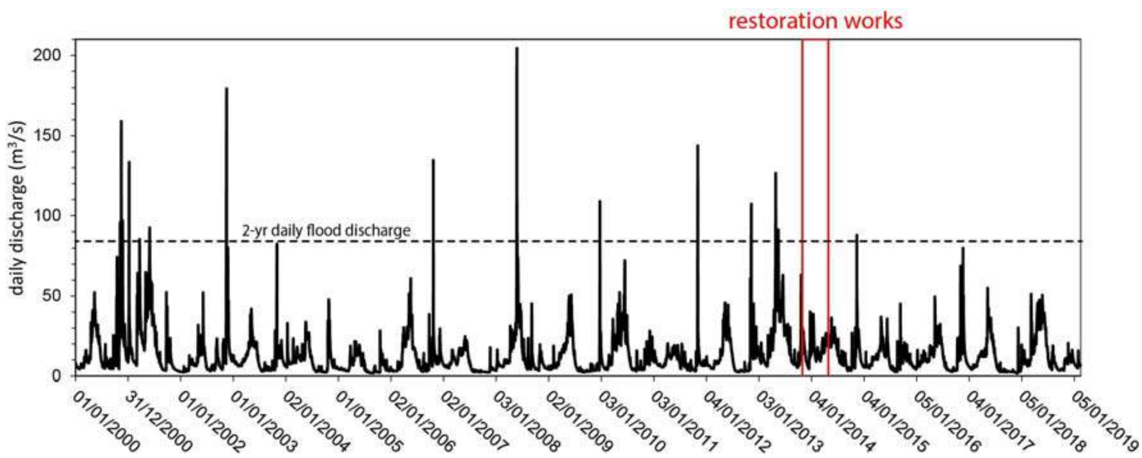

Fig. 10. Upper Drac River hydrology at the Guinguette gauging station (510 km²) from January 2000 to February 2019 (data from EDF)

A strong spatial variability of the active channel bed-level evolution between 2015 and 2018 is observed along the river length comprised between the Chabottes plain and the restored reach (Fig. 11). A general trend of channel aggradation is observed in the Chabottes braided reach (R1 reach), as well as in the wandering transition zone (R2 reach). Along the restored reach, an alternating sequence is observed between two aggraded reaches (D1 and D2), and two degraded reaches (E1 and E2). Aggradation in D1 can be explained by sediment supply from the Chabottes plain, and degradation in E1 is interpreted as regressive erosion in the proximal main channel of the restored reach, induced by a break in slope in the initial restored long profile. Aggradation in D2 is spatially linked with a zone of active channel width increase, which may have enhanced sediment deposition. The distal reach (E2) may have not yet been fed by the sediment supply from the Chabottes plain, as suggested by its degradation trend.

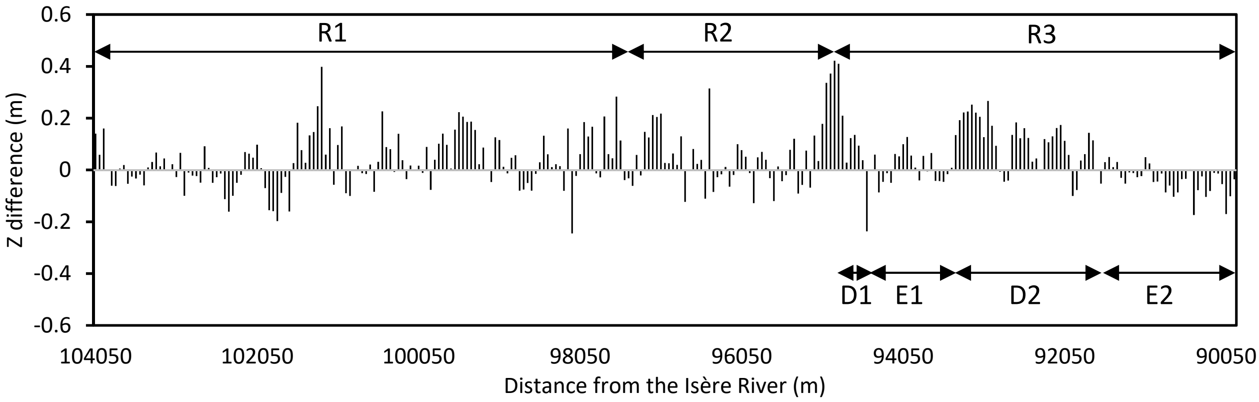

Fig. 11. Drac River bed-level change between 2015 and 2018, based on the mean elevation of the active channel calculated at regularly-spaced cross sections; R1: Chabottes braided reach, R2: wandering transition reach, R3: restored reach

DEM differencing during two periods after the restoration has been used to estimate the sediment budget of the Upper Drac, from the Chabottes plain to the restored reach (Table 6). The aggradation trend along the restored reach is confirmed by the positive net volumetric changes for the two periods. The two upstream control reaches (R1 and R2) show the same trend during the 2015-2018 period. It should however be noticed that those budgets only consider the exposed areas of the active channel, given that infrared LiDAR surveys do not account for the bathymetric relief of the channel. It is not excluded that the inclusion of the submerged portions of the channel into the net volumetric change would provide a stable or a negative net change, since accretion of exposed gravel bars could have been partially or totally compensated by the entrenchment of low-flow channels.

Tab. 6. Sediment budgets of the Upper Drac based on sequential airborne LiDAR surveys; volume uncertainty was estimated using the error model of Anderson (2019) that accounted for systematic errors and spatially correlated random errors

Period	Reach	Systematic error (m)	Spatially correlated random error (m)	Net volumetric change (m^3)
09/2015-09/2016	R3	-0.0045	0.035	5800 +/-2190
09/2016-10/2018	R3	0.0016	0.052	31 200* +/-810
09/2015-10/2018	R1	-0.0003	0.045	16 100 +/-280
	R2			10 000 +/-50
	R3			38 400* +/-150

*Artificial input (2000 m³) has been replenished by CLEDA in R3 in 2017

The spontaneous braiding recovery along the restored reach has been documented using the normalized bed relief index (BRI*), which can be considered as a good proxy of the sediment regime of braided channels (Hoey and Sutherland, 1991; Liébault *et al.*, 2013). It is calculated as the standard deviation of channel elevation along a cross-section of the active channel, normalized by the active channel width. Low values of the BRI* tend to sign transport-limited conditions, whereas high-values tend to sign supply-limited conditions. A linear increase of the BRI* is observed for the restored reach since 2014 (Fig. 12). This clearly shows a spontaneous braiding recovery related to the formation of a network of anabranches (main and secondary low-flow channels) in the restored reach. This morphodynamics is clearly visible on DEM differencing as well as on aerial pictures of the restored reach (Fig. 13 and 14). By considering the BRI* value of the Chabottes braided reach (0.0045) as a reference for braiding conditions of the Upper Drac environmental setting, it can be seen that the BRI* of the restored reach get closer through time to this reference, but the braided morphology has not totally recovered 4 years after the restoration.

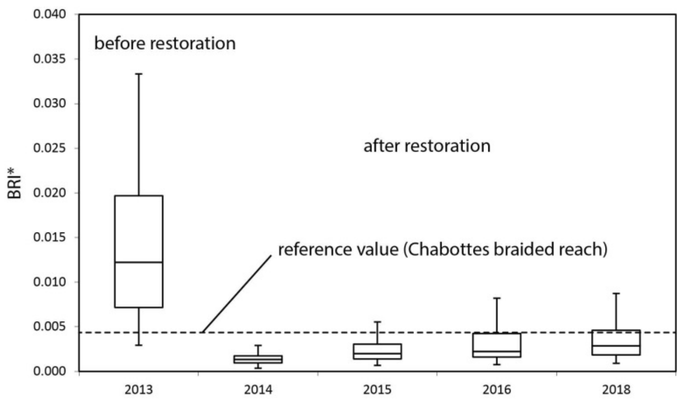

Fig. 12. Bed Relief Index (BRI*) evolution in the restored reach before and after restoration

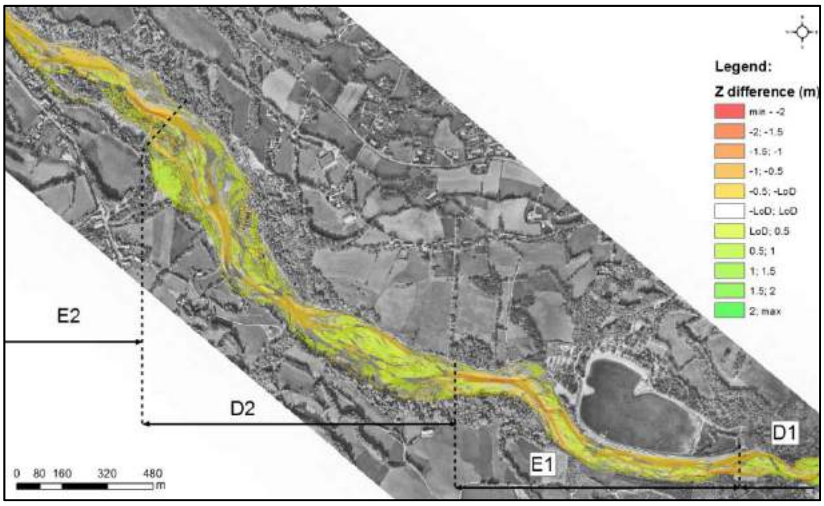

Fig. 13. DEM of difference between 2015 and 2018 in the restored reach, based on airborne LiDAR surveys, showing the formation of a network of anabranches, typical of the braiding fluvial pattern

Fig. 14. Drone view of the restored reach of the Upper Drac in 2018, showing the spontaneous recovery of the braided channel morphology (@SIGosphère)

Bedload tracing from the Chabottes plain

Since January 2017, the bedload tracing program initiated at the distal end of the Chabottes plain using artificial stones equipped with active UHF-RFID tags allows to evaluate the coarse sediment transport connectivity between the restored reach and its first upstream significant bedload sediment source.

Four tracer inventories have been done between August 2017 and September 2018 (Table 7). Results show a rapid dispersion of tracers between the Chabottes plain and the restored reach, with frontrunners already reaching the restored reach only 20 months after their deployment, despite relatively low hydrological forcings (Fig. 15). Recovery rates based on the total population of tracers are high (from 79 to 97 %). Recovery rates for mobile tracers only are lower, and strongly decline through time, passing from 80% to 36% between the first and last inventories. It should however be mentioned that only a small fraction of deployed tags have been mobilized during the period (Table 7). Those correspond to tracers deployed in or close to the main low-flow channel. Tracers initially deployed on gravel bars were much less mobile, since gravel bars in the Chabottes plains do not show a strong morphological activity during the period.

These observations confirm a strong bedload connectivity between the restored reach and its main sediment source, which is an important condition for the maintenance of the restored braided pattern.

Tab. 7. Summary reports of results from the bedload tracing program using UHF-RFID active tags in the Upper Drac River

Tracer inventories	Recovery rates (%)*	Mobile tracers (%)**	Mean distances of transport (m)	Maximum distances of transport (m)	Cumulative mean distances of transport (m)	Cumulative maximum distances of transport (m)
August 2017	96(80)	17(12)	440	1276	440	1276
December 2017	97(60)	4(3)	1037	2894	646	2894
April 2018	95(33)	3(2)	150	186	670	2894
September 2018	79(36)	15(9)	852	2702	1328	3121

*In brackets, recovery rates for mobile tracers only

** In brackets, the number of recovered mobiles tracers

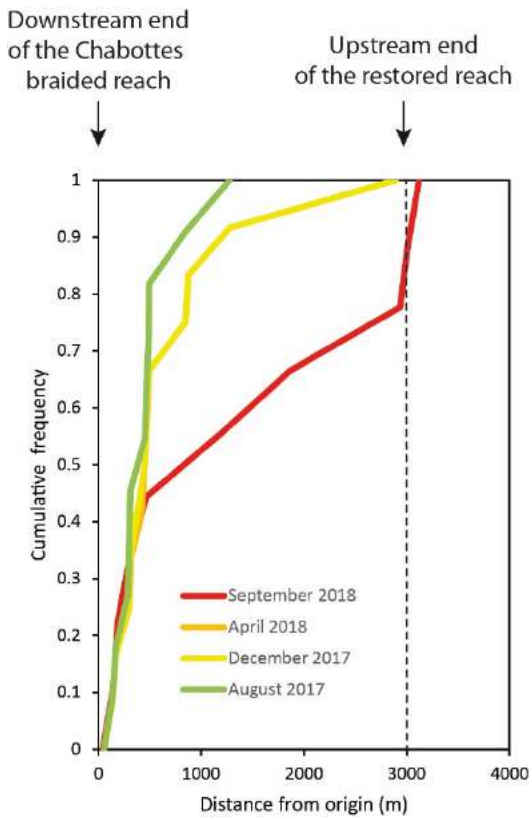

Fig. 15. Cumulative distributions of transport distances of RFID tracers deployed in the Chabottes plain

Restoration effect on physical habitat heterogeneity

As for the Buëch case study, high resolution (~5 cm) DEMs and orthophotos were produced with a SfM photogrammetric process. A specific procedure was developed to correct on the DEM the effects of air/water interface refraction on water depth.

Physical conditions supporting habitats are characterized from the main physical features, extracted from the analysis of DEMs and orthophotos: the relative elevation to the water level (obtained as for the Buëch reach), the variance of roughness which is an indirect measure of the grain size on gravel bars and under the water (Vazquez-Tarrio et al. 2017; Corbin, 2018) and the map of presence / absence of fine sediments.

Relative elevation to the water level was discretized into 7 classes, i.e. 3 classes under the water level, and 4 above, with the following class boundaries which correspond to rounded percentile values of the composite distribution of 2017 and 2018 values.

Tab. 8. Discretization of the relative elevation to the water level

Classes boundaries	<-0.35	-0.35- -0.1	-0.1 - 0	0 - 0.1	0.1 - 0.35	0.35 - 1.2	> 1.2
Percentile of the composite distribution	Under Perc. 0.01	Between Perc. 0.01 and 0.1	Between Perc. 0.1 and 0.25	Between Perc. 0.25 and Median	Between Median and Perc. 0.75	Between Perc. 0.75 and 0.98	Above Perc. 0.98
Class number	1	2	3	4	5	6	7

Variance of roughness was classified into 4 classes corresponding to quantile values of the distribution of 2018 values without considering 0. The 2018 distribution was chosen arbitrary but it is close to the 2017 distribution. The classes boundaries are the following (Table 9).

Tab. 9. Discretization of the variance of roughness

Classes boundaries	0 - 1.98e-05	1.99e-05 - 7.92e-05	7.93e-05 - 3.36e-04	3.37e-04 - 5.05e-03
Percentile of the composite distribution (excluding 0)	Under perc. 0.25	Between perc. 0.25 and 0.5	Between perc. 0.5 and 0.75	Above perc. 0.75
Class number	1	2	3	4

Values are very low because the roughness indicator was calculated in meters, but the meaning of the classes remains identical: the lower the variance of roughness is, the smaller the sediment are.

The fine sediments on gravel bars are already mapped as a binary map resulting from the analysis of several metrics (class 1 corresponding to fine patches and class 0 corresponding to coarse patches, vegetation, and water, i.e. not fine sediments on gravel bars).

The logical combination of all the unique values of class (i.e. 7*4*2) allowed distinguishing a large set of classes, some being marginally represented. The total number of classes is 40 as some combinations of the criteria are not possible (i.e. no terrestrial fine sediments considered under the water).

This methodology was apply for 2017 and 2018 campaigns where the discharge of the Drac was at low flow and nearly identical for both campaigns (Fig.16). The extent was limited to the maximal spatial coverage available for both dates within the active channel.

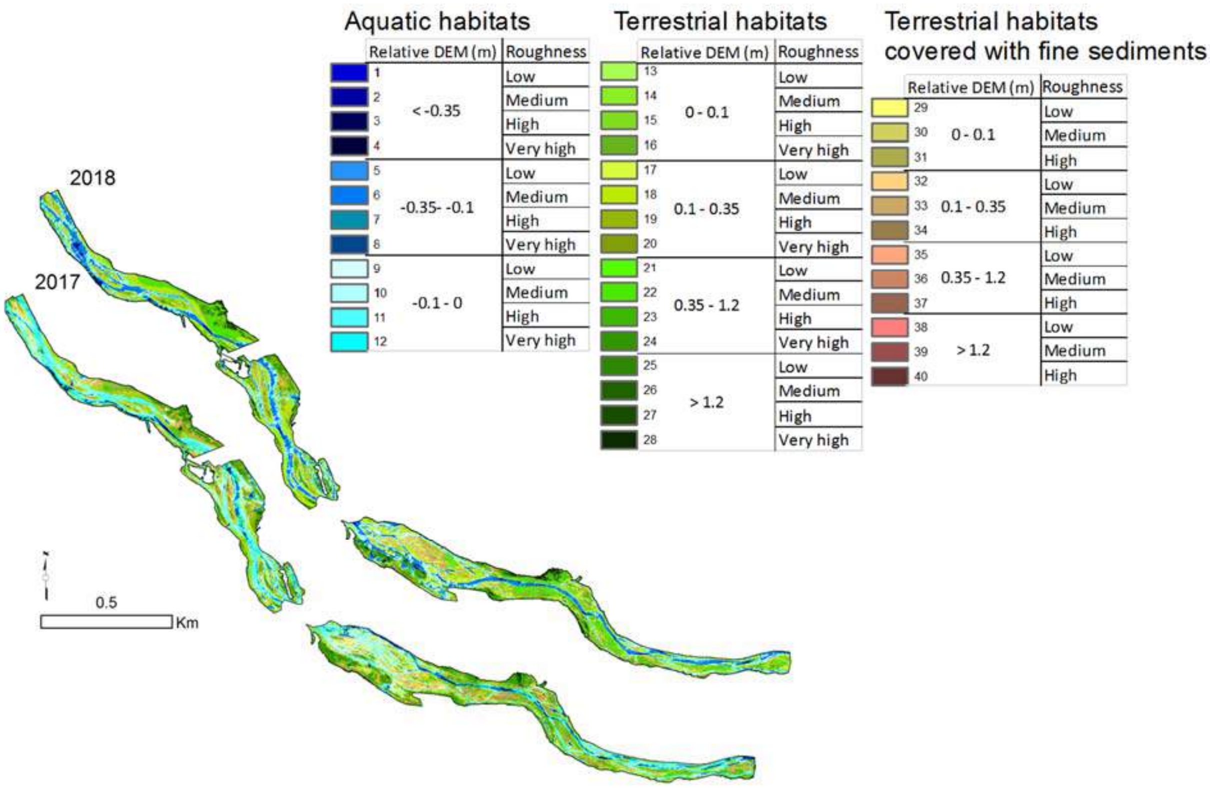

Fig. 16. Characterization of physical conditions supporting habitats in 2017 and 2018 along the Upper-Drac restored reach

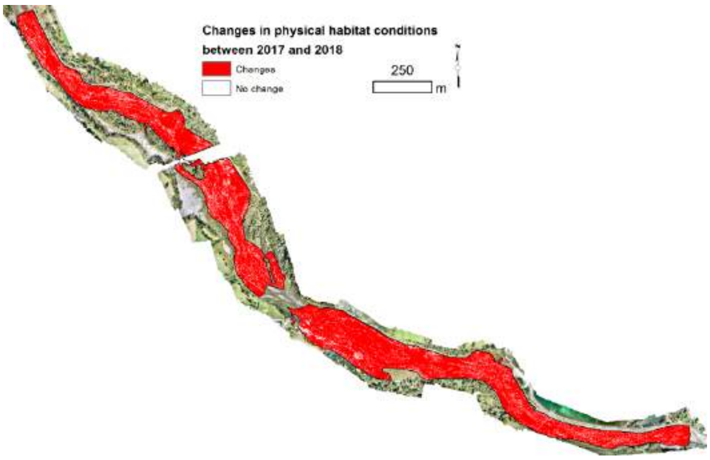

Fig. 17. Location of changes in physical habitat conditions along the Drac restored reach between 2017 and 2018.

The map of changing habitat conditions between 2017 and 2018 (Fig. 17) shows many habitat changes in this period. Only 15% of the habitats remained strictly identical. Aquatic habitats remained aquatic for 24.6% of them and 50.4% of terrestrial habitats remained terrestrial. A slight part of terrestrial habitats in 2017 became aquatic in 2018 (10.3%) and reciprocally aquatic habitats became terrestrial (14.3%).

The frequency distributions of habitat types (Fig. 18) are very close for 2017 and 2018. At the reach scale, it does not allow to conclude on the distribution equality neither in 2017, nor in 2018. Some habitat types are particularly more frequent in 2017: very shallow channels (< -0.1m in depth) with medium to high size of gravels (classes 10 and 11) and exposed bars between 0.35 m and 1.2 m above the water level and composed of boulders (class 24); in 2018 shallow channels composed of gravel, and exposed bars with medium grain size of gravels (between 0 to 1.2 m above water level) are also more frequent. In 2017 and 2018, some habitat types are on the contrary less frequent, like channel showing a depth above 0.35 m, and exposed gravel bars 1.2 m above the water level (less frequently inundated).

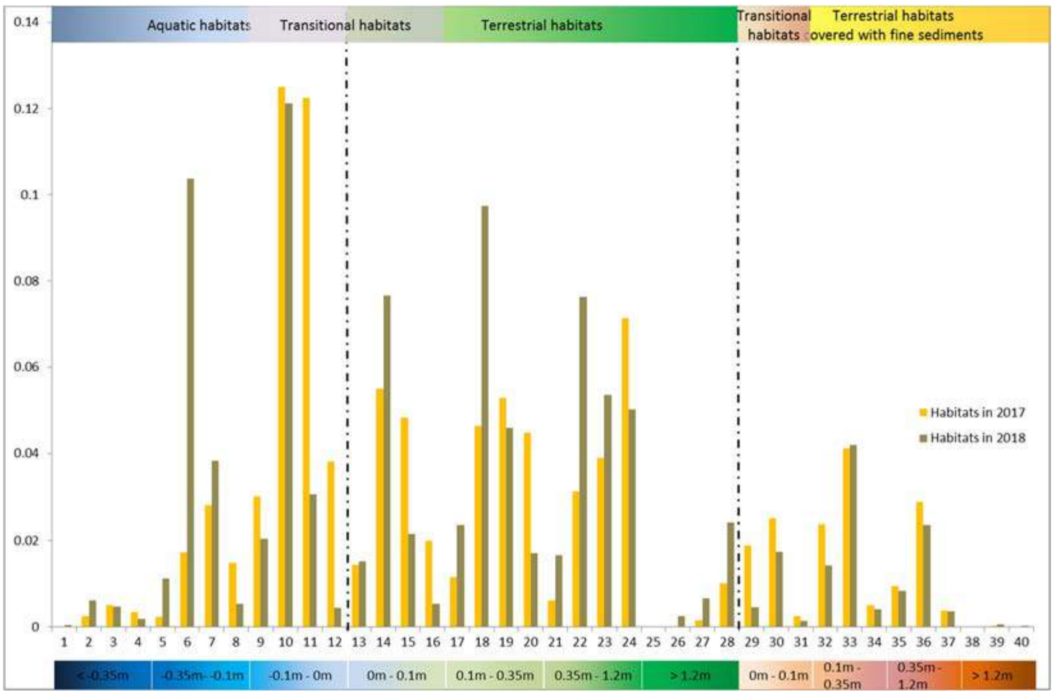

Fig. 18. Frequencies of physical habitat types at the Drac restored reach scale, for 2017 and 2018 low flows

The proportion of transitional habitats decreased between 2017 and 2018 associated with a simplification of the braiding pattern (the number of channels decreased, some channels incised and some terrestrialized): the number of pixels of very shallow channels was divided by 1.78 and respectively exposed bars near the water level (0-0.1m) by 1.29, while in the same time, the number of pixels of shallow channels was multiplied by 2.54, respectively exposed bars between 0.1 and 0.35 m above the water level by 1.08, respectively exposed bars between 0.35 and 1.2 m above the water level by 1.22, and respectively exposed bars 1.2 m or more above the water level by 2.78.

All habitat types taken together, the mean size of the sediments decreased between 2017 and 2018, respectively an increase of the class low from 7.9% to 10.2% and from 33.2% to 56.06% for the class medium and an decrease from 34.5% to 22.2% for the class high and 22.2% to 11.3% for the class very high grain size. Major changes are observed for medium grain size within aquatic habitats (strong increase from 1.9% to 10.9%), and for transitional habitats with a strong decrease of the high and very high grain size classes (respectively 17.0% to 5.2% and 5.8% to 0.9%).

Pixels corresponding to classes of terrestrial habitats covered by fine sediments do not represent pure coverage of fine sediments (because of the aggregation of the classes at 1m resolution). It might represent various proportion of coverage of fine sediments depending on which class of relative elevation to the water level and on which class of the proxy of grain size. For relative elevation above 1.2 m above the water level, this proportion of coverage is really low whatever the class of grain size is. Classes combining low grain size and a relative elevation to the water level between 0 and 1.2 m correspond to fine sediment mixed with gravels with a proportion of coverage of fine sediment really variable. For classes combining medium grain size and a relative elevation to the water level between 0 and 1.2 m, fine sediment are mixed with gravel to boulders, pioneer vegetation and also wood jams. Classes combining high grain size and a relative elevation to the water level between 0 and 1.2 m correspond to fine sediment mixed with large boulders, pioneer vegetation and also large wood jams. Not considering the relative elevation to the water level, the proportion of the classes corresponding to fine sediments mixed with gravels was divided by 2 between 2017 and 2018 whereas mixes of other grain size classes remain stable through time. As the proportion of coverage of fine sediments for each pixel is variable it is difficult to conclude on the evolution of the fine sediment itself at the reach scale.

At the reach scale we calculated a Shannon index (Eq. 1) of diversity of aquatic and terrestrial habitats considered both together and separately (Table 10).

Tab. 10. Evolution of the diversity of habitat types between 2017 and 2018 assessed with the Shannon index calculated for aquatic and terrestrial habitat conditions on the Upper Drac

	2017	2018
Shannon index (all 40 habitat types together)	4.47	4.40
Shannon index (only aquatic habitats)	2.55	2.52
Shannon index (only terrestrial habitats)	4.12	3.99

A spatial analysis of the Shannon diversity index (Figure 19) conducted at the sub-reach scale (the reach was divided into 39 sub-reaches where previous topographic data were available, i.e. between 70-200 m in length), shows that for most of them the diversity of physical conditions decreased between 2017 and 2018, as observed at the reach scale. However we can distinguish more precisely 3 behaviours: for most a clear decrease (segments n°1-2, 6-8,11, 13, 15, 23, 26-29, 31-35, and 38-39), a stagnation (segments n°3, 4, 9, 21-22, 24-25, 30, 36-37), and a net increase (segments n°5 and 16-20).

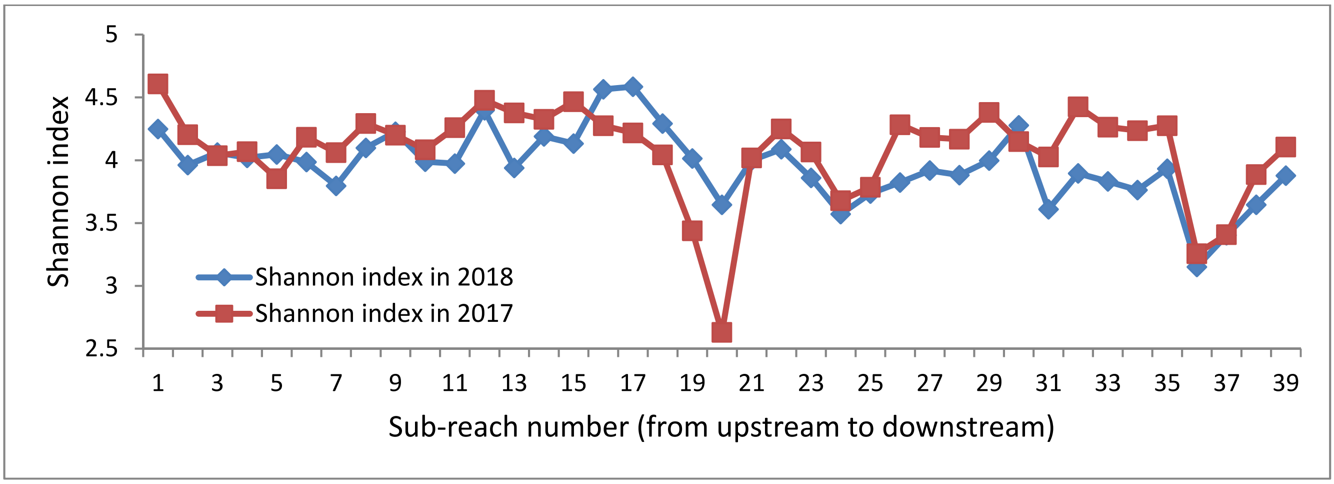

Fig. 19. Spatial tendencies of Shannon diversity index along the restored reach (from upstream to downstream)

The segments n°16-20 show a net increase in habitat conditions diversity. Within this well-developed braided pattern (in the middle of the restored reach), the number of very shallow channels decrease (terrestrialization) while some incised. The mean grain size decreased (more classes low and medium in 2018) and fine sediments deposed on the exposed gravel bars (which were partly inundated in 2017). Both aquatic and terrestrial habitats diversified in this period within these braided sub-reaches.

4 Ecological effects

4.1 Upper-Drac

4.1.1 Analysis of aquatic invertebrates

The methods used to analyze changes in aquatic invertebrates as markers of water quality are:

- IBG DCE: Global Biological Index based on the WFD;
- Semi-qualitative method of the lotic facies (IRSTEA method).

Using the data of Département des Hautes-Alpes and French Water Agency (Agence de l'Eau RMC), the main results show an increase of benthic invertebrate density and species richness, mainly as the result of high nutrient of upper basin loading (Fig. 20 and 21).

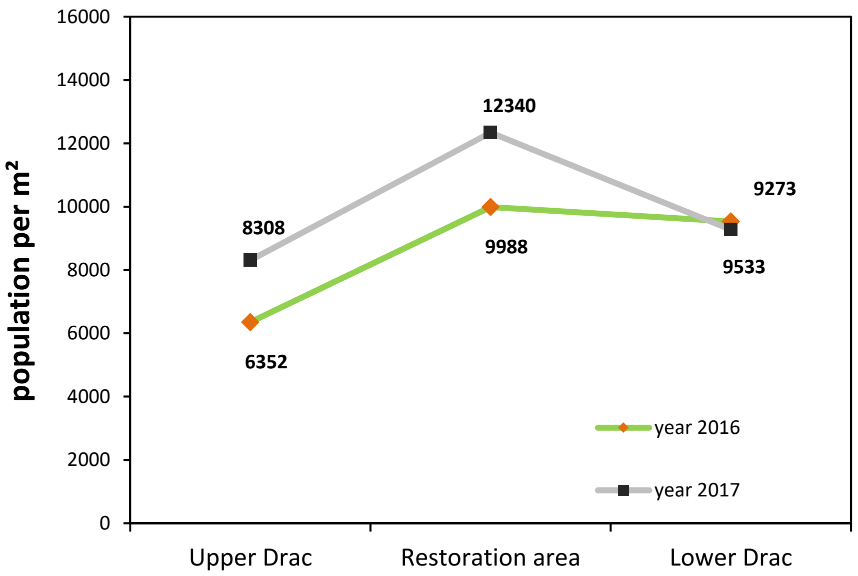

Fig. 20. Evolution of faunal densities from upstream to downstream in the three monitoring stations in 2016 and 2017 (after restoration)

- Comparing the periods before and after restoration, there is an improvement in biological quality over the entire study area related to improved wastewater treatment on the Upper Drac (not related to the restoration work).
- This improvement in quality is visible in the composition of the stand, especially the decrease in the relative abundance of taxa that eat fine organic substance (saprobic taxa).

- After restoration, the increase in biological quality is more spectacular in the restored area. This clear improvement can be likely explained by a gain in the accommodation capacity of aquatic ecosystem (self-cleaning of stream channel, substrate quality, a decrease of the suspended sediment concentration related to the reduction of clay outcrops in the active channel).

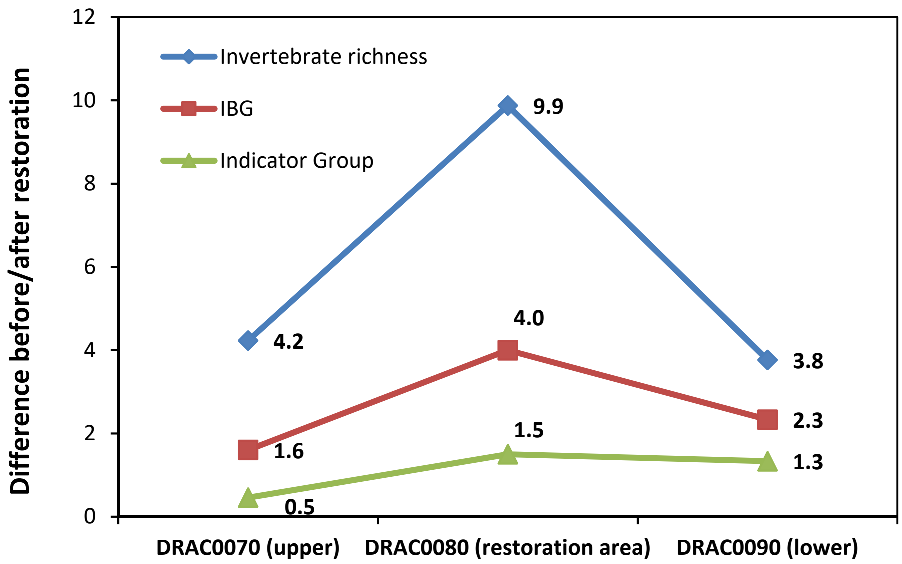

Fig. 21. Differences in averages calculated before and after restoration in the three stations monitored in the Drac (taxonomic richness, IBG scores and Indicator Group (GI))

Biological quality evolves positively after restoration over the entire study area. This improvement is maximum in the restored sector, where the quality of the habitat and the accommodation capacity are increased following channel restoration.

4.1.2 Physio-chemical water quality

A physical and chemical water quality analysis has been implemented before and after restoration on different parameters. The main conclusions are:

- ✓ Before the restoration (2014), the winter water quality is marked by high concentrations of ammonium, revealing inputs of poorly treated wastewater downstream of the ski resorts.

- ✓ Monitoring data from the Water Agency in St Julien-en-Champsaur shows that, despite a peak of pollution in February 2015, an overall improvement in the quality of water in the area studied is noted. It is linked to the better functioning of sanitation systems on the upper Drac during the period under consideration.
- ✓ The comparison between the St Julien station (upstream restored zone) and the Chauffayer station (remote downstream restored zone) shows an effective self-purification of the watercourse before and after restoration (Fig. 22).

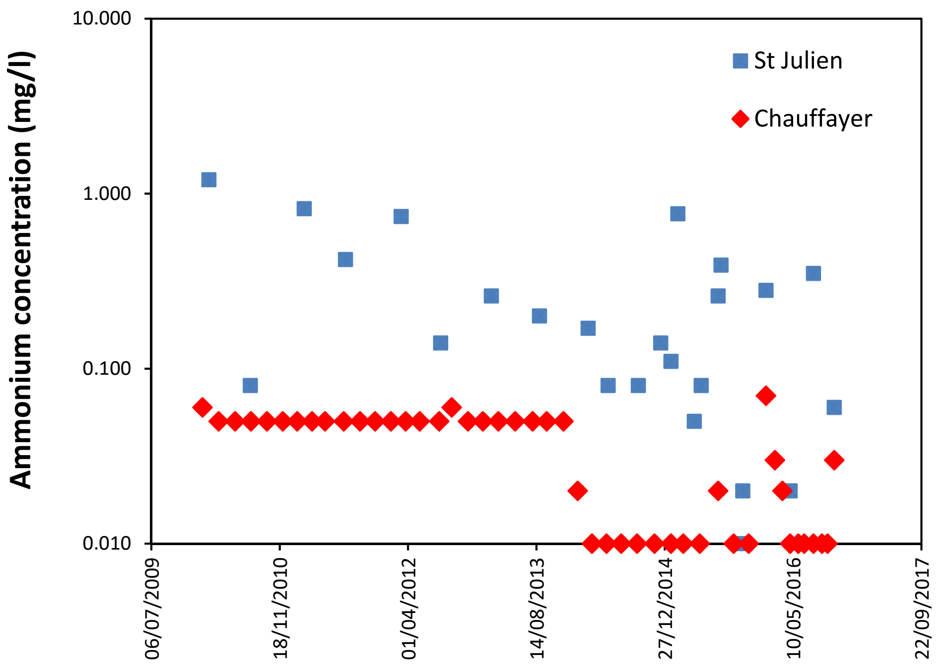

Fig. 22. Illustration of the self-purification along the Drac River on the ammonium parameter.

- ✓ Suspended sediment concentrations are consistently higher downstream of the restored area (DRAC0090 station). In the absence of other causes identified in the upstream basin, the erosion of the LGM clay lacustrine deposits seems to continue after the restoration. In fact, not all the clay outcrops have been covered by alluvium along the degraded reaches of the river.

On the physio-chemical compartment, the improvement of the parameters is more related to a better sewage treatment than to the restoration works.

4.1.3 Fish analysis

The following conclusions can be drawn from data analysis:

- Increasing diversity of fish populations: four fish species (***Telestes souffia, Phoxinus phoxinus, Salmo trutta, Cottus gobio***) are observed after the restoration against two in 2013. A strong increase of brown trout (Salmo trutta fario) populations is observed (Fig. 23), a key indicator species of good water quality and high water velocity. These changes in fish population may be due to changes in the environment (habitat, temperature, hydrology), but also to the installation of a fish pass in the downstream part of the restored reach (bridge of Saint-Bonnet-en-Champsaur).

- Sculpin (***Cottus gobio***) populations decrease. This species living in river banks is more sensitive to habitat clogging.

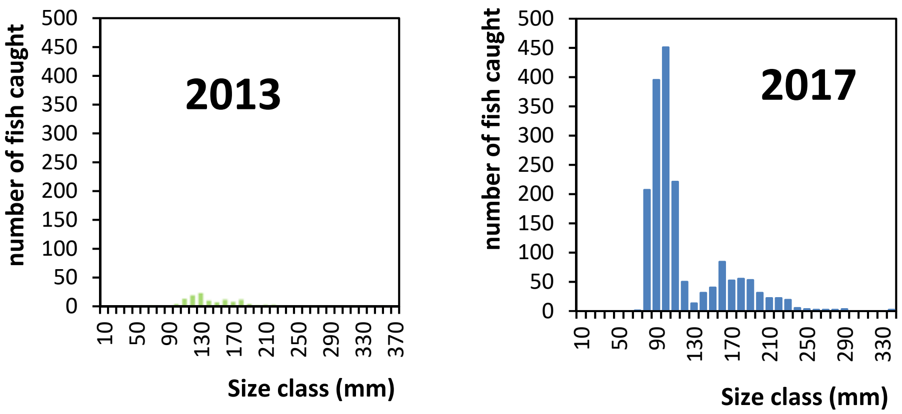

Fig. 23. Size distributions of brown trout populations obtained from electric fishing by AFB at the Upper Drac station in the restored reach in 2013 and 2017

- The size class distribution of brown trout (***Salmo trutta)*** show a good population with a high reproduction rate after restoration, likely reflecting the influence of changes in habitat quality.

The effect of Drac restoration on the fish population is coupled with the influence of the installation of a fishway downstream of the restored area. The number of species and the brown trout population are increasing. The improvement of the quality of the habitat by the restoration seems to favor the reproduction of this species. According to the existing data used on the fish compartment, a spatial comparison between the restored area and a reference site was not possible. Data existed only on the restored area (BA monitoring design).

4.1.4 Riparian vegetation analysis

The diachronic analysis of SPOT satellite images over the period 2014-2017 and a field campaign in 2018 made it possible to map and study the evolution of the different functional units of the riverscape (water, bare alluvium, pioneer phase, herbaceous phase, shrub phase, forest phase, riparian area exploited, riparian zone occupied). This work was carried out on the restored sector and a test area upstream of the restoration zone (plain of Chabottes).Following the restoration work, the functional units diversified with the colonization of the unvegetated alluvial banks by pioneer and herbaceous vegetation. A strong spatial dynamic of the hydrological functional unit (water class) is observed: the erosive processes (alluvium naked towards water) are partly compensated by the processes of deposits (water towards alluvium). A functional break is always present between the riparian fringe and the outer woody strip. Intermediate strata (herbaceous and shrubby) do not provide (yet?) the successional relay (Gramond, 2018).

Fig. 24. Illustration of the recovery of the different layers of vegetation (©Delphine Gramond, Sorbonne University)

4.1.5 Airborne infrared thermal mapping of aquatic channels

A thermal 2D mapping has been realized to evaluate the evolution of the temperatures along the river active channel, using airborne Thermal Infrared (TIR). According to the work undertaken by the CNRS, a temperature longitudinal profile has been obtained along the Upper Drac, including the restored reach (Fig. 25).

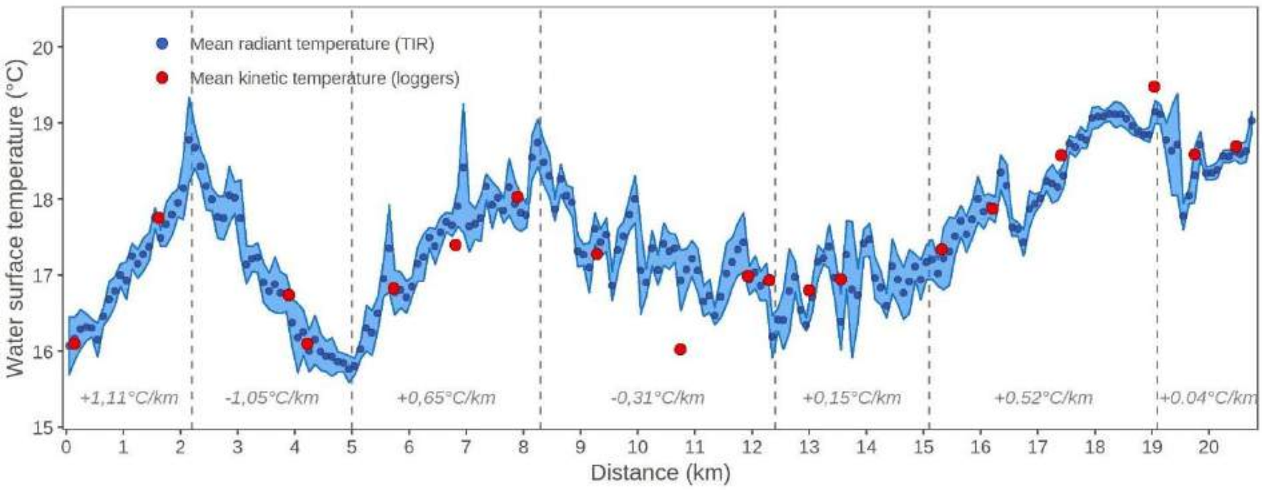

Fig. 25. Longitudinal surface temperature profile of the Upper Drac River, and thermal gradients calculated over homogeneous sections; the restored reach is comprised between 15 and 19 km (from the report of Baptiste Marteau, CNRS, December 2018)

Analysis of TIR results show that the Upper Drac displays contrasting behaviors (positive and negative gradients, Figure 21) and that these are controlled by the density and characteristics of cold water inputs. Temperature decreases in the 'reference' section but increases in the restored section despite both showing a braided morphology. Although differences in hydrogeological context between the two sections prevents any direct comparison (Chabottes plain is a long-established quasi-natural system running on deep alluvium and sustained by a powerful aquifer), the results show that the restoration has had no positive impact on the thermal gradient of the upper Drac River. This does not preclude any potential improvement in the future provided that the restored section continues to evolve towards a more natural-looking system.

4.1.6 General conclusion on the restoration benefits

The chemical quality of the Drac water remains influenced after 2014 by wastewater discharges, especially during winter campaigns where the use of the top Drac for the practice of winter sports is maximum. However, monitoring the Water Agency in St Julien-en-Champsaur seems to indicate an improvement from 2016 that affects the entire study area. An efficient self-purification is observed between St Julien and the Chauffayer station before and after the restoration. It is necessary to underline the specific measures of temperature in the restored sector which reveal a particularly hot water during the summer of 2015 for a mountain stream. The installation of thermal recorders by the Département des Hautes-Alpes and their analysis of the data will confirm or not this warming of the waters in the restored sector.

The influence of organic enrichment on the benthos appears to be attenuated in the IBG samples taken in 2015 and 2016. The aquatic invertebrate stands of the whole study area show an improvement in biological quality. The densities are high, but the stands are less dominated by species feeding on fine organic matter deposited or suspended in the water. The comparison of all the IBG scores calculated before and after the restoration clearly shows a progression in the quality of the entire study area. This improvement is even more marked at the station in the restored area, where changes in habitat quality appear to be beneficial to the benthic settlement.

The electric fishing carried out by AFB in year n + 3 following the works (2017) reveals a fish population composed of four species: brown trout, sculpins, minnow and bream. These last two species are in addition to the first observed in 2013. The presence of these fish, and in particular the blageon, is mainly due to two factors combined: creation of a fishway downstream of the sector and improvement the quality of the habitat. The influence of the thermal remains to be specified. Other fisheries in the coming years should confirm these results. One of the main changes affecting the Drac fish population in the study area is the sharp increase in the number of brown trouts. In 2017, this species becomes dominant at the expense of the sculpin. Examination of the size class distribution reveals an abundant population, especially for young stages, reflecting effective reproduction. The restoration of the bed, by modifying the grain-size distribution and increasing the surface of life, clearly favors the brown trout.

4.2 Buëch

4.2.1 Analysis of aquatic invertebrates

Two stations in the study area have been monitored by the Département des Hautes-Alpes: BUEC0700 (upstream St Sauveur dam) and BUEC0800 (downstream St Sauveur dam, in the restored reach). The main conclusions are:

- Faunistic differences are observed between upstream and downstream stations of the Saint-Sauveur reservoir, the main cause of which seems to be the hydrological and thermal modifications induced by the reservoir in this sector.
- The habitat quality factor is difficult to interpret in a modified hydrological and thermal context, whose influence seems to dominate the stand structure.
- Lack of perspective to really apprehend the effects on the population of the morphological restoration of Buëch downstream of Saint-Sauveur.

The effects of Buëch restoration are hardly perceptible on aquatic invertebrate populations. The impact of the Saint-Sauveur dam, which gives rise to profound thermal and hydrological changes, seems to dominate. These observations based on a year of post-restoration monitoring are to be confirmed by the ongoing monitoring.

4.2.2 Physio-chemical water quality

By using the data produced by EDF and by the Département des Hautes-Alpes, it is possible to conclude that the physio-chemical quality is identical before and after the restoration (quality qualified as "very good"). There is no influence of the restoration on the physio-chemical water quality.

4.2.3 Fish analysis

Concerning the fish investigations, the main observations are:

- ✓ 12 species of fish are counted after the restoration. This stand is very close qualitatively before and after the restoration (Fig. 26).
- ✓ The stand is largely dominated by running-water Cyprinid.
- ✓ The stenothermal species of fresh water such as brown trout and sculpin remain very poorly represented.

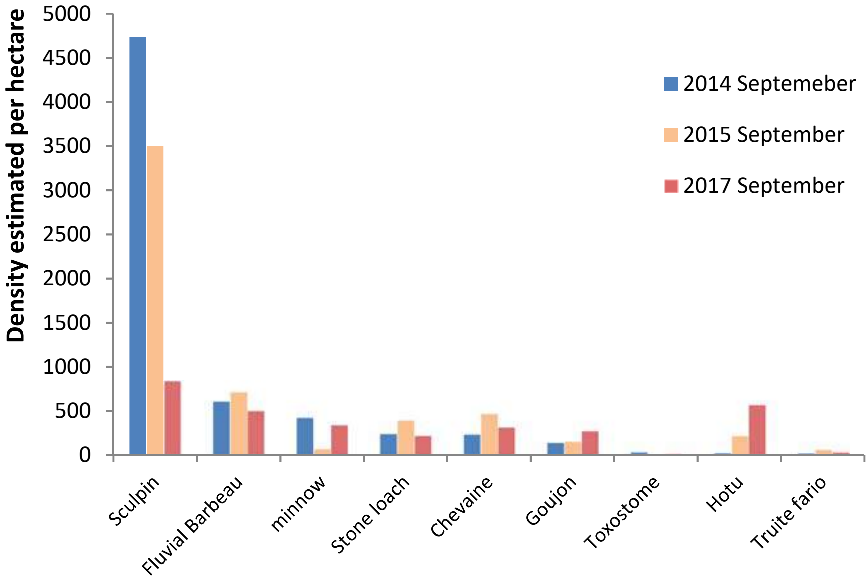

Fig. 26. Density per hectare of main species before restoration (2014 and 2015) and after restoration (2017)

The impact on the fish populations of the restoration action is limited on this case study. It seems possible that the Cyprinid species are resistant to many factors and permit them to be resilient on the changing conditions of their biotopes, on the contrary to the Salmonidae species. According to Fig. 22, the question of the declining of the sculpin population is not resolved and should by analyzed more deeply.

4.2.4 Riparian vegetation analysis

The diachronic analysis of SPOT satellite images over the period 2014-2017 and a field campaign in 2018 made it possible to map and study the evolution of the different functional units (water, bare alluvium, pioneer phase, herbaceous phase, bush phase forest phase, riparian area exploited, riparian zone occupied). This work was done on the restored area and a test area downstream of the recharge area.

Concerning the impacts on the riparian vegetation strip, the active strip has been revitalized and the bio-geomorphological processes have been (re) activated on the site of works but also further downstream. A functional break between the fringe and outer band is still marked. Intermediate strata (herbaceous and shrubby) do not (yet?) provide the successional relay that characterizes the typical facies of a riparian forest in dynamic equilibrium with its recording medium. Regarding riparian vegetation, the active channel has been revitalized but the functional rupture between the riparian fringe and the outer band is still marked (Gramond, 2018).

4.2.5 Thermal mapping investigation

Airborne TIR was used to investigate the evolution of temperature along the river wetted channel. According to the work of the CNRS, the following temperature profile is related around the restored area (Fig. 27):

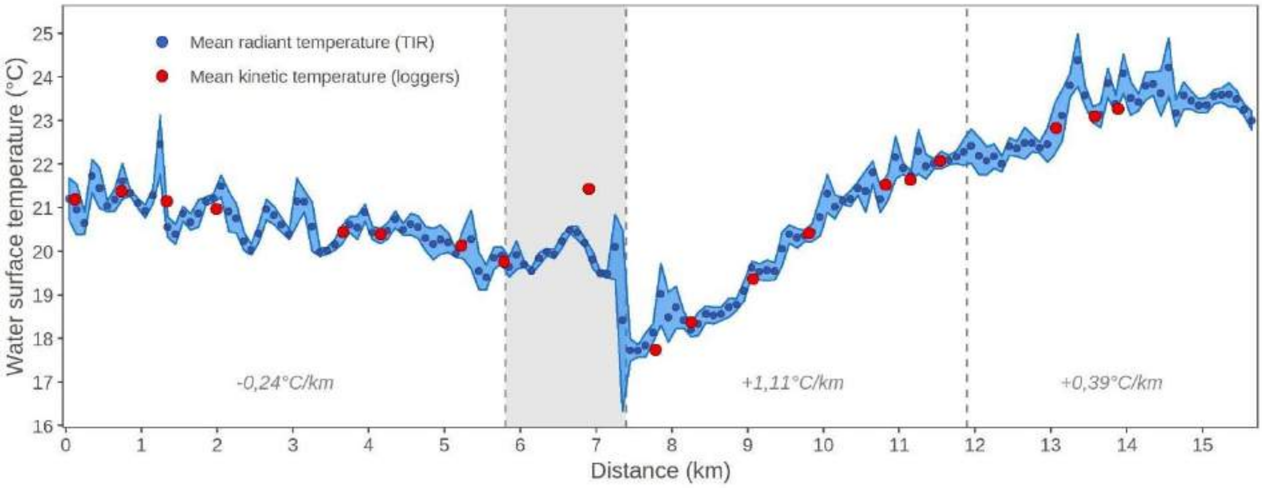

Fig. 27. Longitudinal profile of the Buëch surface temperature and temperature gradients calculated over homogeneous sections; in grey, the St Sauveur reservoir (from the report by Baptiste Marteau, CNRS, December 2018).

Analysis of the results reveals the following conclusion for the studied section of the Buëch River:

- ✓ Surface temperature: the reservoir of Saint-Sauveur influences the thermal behavior of the entire section by delivering a 'buffered' water (i.e. colder than temperature upstream), less subject to short-term variations in air temperature (i.e. lower diurnal variability) although it is influenced by atmospheric conditions (i.e. higher maximum temperature in the summer).
- ✓ Groundwater inflow is non-existent or insufficient in the restored area to limit the rapid warming of the water downstream of the dam (at least in the summer). Although this cannot be proved, it is

likely to also be caused by the presence of the reservoir since the density of cold water patches increases as the river moves downstream from the dam.

The restoration of Buëch River downstream of the Saint-Sauveur dam has had no impact on the quality of the water. Surface temperature is more influenced by the presence of the Saint-Sauveur reservoir. The sediments reinjected downstream of the dam are, for the time being, not sufficient to induce hyporheic exchanges likely to limit the warming of the water.

The study of the temperature reveals a predominant hydrological control by the reservoir of Saint-Sauveur. This section is then particularly responsive to atmospheric conditions, as indicated by the summer values measured, regularly above 25°C, although diurnal variations are lower. It seems that the sediment replenishment is not sufficient for the moment to generate an underflow to influence the thermal regime of this sector.

4.2.6 General conclusion on the Buëch case-Study

The analysis of the physio-chemical quality of Buëch reveals in the study area a medium of good to very good quality. The analysis conducted in 2017 reveal no organic disturbance.

The study of the temperature reveals a predominant hydrological influence of the reservoir of Saint-Sauveur. This section is then particularly reactive to changes in atmospheric temperatures, as indicated by the summer values measured, regularly above 25°C. It seems that the sediment replenishment is not sufficient for the moment to generate an underflow to influence the thermic regime of this sector.

Regarding the faunal population, some faunal differences observed before 2016 between upstream and downstream of the Saint-Sauveur dam are visible on the stand taken in 2017. Thus, Crustacean Gammarus is one of the dominant taxa upstream while it is little represented downstream. Conversely, the genus Caenis (Ephemeroptera) is better represented downstream of the dam than upstream. After the restoration, the same faunal distinction between the upstream and downstream stands of the Saint-Sauveur reservoir is observed, emphasizing that the dam is the main factor influencing the benthic settlement in this area.

The fish population is rich, constituted in 2017 of 12 species. As in 2014 and 2015, the same species are found, and white-footed cyprinids largely dominate. The blageon is however less abundant than before the restoration. Conversely, the hotu sees its numbers increase. As in 2014 and 2015, brown trout and sculpin, stenothermal species of fresh water, are present but in low numbers. As with invertebrates, the fish population would be more influenced by the hydrological and thermal modifications created by the Saint-Sauveur reservoir.

5 Conclusions and perspectives

The HyMoCARES project provided a unique opportunity to implement intensive monitoring programs of two emblematic restoration projects of altered alpine rivers in France. The sediment replenishment downstream of dam in the Buëch, and the artificial recreation of a braided channel in the Upper Drac, are two illustrative examples of ambitious restoration projects based on the idea that putting more gravels into a starved river channel will improve its geomorphic functionality, and subsequently its ecological integrity. What are the main lessons learned from these emblematic restored rivers after few years of monitoring (2 years for the Buëch, and 4 years for the Upper Drac)?

Lessons learned from the Buëch restoration

Sediment replenishment of the Buëch downstream of the St-Sauveur dam clearly improves channel morphology by reversing a long trend towards channel incision and bed simplification, as attested by topographic differencing of the restored reach before and after a 5-yr flood that scoured half of the replenished gravel berms downstream the dam. The combination of repetitive HR topographic surveys and a bedload tracing experiment using HF active RFID tags successfully helps to isolate the downstream propagation of the artificial sediment wave induced by gravel augmentation. The deposition front of this wave was detected at 2.3 km down to the dam, attesting a rapid bedload dispersion along the restored reach, and subsequently a spatially extended morphological recovery of the altered channel. A gravel layer with a mean thickness of c.a. 30-40 cm has been reformed along more than 1.5 km after the first significant flood following the sediment replenishment operation. However, the effective bedload input from the replenishment reach (22 650 m^3) was insufficient to induce a significant shifting of the main channel during the flood, and a subsequent reactivation of braiding in the first unconfined stretch of the Buëch downstream the dam. This could have amplified the downstream propagation of channel recovery, through the lateral erosion of recently vegetated gravel bars along this unconfined reach. More investigations are then needed to optimize sediment replenishment designs to increase as much as possible the remobilization rate of artificial berms. In parallel, more research is also needed to determine the bedload supply needed to reactivate braided processes.

Investigating effects of sediment replenishment on active channel habitat heterogeneity was based on an intensive post-treatment (IPT) monitoring design, which is intrinsically very limited since no before restoration data were available, nor data after restoration on a control site (UAV data processing are too much time consuming and could have only been done for the restored reach). However, orthophotos and DEM obtained from HR imagery have been successively used to produce physical habitat mapping for 2017 and 2018. Although a strong turnover rate of habitat conditions is observed, the general morphological structure of the active channel stayed unchanged during the period, and the global habitat heterogeneity of the active channel can be considered as stable over the 2-yr monitoring period. It would be interesting to extend UAV surveys during the next few years to monitor changing habitat conditions over a longer period. This is also true for the airborne monitoring of surface temperature, which has only been possible after restoration. A winter thermal IR campaign would be useful to compare the role of the Saint-Sauveur reservoir on controlling winter temperature, and improve the understanding of the downstream recovery of thermal behaviour.

Water quality and ecological conditions (macroinvertebrate and fish populations) before and after restoration did not show any evolution that allows us to confirm a positive effect of sediment replenishment. The water quality stayed at a very good level before and after sediment replenishment. Concerning biological conditions, the hydrological and thermic effects of the dam have not been compensated by the sediment replenishment, and the differences between the restored and the control reaches (upstream of the dam) stay dominated by the dam effect. A longer monitoring period would be necessary to determine if the lack of biological response reflects an insufficient morphological recovery following sediment replenishment, or a too short monitoring time window to detect biological trajectories.

Lessons learned from the Upper Drac restoration

The monitoring of the morphological restoration of the Upper Drac clearly reveals a very efficient spontaneous recovery of braiding conditions along the 3-km widened and replenished river reach. Post-restoration HR images acquired from drones show that the initial uniformly flat alluvial platform rapidly evolves towards a typical braided channel with a mosaic of active gravel bars separated by multiple anabranches. From a purely aesthetic point of view, this restoration is a real success, as today, the restored reach really looks like a "natural" braided river reach. Bedload tracing experiment confirm a rapid dispersion of gravels from the Chabottes plain, which is the main sediment reservoir upstream of the restored reach. This strong coarse sediment connectivity is a positive point for the resilience of the braided pattern in the restored reach. Although it is difficult to make any definitive conclusion about the net sediment budget of the restored reach, the fact that exposed unvegetated gravel bars are in accretion since 2015 confirm active sediment supply conditions from upstream. The bed relief index also confirms a favourable morphological trajectory which evolves towards reference conditions, as observed in the reference reach.

The water quality and ecological monitoring of the Upper Drac restoration clearly reveals an improvement of all the investigated parameters. A significant increase of the water quality is observed, in parallel with a higher richness of macroinvertebrate populations, and a strong increase of brown trout populations. However, it is difficult to assert that these effects are the direct consequence of the morphological improvement of the restored reach, as some other positive control factors have likely influenced the monitored parameters (fish pass creation in the weir downstream of the restored reach, commissioning of water treatment plants in the Upper Drac catchment). Despite this complex pattern of forcings, several points converge towards a significant effect of the morphological restoration: (1) rate of changes of macroinvertebrates indicators are systematically higher in the restored reach, as compared to control sites; (2) the decline of ammonium concentrations is much higher downstream of the restoration site than upstream after 2013, supporting an increase self-purification effect related to the recreation of an alluvial substrate.

The morphological changes detected from UAV surveys are not very marked between 2017 and 2018: changes are related to a simplification of the geometry in the braided part, with incision of some very shallow channels and terrestrialization of other very shallow channels, associated with a refinement of the grain-size. As no big flood event occurred between these two years of monitoring, it is highly recommended to extend the monitoring of the Upper Drac. This will be useful for investigating the long-term morphological and biological responses of the restored reach, as well as for better isolating the effect of the restoration from other control factors.

6 References

Anderson S.W., 2019. Uncertainty in quantitative analyses of topographic change: Error propagation and the role of thresholding. *Earth Surface Processes and Landforms*, 44, 1015-1033. doi: 10.1002/esp.4551.

Brousse G., Arnaud-Fassetta G., Liébault F., Bertrand M., Melun G., Loire R., Malavoi J.R., Fantino G., Borgniet, L., in press. Channel response to sediment replenishment in a large gravel-bed river: the case of the Saint-Sauveur dam in the Buëch River (Southern Alps, France). River Research and Applications.

Corbin Y, 2018. Caractérisation des distributions granulométriques par photogrammétrie et typologie des habitats physiques associées à la restauration du Haut-Drac. Mémoire de Master 1 GEOIDES, IUGA, Grenoble, 35p.

Gautier E., 1994. Interférence des facteurs anthropiques et naturels dans le processus d'incision sur une rivière alpine: l'exemple du Buëch (Alpes du sud). *Revue de Géographie de Lyon* 69: 57-62.

Gramond D., 2018. Caractérisation et suivi de la bande riveraine sur les sites restaurés du Drac à Saint-Bonnet-En-Champsaur et du Buëch à l'aval du Barrage de Saint-Sauveur. *Rapport technique pour le compte du Département des Hautes-Alpes*, 55 pp.

Hoey TB, Sutherland AJ. 1991. Channel morphology and bedload pulses in braided rivers: a laboratory study. *Earth Surface Processes and Landforms* 16: 447-462.

Laval F., Guilmin E., 2014. Upper Drac River restoration project: restoration of a braided river bed incised in clay substratum through sediment reloading and bed widening. SHF conference, Nantes, 6-7 October 2014 (oral communication).

Le Guellec G., 2018. Evaluation des effets écologiques de la restauration hydromorphologique de deux tronçons de cours d'eau et évaluation des services écosystémiques associées - cas d'étude du Drac et du Buëch.

Synthèse du diagnostic écologique. *Rapport Technique pour le compte du Conseil Départemental des Hautes-Alpes*, 31 pp.

Liébault F, Lallias-Tacon S, Cassel M, Talaska N. 2013. Long profile responses of alpine braided rivers in SE France. *River Research and Applications* 29: 1253-1266. DOI: 10.1002/rra.2615

Marteau B., Piégay H., 2018, Relevés thermiques aéroportés sur les rivières Drac et Buëch. *Rapport de synthèse pour le Département des Hautes-Alpes*, 32 pp.

Navarro L., Peress J., Malavoi J.R., 2012. Aide à la définition d’une étude de suivi – recommandation pour des opérations de restauration de l'hydromorphologie des cours d'eau. *Guide Technique Onema et Agences de l’Eau*, 42 pp.

Roni P, Liermann M, Muhar S, Schmutz S. 2013. Monitoring and evaluation of restoration actions. In: *Stream and Watershed Restoration: a Guide to Restoring Riverine Processes and Habitats*, Roni P, Beechie T (eds). John Wiley and Sons: Chichester, pp 254-279.

Vázquez-Tarrio D, Borgniet L, Liébault F, Recking A. 2017. Using UAS optical imagery and SfM photogrammetry to characterize the surface grain size of gravel bars in a braided river (Vénéon River, French Alps). Geomorphology. 285. 10.1016/j.geomorph.2017.01.039