# Technical note about the monitoring of hydromorphological restoration of the Buëch River (Hautes-Alpes, France)

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## 1. General presentation of the study site

The Buëch is a gravel-bed braided river draining the Southern French Prealps, most of its catchment being included in the Hautes-Alpes department. It is one of the major alpine tributary to the Durance River, with a confluence at the city of Sisteron. The study reach is located close to the city of Serres, downstream from the EDF dam of Saint-Sauveur, at an elevation of 640 m above sea level. This reach drains a 836-km² upland catchment with a maximum elevation of 2709 m (Pic de Bure in the Dévoluy Massif) (Fig. 1, Table 1). The catchment geology is exclusively composed of sedimentary rocks, mainly of Jurassic and Cretaceous ages. Outcroppings of Cenozoic rocks are only marginally observed upstream the city of Veynes. The lithology is dominated by alternating sequences of marls and limestones, which are typical of the Southern Prealps. Glacial deposits from the Last Glacial Maximum (LGM) are only marginally observed in the catchment, mostly along the upper part of the eastern Petit Buëch branch. However, considerable quantities of loose surficial debris are present in the subcatchments draining the Dévoluy Massif, where Cretaceous limestones sensitive to frost cracking supply massive talus slope deposits. The climate is Mediterranean, with a mean annual rainfall of ~800 mm. Heavy rainfalls typically occur during autumn, and secondary during spring. The hydrological regime is also influenced by a moderate spring snowmelt.

| | |
|---|---|
| Drainage area (km²) | 836 |
| Location | 44°23'48''N, 5°43'51''E |
| Length of the study reach (km) | 2.2 |
| Active channel width (m) | 180 |
| Channel slope (m/m) | 0.009 |
| Planform morphology | Braided/wandering patterns |

*Table 1. Main physical features of the Buëch River at the restoration site*

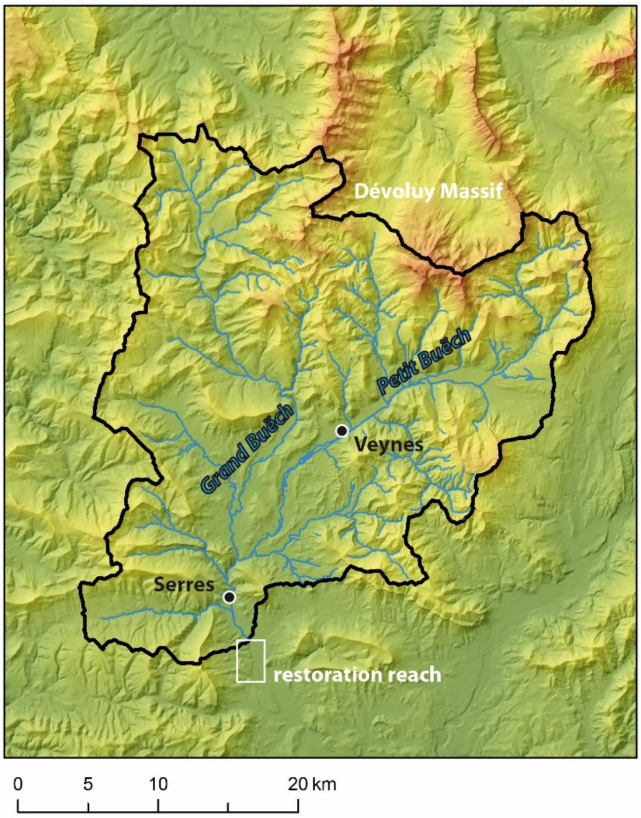


*Figure 1. General relief map of the Buëch catchment at the restoration site*

The study reach extends from the Saint-Sauveur dam down to the confluence with the *Torrent de Channe*, a left-bank tributary to the Buëch joining the main stream near the village of Montrond (Fig. 2). This 2.2 km reach presents a mean active channel width of 180 m and a mean channel slope of 0.009 m/m. The channel morphology is a succession of segments characterized by wandering and braided patterns. The dominant substrate is composed of gravel-sized sediments, with a $D_{50}$ of 20 mm ($D_{84}$ = 40 mm). Although the reach is included in a ~1 km wide alluvial floodplain, the lateral confinement related to roads or bedrock outcrops is important. Well-preserved patches of alluvial forests are only observed in the right-side of the channel immediately downstream from the dam and in the left-side downstream of the confluence with the *Torrent de Channe*. Most of the floodplain is occupied by cultivated lands. The hydrological regime of the reach is impacted by the Saint-Sauveur dam, which diverted more than 75% of the natural flow (Fig. 3A). The guaranteed flow downstream from the dam does not exceed 2.5 $m^3$/s. The water discharge is monitored since 1964 at the Serres gauging station, located 4 km upstream from the dam. The water regime is characterized by a major peak during spring, and a secondary one during autumn. The mean daily discharge is 14.10 $m^3$/s, and the 2, 10, and 50 yr daily flood discharges are estimated at 140, 250, and 350 $m^3$/s, respectively.

Although the Saint-Sauveur dam is equipped with 3 flood gates, allowing some sediment transport continuity during floods, most of the coarse sediments are trapped in the proximal part of the reservoir. Therefore, most of the sediment supply of the restoration reach comes from bank erosion downstream from the dam, since no major tributaries are joining the reach upstream from the *Torrent de Channe*. The Buëch River is then disconnected from its major active tributaries, like the Abéoux Torrent, which conveys sediment production from the massive Dévoluy talus slopes.

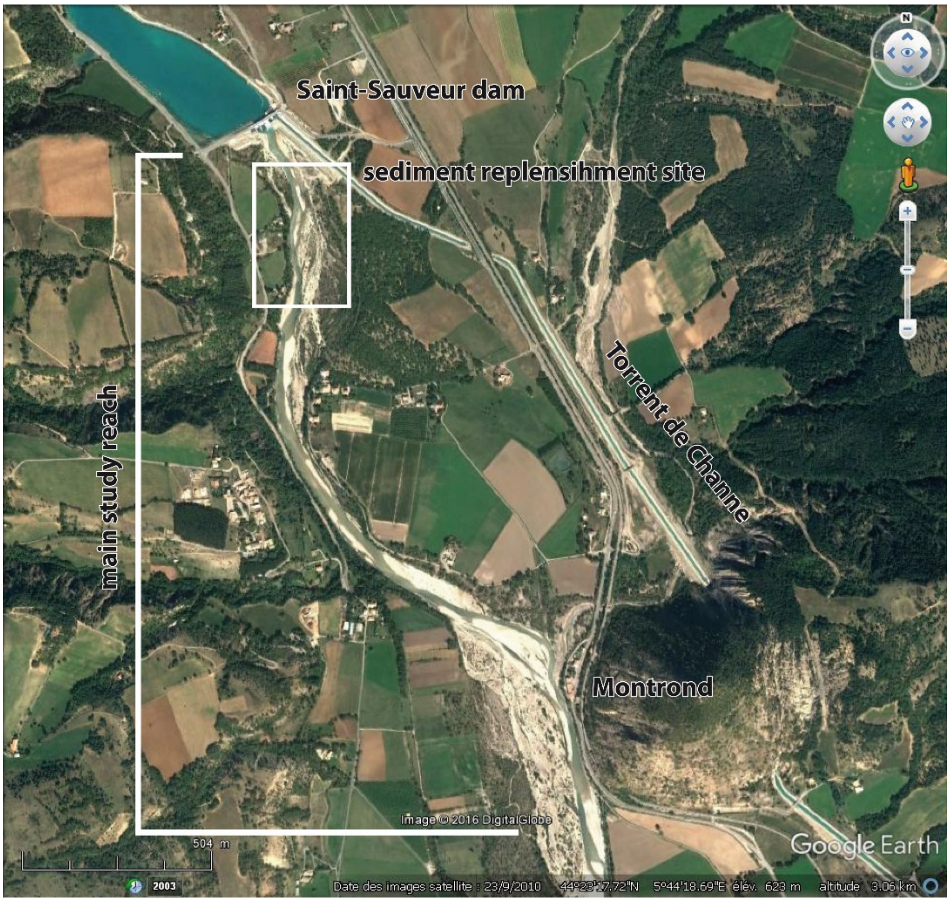


*Figure 2. Google Earth view of the gravel replenishment site downstream of the Saint-Sauveur dam, with extent of the monitoring reach*

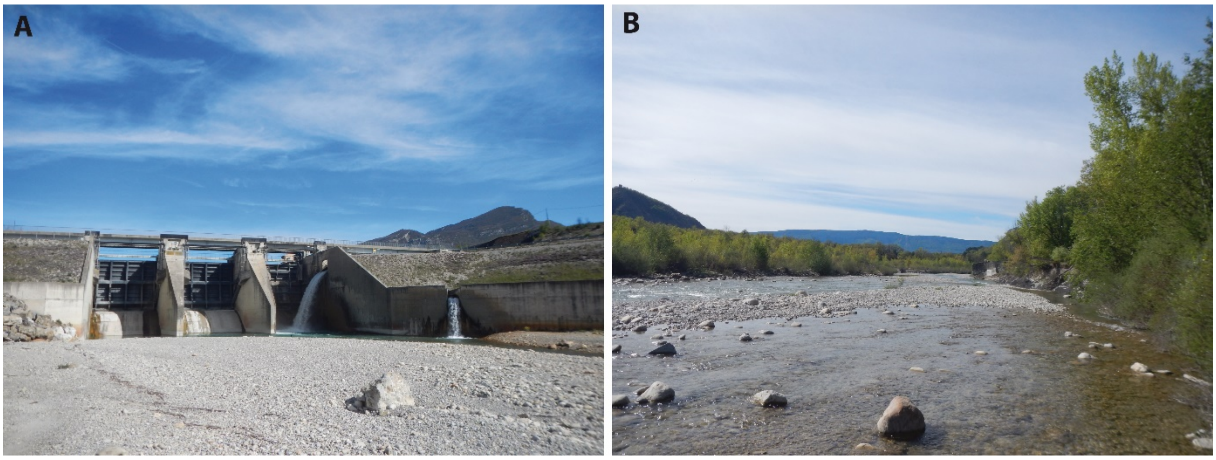


*Figure 3. The EDF Saint-Sauveur dam (A) and the "hungry water" impacted reach downstream from the dam; view looking downstream (B) (©Irstea)*

## 2. The hydromorphological restoration project

### *2.1. Human alterations of the physical fluvial corridor*

Like most of alpine braided rivers in France, the Buëch has been highly impacted by intensive gravel mining since the late 1960s (Gautier, 1994: Liébault et al., 2013). In the early 1990s, the total volume of gravels extracted from 3 active mining sites was estimated at 5 $Mm^3$ (Gautier, 1994). A more recent investigation about the bedload transport management of the river provides an estimate of 9.7 $Mm^3$ (Hydrétudes, 2013). Due to local temporary administrative permissions related to dredging needs, this activity stops only very recently along the Buëch, contrary to most of the other French alpine rivers where gravel mining stops in the mid-1990s, following a decree of September 1994. The last gravel mining activity was operating along the Petit Buëch and it stopped in 2012.

In addition to gravel mining, the bedload transport continuity has been strongly impacted by the construction of the Saint-Sauveur dam, the last hydropower dam deployed in the French Alps. This 10-m high and 260-m wide barrier was constructed between 1990 and 1991, and the commissioning started in 1992. The construction necessitates the dredging of 600 000 $m^3$ of sediment. The full storage capacity of the reservoir is 1.72 $Mm^3$, and the water is used for irrigation, hydroelectricity, and touristic development. The dam serves as a water intake structure, supplying a diversion canal, with a maximum hydraulic capacity of 30 $m^3/s$, conducting water to the Lazer hydropower plant located 10 km downstream. The restitution of the diverted water is located at Sisteron, near the confluence with the Durance River. The dam is of gate-structure type, and it is equipped with 3 hydraulic gates. The guaranteed flow downstream from the dam fluctuates seasonally between 0.5 and 2.5 $m^3/s$. 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, highlighting the strong and rapid geomorphic effect of the dam (Gautier, 1993). In 2014, the guaranteed flow has been increased from 0.5 to 0.9 $m^3/s$.

Upstream from the Saint-Sauveur dam, the Buëch River is also locally regulated by embankments. The most significant artificially straightened and confined reaches are located near the cities of Veynes (~6 km reach), Aspres-sur-Buëch (~4 km reach), and Serres (~2.5 km reach). These dikes were deployed mainly between the 1770s and the 1840s, not only for the protection of populations against the catastrophic floods that occurred during this hydrologically active period, but also for the expansion of arable lands, since this valley was highly populated at that time ; the peak of population in the Hautes-Alpes department occurred in 1846 (Gautier, 1992). The estimated gain of arable lands related to the embankment of the Buëch has been estimated at 800 ha (Gautier, 1993). These lands are still occupied today by an intensive agricultural activity, mostly concerned by orchard production.

All of these reach-scale alterations of the channel morphology and sediment transport may have been amplified 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 (Liébault and Piégay, 2002; Piégay et al., 2009; Liébault et al., 2013).

These human alterations of the sediment regime resulted in important channel responses, like active channel narrowing, attested by historical aerial photographs (Fig. 4), and channel degradation, as attested by the historical long profile of 1908 (Liébault et al., 2013). A shift from a braided to a wandering pattern can be clearly observed along several reaches, including the study reach. Downstream from the dam, the incision reaches 3 m, and propagates downstream (Hydrétudes, 2013). Some marly bedrock outcrops are observed along the degraded reach, as well as undercut groynes on the right-bank. 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 LGM (Gautier, 1994).

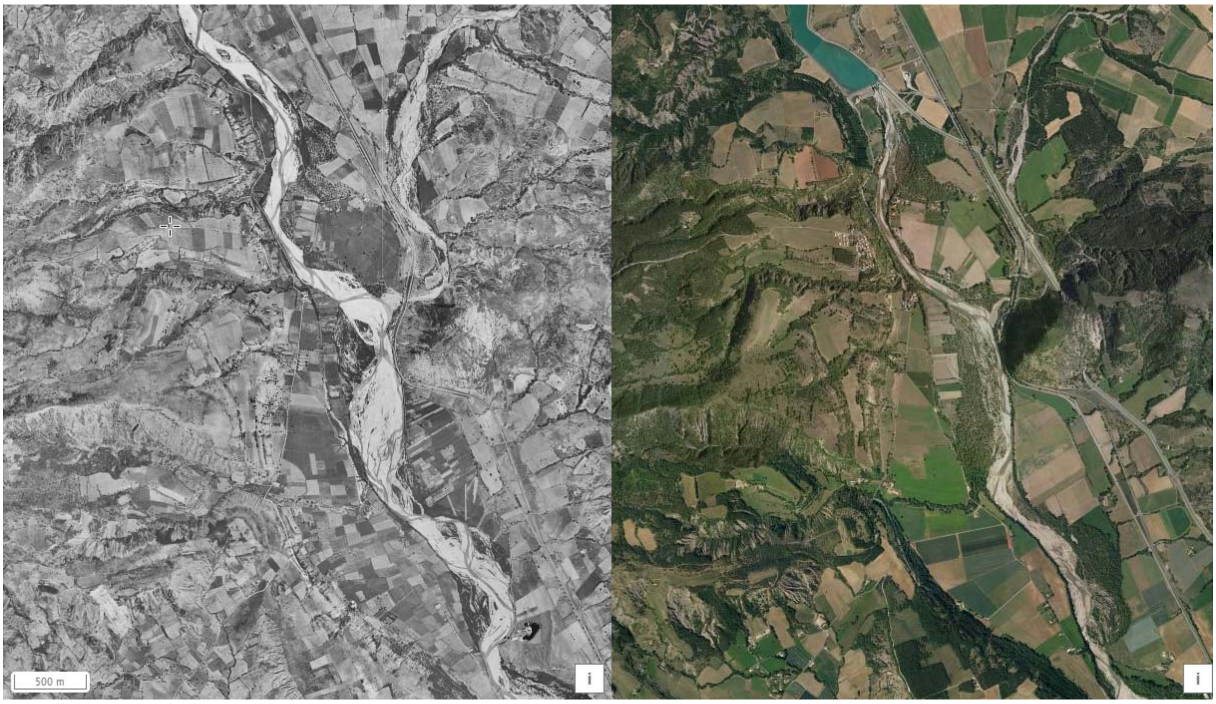


*Figure 4. The dying-off braided corridor of the Buëch River near Saint-Sauveur dam illustrated by aerial photographs comparison (1956-2006) (©IGN)*

## 2.2. The restoration project

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 (Fig. 5). These works were funded and supervised by EDF, the power plant company in charge of the dam. 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. A complementary objective is to reduce the flooding risk upstream from the dam, by dredging the aggrading alluvial fan that progrades into the Saint-Sauveur reservoir. This accelerated sediment deposition represents a threat for the Germanette leisure center located on the left side of the reservoir.

*Figure 5. Artificial gravel replenishment downstream from Saint-Sauveur dam ; 44 000 $m^3$ of coarse sediment has been reinjected in September 2016 (©EDF)*

## 3. Monitoring activities

### *3.1. General objectives of the monitoring program*

The main objective of the monitoring program is to capture the geomorphic and biological responses of the degraded reach to the artificial gravel recharge. The increase of sediment supply is expected to induce a raise of the bed-level (e.g. increase of sediment storage), and the spontaneous development of macroforms like riffle-pool-bars, typical of braided river patterns. The monitoring program should also provide a quantitative evaluation of the sediment input to the reach (how much gravels have been effectively released from the artificial berms?) and of the fate of these sediments (where do the gravels get deposited after flow events? What will be the residence time of these gravels into the degraded reach?). Theses improved geomorphic conditions should also be favorable in terms of aquatic and terrestrial habitat diversity, and should have subsequently a positive impact on macroinvertebrate and fish communities of the Buëch. The physical monitoring of the restored reach will then be combined with biota field surveys during all the project implementation period (2017-2019).

### 3.2. *Physical monitoring*

The physical monitoring will combine (i) repetitive high-resolution topographic surveys of the restored reach, (ii) a bedload tracing program using active ultra-high frequency RFID technology, (iii) a high-frequency qualitative survey of channel changes using time-lapse cameras, and (iv) ancillary field surveys for specific data analysis (e.g. bedload transport computation, calibration of imagery-based data processing).

Repetitive topographic surveys of the restored reach will combine high-resolution digital elevation models (DEMs) derived from (i) airborne LiDAR surveys and (ii) UAV high-resolution imagery. Images obtained from drones will be processed with a Structure from Motion (SfM) photogrammetry software (Agisoft Photoscan) to produce high-density 3D point clouds. These leading edge technologies for airborne topographic surveying are increasingly used in river restoration monitoring since they can deliver high-quality and high-density data for change detection along several km long channel reaches (e.g. Tamminga et al., 2015; Marteau et al., 2017). They both produce 3D point clouds of equivalent densities (from 10 to 100 points per m²) and equivalent precision (generally less than 10 cm). The level of detection of significant elevation change is generally comprised between 10 to 30 cm, depending on the nature of the terrain and technical specifications of the survey (e.g. flight elevation, sensor performance).

We will take advantage of the complementarity of these innovative and powerful surveying tools, since they both present some strengths and limitations in terms of spatial coverage, time frequency of data acquisition, and data quality for specific surface conditions (e.g. vegetated surfaces and submerged areas of the active channel). The main advantage of airborne LiDAR is the possibility to rapidly cover long stream reaches (e.g. 10 to 100 km length) with high quality topographic data on exposed vegetated and unvegetated surfaces. This technique makes possible to monitor an extended linear of stream network and to easily include in the monitoring program some reference reaches unaffected by the restoration project for inferring restoration effects. However, the expensive nature of such data prevents its use for high frequency repetitive surveys (like event-based surveys), contrary to UAV flights that can be more easily implemented and funded. One advantage of LiDAR over SfM is the possibility to extract the topography under the vegetation cover, since some ground echos can be detected and filtered from raw 3D point clouds of vegetated surfaces. This makes possible to integrate in sediment budget analysis volumes coming from eroded vegetated islands, bars, or terraces. However, the most common LiDAR sensors are using an infrared wavelength that did not penetrate water, making not possible the extraction of the bathymetry. This can be solved by using optical bathymetric mapping from orthophotos (e.g. Lane et al., 2003), SfM 3D point clouds that can provide bathymetric data under clear and shallow water conditions (e.g. Woodget et al., 2015), or green bathymetric LiDAR (e.g. Mandlburger et al., 2015).

The topographic monitoring of the Buëch restoration project will be based on 5 airborne LiDAR surveys, including three that have been already done (Table 2), and two that will be planned in collaboration with EDF during the next 2-3 years. The pre-restoration survey has been done in February 2015 between Serres and Montrond, along a 6 km reach. Two post-restoration surveys have been done in November and December 2016 between Serres and Eyguians, along a 11 km reach. The November 2016 survey provides a snapshot of the channel just after the sediment replenishment works; this survey can be used for characterizing initial conditions not only for the restored reach, but also for a reference reach that will be defined in the far downstream vicinity of the dam, between Montrond and Eyguians. This survey will also be used to quantify the volume of sediment released from the artificial gravel berms built in the replenishment reach, by providing the initial topography of the gravel berms. The December 2016 survey was done just after the occurrence of a major flood event that occurred between November 21st and 25th, with an estimated return period of 10 years, providing the opportunity to investigate the effect of the flood on the channel response of the degraded reach. The two forthcoming LiDAR surveys will be planned according to the hydrological activity of the river during the next 2-3 years.

| Date | Data source | Before/after restoration | Spatial coverage |
|---|---|---|---|
| 15/01/2015 | EDF/Sintegra | pre-restoration | Serres-Montrond (6 km) |
| 04/11/2016 | EDF/Sintegra | post-restoration | Serres-Eyguians (11 km) |
| 22/12/2016 | EDF/Sintegra | post-restoration | Serres-Eyguians (11 km) |

*Table 2. High-resolution airborne LiDAR data of the Buëch River restoration project*

UAV surveys of the Buëch will be conducted between LiDAR flights to increase the time frequency of topographic snapshots, but along a more restricted channel reach, given the time necessary to complete a full coverage of the active channel with high-resolution imagery. We will proceed with low-elevation flights (for a better resolution and precision of 3D point clouds) that must be preceded by the deployment of a large set of ground control points (around one every 50 m) for image georeferencing and for quality assessment of the topographic restitution. It is expected to flight over a 2.2 km reach located between the St Sauveur dam and Montrond (Fig. 2). The first flight will be done during summer 2017, and the other ones will be planned after the occurrence of significant flow events during the project period. We expect 2 UAV surveys per year, one after snowmelt spring high flows, and one after autumn flow events. UAV flights will be combined with dGPS surveys of water depths in the submerged areas of the active channel, to test for the quality of SfM bathymetric restitution, and to offer the possibility of using optical bathymetric mapping from orthophotos produced with drone imagery.

High resolution LiDAR and SfM 3D point clouds will be used to extract several morphological variables and to quantify different geomorphic processes along the restored and the reference reaches (Table 3). Hydrological records from the Serres gauging station will be used for the interpretation of geomorphic changes detected by repetitive surveys. Some of the forms and processes analysis will be possible only for the restored reach, where SfM 3D point clouds will be available. This is for example the case of surficial grain-size extraction on gravel bars based on channel roughness metrics. This has been successfully tested recently on the Vénéon braided channel (Fig. 6). Channel change detection maps will be produced using a classic DEM differencing approach for both reaches, including or not the submerged areas of the active channel, depending on the availability of high quality bathymetric reconstitutions (Fig. 7).

| | Restored reach | Reference reach |
|---|---|---|
| Bed-level (long profile) | x | x |
| Active channel width | x | x |
| Bed roughness (grain-size proxy) | x | |
| Surface GSD | x | |
| Macroform mapping | x | x |
| Sediment budget including submerged areas | x | |
| Sediment budget excluding submerged areas | | x |
| Bank erosion | x | x |
| Scour and fill depths including submerged areas | x | |
| Scour and fill depths excluding submerged areas | | x |

*Table 3. Morphological and textural variables that will be used to infer the effects of the sediment replenishment on the Buëch hydrogeomorphic conditions*

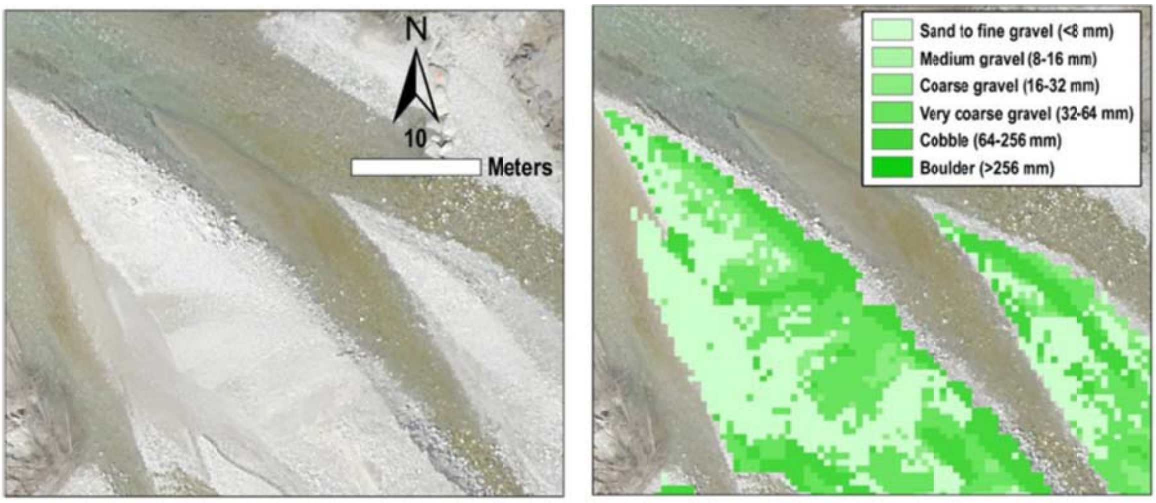


*Figure 6. Surface GSD chart derived from UAS-SfM point clouds (right). Left, the ortophotograph (2-cm pixel size). Visual inspection shows correspondence between GSD chart and ortophotograph (Vazquez-Tarrio et al., 2017)*

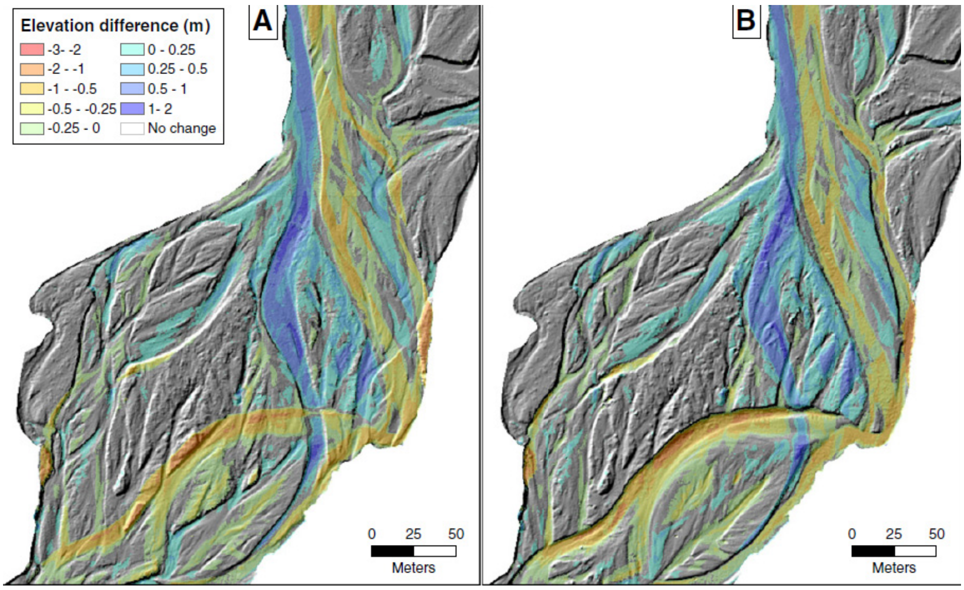


*Figure 7. Change detection map of the Bès River braided channel after the December 2009 flood, draped on hillshade views of (A) 2008 and (B) 2010 LiDAR-derived DTMs (Lallias-Tacon et al., 2014)*

Repetitive topographic surveys will be combined with a bedload tracing experiment using ultra high frequency active RFID (UHF RFID tags). The main advantage of these tags compared to more common low frequency PIT tags is that their range of detection is much more important (around 2-3 m under water), so that the recovery rate is largely improved, and the time necessary to relocate them is significantly reduced, especially in large gravel-bed rivers such as the Buëch. A set of 150 tags will be inserted in artificial gravels of similar size and density of natural gravels; they will be deployed upstream from the dam, to evaluate the sediment transparency of the dam, and to constrain the travel distance of the gravels reinjected downstream from the dam. This will help us to characterize the residence time of gravels in the restored reach, and to evaluate the frequency with which gravel replenishment operations should be planned in the future. RFID tags will also be used to evaluate the time-integrated bedload yield between inventories, following the virtual velocity approach of bedload transport (Liébault and Laronne, 2008; Mao et al., 2017). A comparison with estimates using bedload transport equations will be made.

## 3.3. *Ecological monitoring*

Sediment replenishment operations in alpine rivers are good opportunities to have a better knowledge on how hydromorphology and ecology interact. However, it is necessary to proceed to relevant physical and biological monitoring, as simple, robust, and reproducible as possible, to be repeated in space and time. The ecological monitoring should allow evaluating the efficiency of the restoration project in terms of ecosystem health and integrity. A description of the ecological monitoring protocol planned 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).

Different sources of ecological data exist on the different ecological compartments. An inventory of the existing data has been made and the following protocol will combine those data to evaluate the ecological effects of the Buëch restoration project. In order to constrain the ecological response, it is necessary to combine a local scale approach (monitoring stations) and a reach scale approach. However, it will be difficult to foresee the measurable impacts; the multiscale option appears to be the most efficient investigation.

To proceed to a relevant spatial and temporal comparison, it is necessary to define permanent monitoring stations, following recommendations from the French Water Agencies. Concerning the Buëch, the monitoring stations have yet to be defined, even if they are forecasted. At least one station in the restored reach and one in a reference unrestored reach will be monitored.

According to the classification of water bodies (WFD) and the typology of each river, the baseline conditions for aquatic invertebrate distribution are specific to each hydroecoregion. The Buëch River is a part of the “Prealps hydroecoregion”. This functional biogeographical unit of running water ecosystems determines the choice of the hydro-biological frame of reference for the estimation of the quality of the rivers (IBGN).

Following recommendations from Onema and French Water Agencies (Navarro et al., 2012), the CD05 monitoring protocol includes 3 interconnected biological compartments (macroinvertebrates, fishes, and riparian ecosystems).

### 3.3.1. *Hydro-biological monitoring*

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

#### 3.3.1.1. *Water Framework Directive protocol (WFD protocol)*

In addition to the physical monitoring, it is interesting to characterize the evolution of the macroinvertebrate fauna, which is fully linked to river channel habitats. The French IBGN (*Indice Biologique Global Normalisé*) methodology will be used (12 samplings per station based on pollu-sensitive taxa). The field sampling will follow recommendations from the AFNOR norm XPT90-333 of September 2009. This approach will be completed with a French normalized diatoms sampling, called IBD (*Indice Biologique Diatomées*). All these metrics result in a score out of 20.

Two databases based on the WFD protocol will be used for evaluating the effect of the restoration project on benthic invertebrate fauna:

- Data from the environmental monitoring of the Buëch following the increase of the ecological flow and the artificial sediment replenishment, led by EDF and a private company Gay Environment since 2014 on 3 different stations (Downstream the St Sauveur dam, Montrond, Ribiers) once a year (Maison Régionale de l'Eau, 2015).

- Data from the departmental monitoring of watercourses, led by the *Département des Hautes-Alpes* since 2004 on 3 different stations (Serres, Méreuil and Sisteron) at least once a year (Département des Hautes-Alpes, 2016).

A statistical data processing will be applied and, from the new multi-bio-indication index of rivers ($I_2M_2$ from Mondy et al., 2012), five metrics will be calculated in EQR (Ecological Quality Ratios based on different indicators as abundance, biomass, and annual/seasonal variability).

##### *3.3.1.2. Qualitative method (specific protocol for alpine rivers)*

A protocol based on flow facies will be used for the analysis of benthic invertebrate samples dedicated to a functional evaluation strategy. The field protocol consists of sampling the invertebrate diversity of lotic aquatic habitats (with water velocity > 30 cm/s) and of identifying *in situ* the species of harvested individuals (one or more individuals per taxon are conserved for laboratory validation). Habitat parameters such as position in the channel, dominant grain-size, clogging, and water velocity are compiled for each sampling. The objective of this protocol is to capture the diversity of benthic invertebrates present in a station at a given time. Thus, sampling is stopped when no new taxa appear. This protocol makes it possible to monitor the seasonal and inter-annual evolution of the benthic communities of the stations by limiting the time and the effort required compared to the standardized protocols.

Two sampling campaigns will be carried out on the Buëch (winter and summer) to accurately estimate the biological potential of the stations, due to the seasonal nature of the life cycles of some benthic invertebrates. Moreover, the determination can be improved for some taxa, especially for the *Baetidae* ubiquist; this family counts several species in the Hautes-Alpes with a distribution depending on water temperatures.

##### *3.3.1.3. Complementarity of the two invertebrate sampling protocols*

The WFD protocol has been primarily developed to identify alterations (e.g. organic pollution). It should also be completed by other approaches for braided river environments, which are characterized by particularly complex spatiotemporal patterns of habitats.

Standardized stream biological metrics (diatoms, macrophytes, macroinvertebrates, oligochaete, and fish) have been designed for assessing the status of biological compartments and ranking them into qualitative groups (like good or bad status). Even if these metrics can be used for characterizing a single functionality of the ecosystem, none of them are sufficiently integrative to inform about the overall functioning of the ecosystem. However, in the context of stream restoration and protection, it becomes crucial to produce integrative information for the global understanding of ecosystem functionality. The complementary qualitative survey of macroinvertebrate fauna will contribute to improve the characterization of the stream biological dynamics.

This biological dynamics is composed of a great variety of bio-cycles, in terms of duration (from several months to several years), seasonality (growth in cold, temperate or warm waters), and habitat preferences. The on-site specific composition of aquatic populations is the result of a complex biogeographical history (long-term imprint), which is modulated by random hydrological disturbances.

The table 4 shows the hydro-biological surveys planned for 2018 by CD05.

| Station Code | Study Code | Station Name | Network Type | Physical-chemistry | Bacteriology | IBGn T90-388 | Macroinvertebrates (qualitative surveys) | IBD 90-354 norm | Flow discharge gauging |
|---|---|---|---|---|---|---|---|---|---|
| 06154960 | BUEC0700 | SERRES | WFD | 4 | 1 | 1 | | 1 | 4 |
| 06155050 | BUEC0800 | MÉREUIL | WFD | 4 | 1 | 1 | | 1 | 4 |
| 06750950 | BUEC1200 | RIBIERS | WFD | 4 | | 1 | | | 4 |
| 06156400 | BUEC1300 | SISTERON | WFD | 4 | 1 | 1 | | 1 | 4 |
| 06154430 | BUEC0200 | LUS-LA-CROIX-HAUTE | Qualitative Method | 2 | | | 2 | | 2 |
| 06156020 | BUEC1100 | LARAGNE-MONTEGLIN | Qualitative Method | 2 | | | 2 | | 2 |

*Table 4. Hydro-biological monitoring planned by Département des Hautes-Alpes during the HyMoCARES project for the Buëch River*

#### 3.3.1.4. Fish monitoring

The fish biological compartment will also be investigated to characterize the ecological response to the restoration project (IPR index and mapping of spawning zones). However, it should not be forgotten that fish populations are mainly indicative of the long-term history of the river and of large-scale habitat conditions, since the lifetime of fishes largely exceeds 1 year. Data will be produced by AFB and Gay Environment:

- AFB: existing data for the stations of Méreuil, Montrond and Ribiers between 1988 and 2013.
- Gay Environnement: 3 yearly inventories will be conducted during summer low-flow conditions (2017, 2018 and 2019) according to De Lury's protocol + survey of potential spawning grounds downstream of the dam for southern barbeau (*Barbus barbus*) and blageon (*Telestes souffia)* species over a ~8 km reach (Gay Environnement, 2017).

### 3.3.2. The physical chemistry monitoring

#### 3.3.2.1. Water quality sampling

To have a precise image of the chemical and physical properties of the river, a set of parameters will be investigated using punctual water sampling during the project (Table 5). Those parameters are classically used to characterize the water quality of biological monitoring stations. Each water sampling will be systematically associated with a discharge gauging using water velocity measurements.

| 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 matter | *Escherichia Coli* |
| | intestinal enterococci |

*Table 5. List of monitored physical chemistry parameters*

Beyond these physical-chemical parameters, two indicators of bacteriological status will also be monitored: intestinal enterococci and *Escherichia coli*. These data are important to acquire for bathing use widely practiced on the Buëch. They will also provide guidance for estimating the ecosystem service related to recreational uses. This field survey (physical/chemical/flow/bacteriology) will be done four times a year on each of the four stations managed by the *Département des Hautes-Alpes* (Table 4).

### *3.3.2.2. Continuous physical chemistry monitoring*

On those specific mountain rivers and according to the special climatic conditions in the Southern Alps, large inter-daily and inter-seasonal variations of water quality are observed. There is a real necessity to check the evolution of the basic parameters to constrain the ecological status and finally verify if the punctual temporal monitoring is representative or not of the temporal variability. To address this question, continuous multi-parameter probes will be installed on the Buëch River for the continuous monitoring of different parameters (pH, temperature, dissolved $O_2$, $O_2$ saturation rate, conductivity). The water temperature appears to be a determinant factor for the river biodiversity and it will be the most studied.

Two sites of continuous physico-chemical monitoring have been defined: a control station and a station located along the restored reach: (1) the Méreuil station, directly downstream from the dam in the restored reach (Fig. 8); (2) the Ribiers station, as a control station.

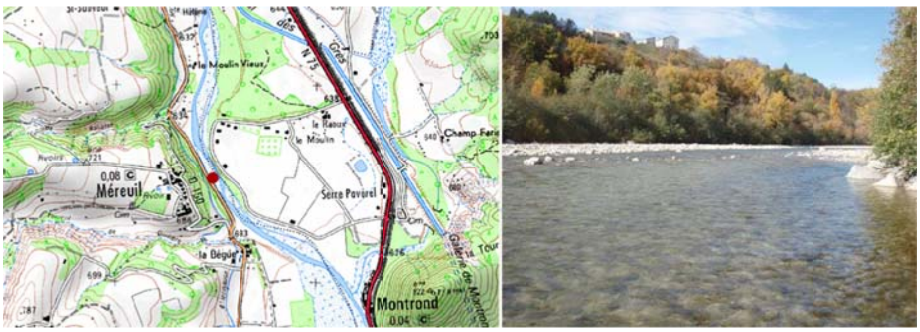


*Figure 8. The RCD station of the Buëch River at Méreuil (BUEC0800/06155050)*

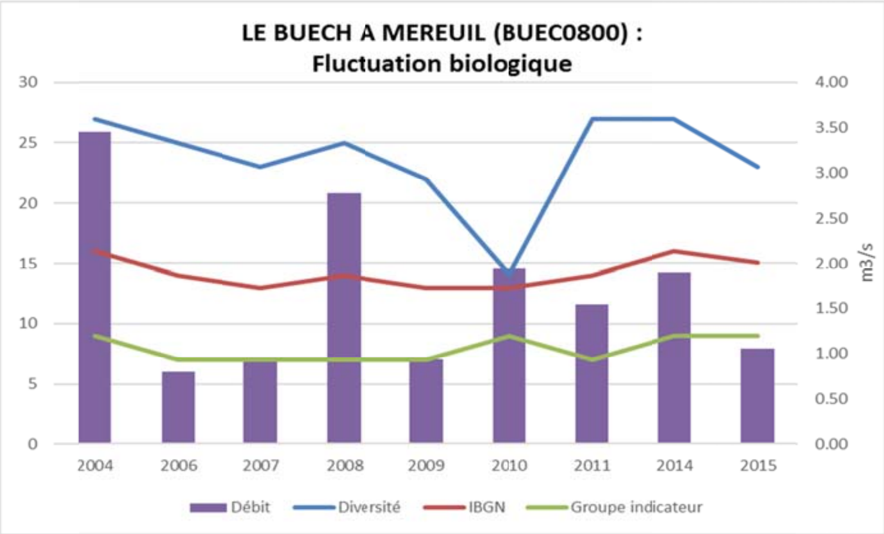


*Figure 9. Results of the biophysical monitoring between 2004 and 2015*

#### *3.3.2.3. Complementary data acquisition: "Increased" aquatic monitoring*

To complement the physical description of the aquatic compartment, the following data acquisition protocols will be implemented along the restored reach:

- Reconstruction of the water temperature heterogeneity of the braided channel using very high resolution thermal infrared imagery, following the methodology developed by Wawrzyniak et al. (2013, 2015).
- Map of the habitats and "Adoux" to follow evolution of the pioneer plant associations (complementing data of terrestrial monitoring).

Those remote sensing data will provide information about the connection with fresh groundwater, suspected to be refugee habitats for many aquatic species. Data acquisition will be completed during summer 2018.

### 3.3.3. *Monitoring of the riparian terrestrial environment*

The third part of the monitoring program will concerns the monitoring of the terrestrial compartment of the Buëch active channel and floodplain.

#### *3.3.3.1. Habitats mapping by “Pléiades satellite images and aerial photographs”*

Based on the present knowledge about the terrestrial compartment, an evolution of the terrestrial habitats based on the "Corine Biotope" mapping protocol (European soil typology) will be reconstructed. A compilation of historical aerial photographs combined with the recent Pléiades satellite imagery will be used for the comparison, following the methodology proposed by Wawrzyniak et al. (2017).

#### *3.3.3.2. Zooms on representative assets species of braided channels on a buffer zone*

Many technical reports exist on the Buëch River and its riparian environment. Based on this knowledge, terrestrial assets species will be investigated to observe their evolution, according to inventories realized before the restoration project. Possibly, a suitable protocol

RhoméO could be tested and mitigated, to adjust its application to alpine rivers (refocused on bio-monitor species of braided rivers). A precise definition of the list of species has to be defined. It concerns many faunal families, from invertebrates to birds. This will be investigated in 2018 (summer). On the Buëch, it is probably around the corteges of insects living in the active channel of the river.

### *3.3.4 Summary of ecological monitoring on the Buëch River*

Table 6 summarizes the ecological monitoring planned during the HyMoCARES project to characterize the river evolution.

| **Ecological monitoring** | **EDF / Gay Environment 2017 to 2019** | **Département des Hautes-Alpes 2018 and 2019** |
|---|---|---|
| Hydrobiological monitoring | Characterization of the benthic invertebrate fauna on 3 stations (downstream from the St Sauveur dam, Montrond, Ribiers) according to the WFD method (summer 2017, 2018 and 2019)<br><br>3 fish inventories during summer low-flows (2017, 2018 and 2019) according to De Lury's protocol<br><br>Survey of potential spawning grounds downstream of the dam for southern barbeau (*Barbus barbus)* and blageon (*Telestes souffia)* species along an 8 km reach | Water quality assessment by monitoring benthic invertebrate fauna according to quantitative and qualitative methods<br><br>Analysis of AFB data on fish inventories |
| Hydrology | Two gaugings of water discharge for each of the four ecological flow periods (between 2017 and 2020) on 9 stations between the Saint Sauveur dam and the confluence with the Durance | Four gaugings of water discharge on 4 stations (Serres, Méreuil, Ribiers and Sisteron) per year |
| Thermal monitoring | Monitoring of thermometers installed by EDF downstream of the St Sauveur dam - 3 stations | Aerial thermal investigation during low-flow periods to define refugia zones for aquatic species using a method developed by the CNRS + continuous monitoring for the temperature on a control station (Buëch at Sisteron) and directly in the restored area (Méreuil) |

| | | |
|---|---|---|
| physicochemical parameters | Punctual surveys of physicochemical parameters (T °, O2, conductivity and pH) on 3 stations (downstream of the St Sauveur dam, Montrond, Ribiers) | Punctual surveys of physicochemical parameters (T °, O2, conductivity and pH) on 3 stations (Serres, Méreuil and Ribiers) each year + continuous monitoring of those parameters at the control station and in the restored area |
| Riparian habitats and dynamics | No investigation | mapping of the riparian habitats from Pléiades satellite images and aerial photographs<br><br>field approach for definition of plant architecture<br>monitoring of post-works biogeographic dynamics<br>synoptic mapping of functional units of riparian strips.<br>Diachronic analysis of riparian strips at the scale of functional units<br>Comparative analysis of biogeographic dynamics in restored and non-restored areas |

*Table 6. Summary information about the ecological monitoring of the Buëch River planned during the Hymocares project*

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