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

Irstea Grenoble
Conseil Départemental des Hautes-Alpes

This project is co-financed by the European Regional Development Fund through the Interreg Alpine Space programme
www.alpine-space.eu/hymocares

1. General presentation of the study site

The Upper Drac is a gravel-bed braided river draining the southern flank of the Ecrins Massif, a geological unit belonging to the alpine outer crystalline massif, the northern flank of the Dévoluy Massif, which is part of the sedimentary Southern Prealps, and the Flysch thrust zone, composed of Cenozoic sedimentary rocks. The entire catchment is included in the Hautes-Alpes department, and the headwater catchments of the Drac Blanc and Drac Noir are included in the Ecrins National Park. The Drac is one of the major alpine tributary to the Isère River, with a confluence at the city of Grenoble. The study reach is located close to St-Bonnet-en-Champsaur, downstream from the Champsaur leisure center, at an elevation of 1000 m above sea level. This reach drains a 340-km² upland catchment with a maximum elevation of 3441 m (*le Sirac* in the Ecrins Massif) (Fig. 1, Table 1). The catchment geology is composed of a complex assemblage of crystalline and sedimentary rocks. Metamorphic rocks (mainly gneiss) are located in the upper catchment of the Drac Blanc; the rest of the catchment is underlain by sedimentary rocks from Jurassic (black marls), Cretaceous (limestones), and Cenozoic (sandstones) ages. Imprints from the Last Glacial Maximum (LGM) are widespread in the catchment, with important till deposits on hillslope, and paraglacial sediment in the valley floor. 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 (Montjuvent, 1978). These clay deposits are covered by the thin contemporary alluvial fill of the Drac River. The climate is characterized by a mean annual rainfall of ~950 mm. The hydrological regime is influenced by a strong spring snowmelt.

Drainage area (km²)	340
Location	44°39’17’’N, 6°6’23’’E
Length of the study reach (km)	3.7
Active channel width (m)	110
Channel slope (m/m)	0.01
Planform morphology	Braided pattern

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

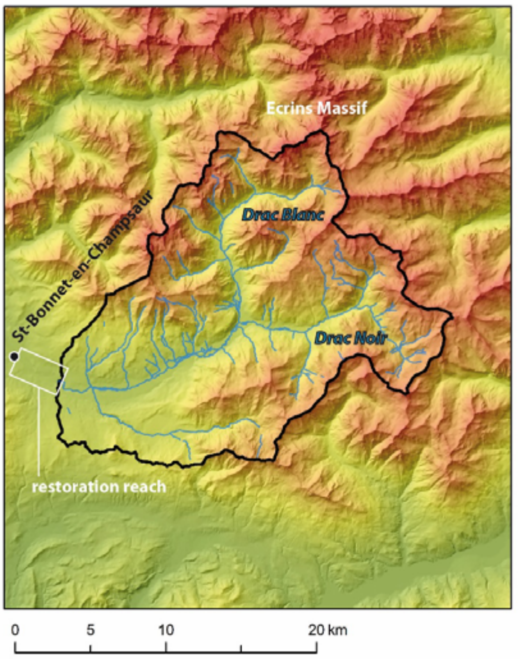

Figure 1. General relief map of the Drac catchment at the restoration site

The study reach extends from the Champsaur leisure center to the village of St-Bonnet-en-Champsaur (Fig. 2). This 3.7 km reach presents a mean active channel width of 110 m and a mean channel slope of 0.01 m/m. The channel morphology is an artificial wide and shallow channel with a rectangular cross-section recreated by the restoration project; it is expected to rapidly transform into a braided channel (Fig. 3). The dominant substrate is composed of gravel-sized sediments, with a D_{50} comprised between 40 and 80 mm. This reach is included in a 300-400 m wide alluvial floodplain, confined by alluvial fans and landsliding deposits. Well-preserved patches of alluvial forests are only marginally observed along the channel. Most of the floodplain is occupied by cultivated lands. The water discharge is monitored since 1972 at the Ricous gauging station, located 14 km upstream from the study reach. The water regime is characterized by a major snowmelt peak during May and June. The mean daily discharge is 5.46 m^3/s, and the 2 and 10 yr daily flood discharges are estimated at 41 and 61 m^3/s, respectively.

The main proximal sediment source of the restoration reach is the well preserved braided corridor of the Chabottes plain, located 3.5 km upstream from the reach. A secondary sediment source is the Brutinel Torrent, a left-bank tributary to the Drac draining the Dévoluy Massif and forming an alluvial fan at the confluence with the Drac. This tributary joins the Drac in the middle section of the restored reach (Fig. 2). Distal sediment sources are mainly composed of small active debris-flow torrents of the Drac Blanc and Drac Noir catchments.

Figure 2. Geoportail view of the restoration site of the Upper Drac River near St-Bonnet-en-Champsaur

Figure 3. The restored reach of the Upper Drac River near St-Bonnet-en-Champsaur; view looking upstream (©Irstea)

2. The hydromorphological restoration project

2.1. Human alterations of the physical fluvial corridor

Like most of alpine braided rivers in France, the Drac has been highly impacted by intensive gravel mining since the late 1960s (Liébault et al., 2013). For obscure reasons, this activity stops only very recently along the Drac, contrary to most of the other French alpine rivers where gravel mining stops in the mid-1990s, following a decree of September 1994. The gravel mining activity in the Chabottes plain was active from 1970 to 2012, at a rate exceeding 15 000 m^3/year (Laval and Guilmin, 2014). Another mining site was active at St-Bonnet during the 1970s and 1980s, generating regressive erosion along the Drac. The Upper Drac is not impacted by any dam, and it is marginally affected by embankments.

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 1913 (Liébault et al., 2013). 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 reached 2 to 4 m, and propagates upstream (Laval and Guilmin, 2014) (Fig. 5). This incision rapidly cut through the relatively thin alluvial layer and starts to scour lacustrine clay deposits from the LGM. 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.

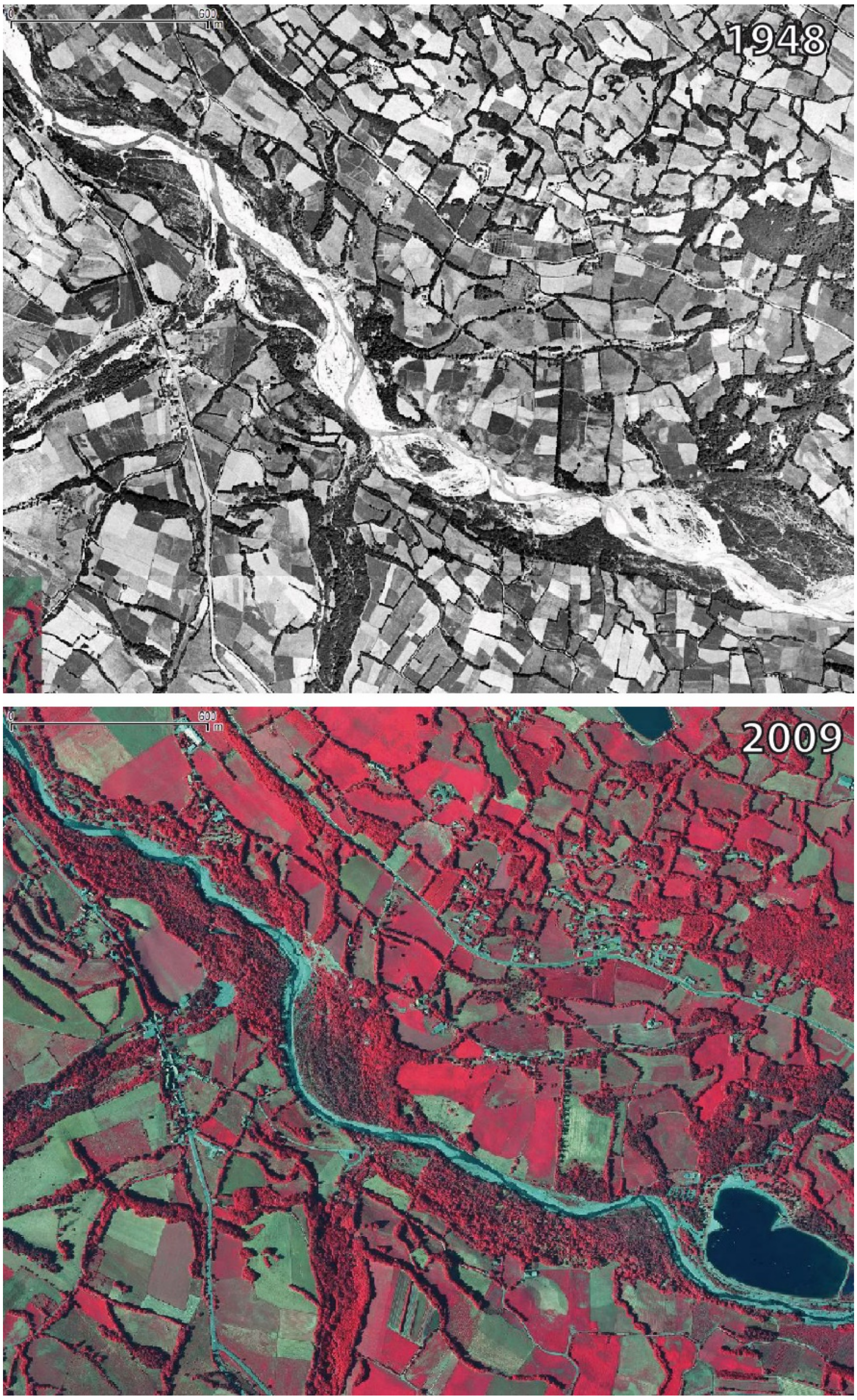

Figure 4. The dying-off braided corridor of the Drac River near St-Bonnet-en-Champsaur illustrated by aerial photographs comparison (1948-2006) (©IGN)

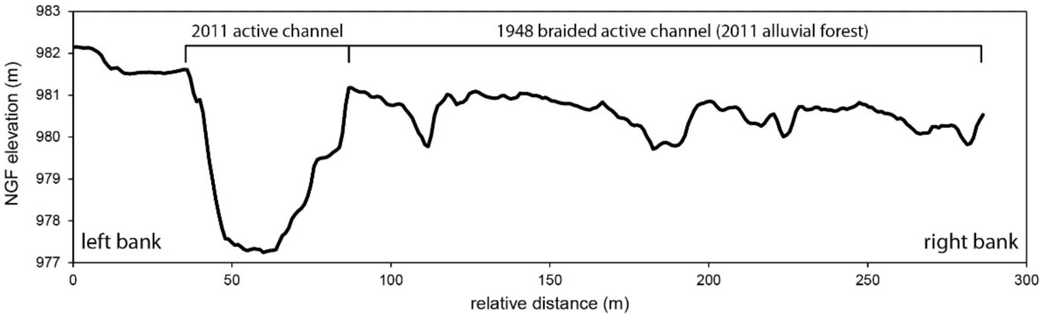

Figure 5. Channel incision of the Upper Drac River, illustrated by a cross-section extracted from the 2011 airborne LiDAR survey, in the upstream vicinity of the confluence with the Brutinel Torrent; the 2011 active channel is 4 m deep entrenched into the right-bank alluvial forest, which was part of the braided active channel of the Drac on 1948 aerial photos

2.2. The restoration project

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 (Fig. 6). 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 PACA Region, and EU (total cost of ~5 millions of euros).

The general objective of the restoration project is to recreate a braided channel corridor. A complementary objective is to avoid the destabilization of the right-side dike protecting the artificial pond of Champsaur.

Figure 6. Artificial recreation of a braided channel corridor along the Upper Drac River near St-Bonnet-en-Champsaur (©CLEDA)

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 newly created channel morphology, and to provide a record of the expected self-recovering towards a braided corridor. The monitoring program should also provide a quantitative evaluation of the sediment budget of the reach, and an evaluation of sediment input to the reach. The key issue here is the sustainability of the targeted braided pattern, which will be clearly conditioned by the present-day sediment supply to the reach. It is expected that the stopping of gravel mining in the upstream braided Chabottes plain will ensure a sufficient bedload supply to the restored reach. The monitoring program will provide a first evaluation of this hypothetical morphological trajectory, based on intensive observations of channel changes during the next 3 years. This expected physical trajectory 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 Upper Drac. 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 strength 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 non-vegetated 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 echoes 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 Upper Drac restoration project will be based on 5 airborne LiDAR surveys, including four that have been already done (Table 2), and one that will be planned in collaboration with the French Water Agency during the next 2-3 years. Two pre-restoration high-resolution LiDAR surveys are available: one in February 2011 from the upstream end of the Sautet reservoir (*Le Motty*) to the confluence between Drac Noir and Drac Blanc, along a 35 km reach, and one in October 2013 along the 3.5 km degraded reach of St-Bonnet, taken just before the implementation of the restoration project. One post-restoration low-resolution terrestrial dGPS survey has been done in April 2014, to capture the topography of the reach just after the restoration works. Two post-restoration airborne LiDAR surveys are available: one in September 2015, along the 35 km reach of the Upper Drac, between the Sautet reservoir and the Drac Noir-Drac Blanc confluence, and one in September 2016 along the 3.5 km restored reach. The September 2015 survey provides a snapshot of the channel after two post-restoration snowmelt flow seasons (2014 and 2015); this survey will be used for characterizing the channel response of both the restored reach and one reference reach. This survey will also be used to quantify the sediment budget of the restored reach. The September 2016 survey will be used to reconstruct channel changes after the 2016 snowmelt season, but only for the restored reach. The forthcoming LiDAR survey will be planned according to the hydrological activity of the river during the next 2-3 years.

Date of the survey	Type of survey	Data source	Before/after restoration
08/02/2011	airborne LiDAR	CG05 / Sintegra	pre-restoration
15-28/10/2013	airborne LiDAR	CLEDA / Vinci	pre-restoration
11-17/04/2014	dGPS terrestrial survey	CLEDA / Vinci	post-restoration
10/09/2015	airborne LiDAR	CD05 / Sintegra	post-restoration
22/09/2016	airborne LiDAR	CD05 / Sintegra	post-restoration

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

UAV surveys of the Upper Drac will be conducted during the project period 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 the 3.5 km restored reach located between St-Bonnet and the Champsaur leisure center (Fig. 2). The first flight will be done during summer 2017, and the other ones will be planned after the snowmelt flows of 2018 and 2019. We expect 1 UAV survey per year, after snowmelt spring high flows, but if a major flood occurs during the project, one supplementary flight will be done. 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 Ricous 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

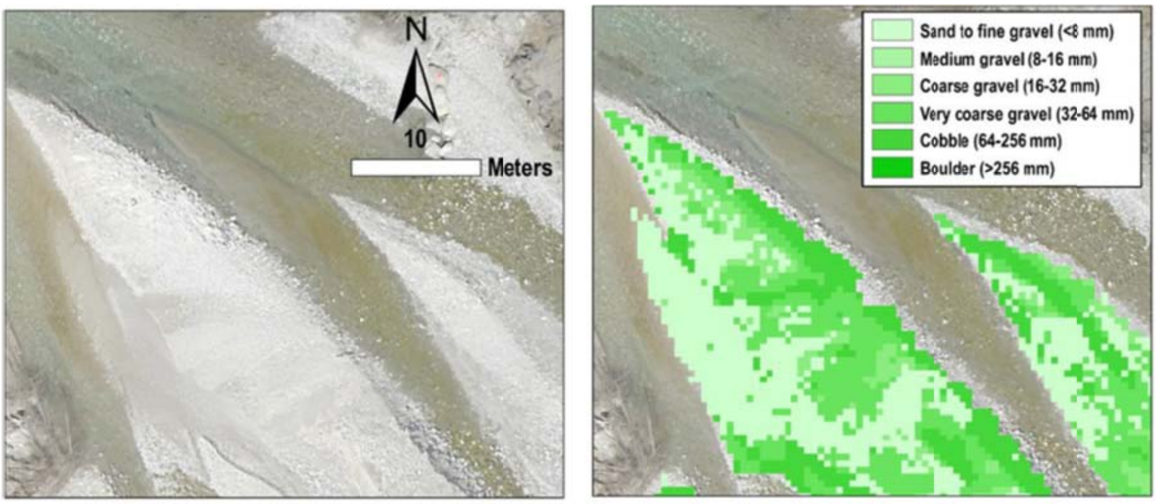

Figure 6. Surface GSD chart derived from UAS-SfM point clouds (right). Left, the ortophotograph (2-cm pixel size). VISUal inspection shows correspondence between GSD chart and ortophotograph (Vazquez-Tarrio et al., 2017)

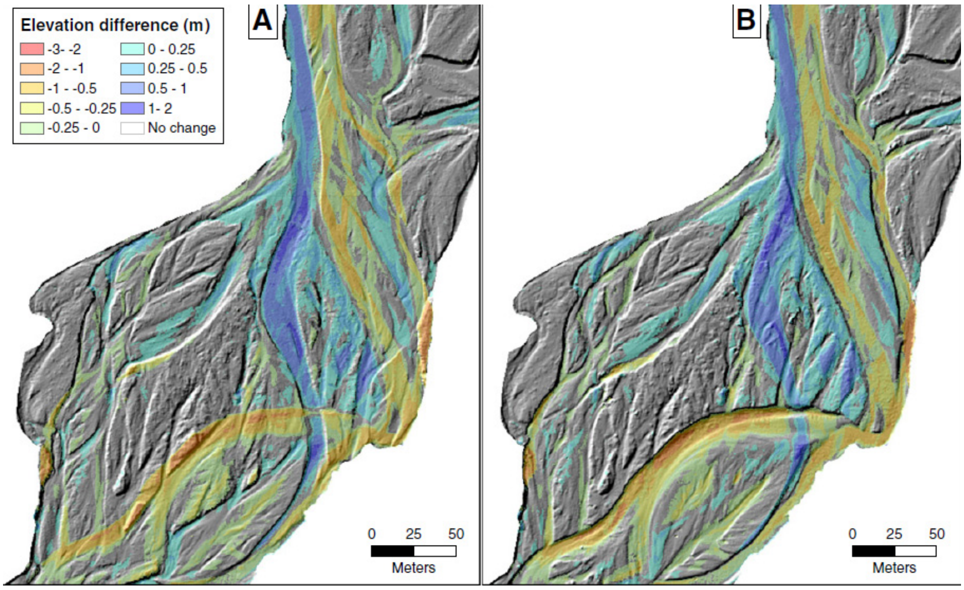

Figure 7. Change detection map of the Bès River braided channel after the December 2009 flood, draped on hillshade views of (A) 2008 and (B) 2010 LiDAR-derived DTMs (Lallias-Tacon et al., 2014)

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 Drac. A set of tags will be inserted in artificial gravels of similar size and density of natural gravels; they will be deployed in the braided Chabottes plain, to evaluate the bedload transit time from this major sediment source and the restored reach. 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 fix any monitoring station, scalar analysis promulgated by the national guide of the water agency. Concerning the Drac River, the control stations are already defined and conditioned by the existing monitoring of the Département des Hautes-Apes, The Agency de l'eau RMC and the AFB fishes' investigations.

According to the classification of water bodies (WFD) and the typology of each river, the baseline conditions for aquatic invertebrate's distribution depend to hydroecoregion. The Drac River is a part of the "Alpes-Internes Hydro-ecoregion". This geographical frame of running water ecosystem functioning 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). Starting with those 3 working conditions, the frame of the monitoring protocol is detailed below.

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 could 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 "demonstration site" produced by the Agence de l'Eau Rhône Mediterranée Corse on 2 different sites (Agence de l'Eau Rhone, Mediterranée, Corse, CCTP, mise en place de suivis écologiques dans le cadre de projets de restauration de l'hydromorphologie): Saint Bonnet en Champsaur in the area of the restoration work and Forest Saint Julien, upstream of restoration work.

- Data from the departmental monitoring of watercourses, led by the Département des Hautes-Alpes since 2004 on 4 different stations (Orcières, Chabottes, pont du Fossé et Saint Bonnet en Champsaur) at least once a year (Département des Hautes-Alpes, 2016, Suivi de la qualité des cours d'eau).

A statistical data processing will be applied, and, from the new multi-bio-indication index of rivers (I2M2), 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 Drac (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 deepened 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" methods

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 dynamic 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**	Physico-chimie	**Bactério**	**IBGn T90-388**	**Invertébrés qualitatifs**	**IBD norme 90-354**	**Gaugins**
06142440	**DRAC0030**	LE DRAC A ORCIERES	WFD	4	1	1		1	4
06142470	**DRAC0060**	LE DRAC A CHABOTTES	Qualitatif				1		1

06710120	**DRAC0080**	LE DRAC A SAINT BONNET	Qualitatif				1		1
06710130	**DRAC0090**	LE DRAC A SAINT BONNET	WFD	4	1	1		1	1
06820109	**DRAC0100**	LE DRAC AU MOTTY	WFD	4	1	1		1	4

Table 4: Watercourses Hydro-biological monitoring led by Département des Hautes-Alpes in HyMoCARES framework for the Drac River.

3.3.1.4. Fishes 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, Agence de l'Eau RMC and Agence VISU:

- AFB: inventory of fishes' populations between 1988 and 2017
- Agence de l'Eau RMC: Inventory of fishes' population and spawning ground mapping
- Agence VISU: Spawning ground mapping from VISU Agency (Agence VISU, 2012, Projet de restauration du lit du Drac en amont de Saint-Bonnet en Champsaur par recharge sédimentaire du lit mineur) in 2013 in the framework of the impact study before the restoration work (Alcotra program : Pellidrac - Burgéap, 2012, Le Drac en amont de Saint Bonnet en Champsaur).

The comparison of this data is a good indicator of the evolution of the fishes around the restoration work area.

3.3.2. The physical chemistry monitoring

3.3.2.1. Water quality samplings

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

Bacteriology (see table 4 and 5):

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 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 are chosen: a control station and a station located along the restored reach: (1) the Drac River in Pont du Fossé as a control station, (2) the Drac River in Saint Bonnet en Champsaur in the restoration area

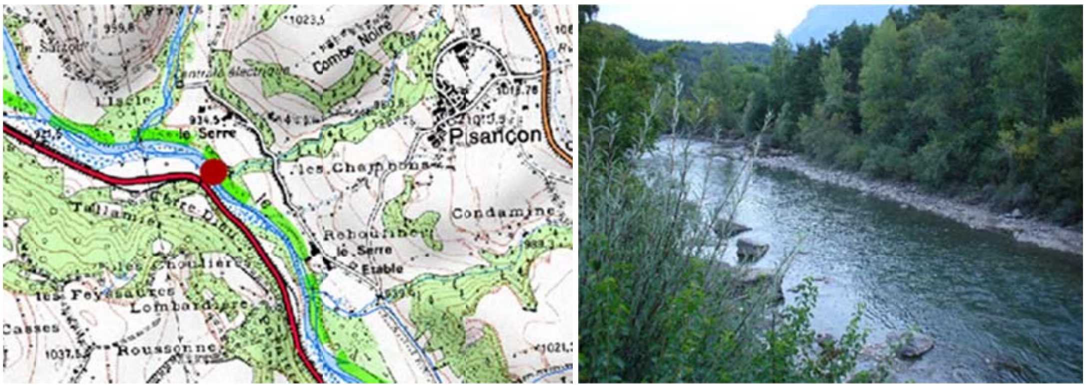

Fig 8: The RCD Station of the Drac River at Saint-Bonnet-En-Champsaur (DRAC0080 / 06710120)

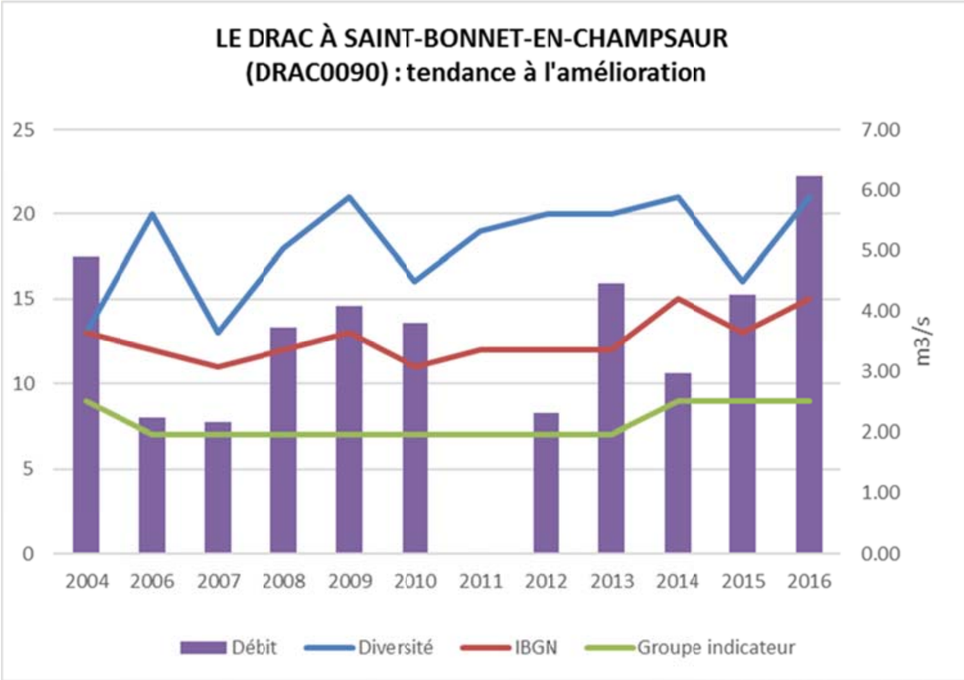

Figure 9: Results of biophysical monitoring between 2004 and 2016

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.

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 riparian environments

The third part of the monitoring program will concern the monitoring of the terrestrial compartment of the Drac 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 "patrimonial" species of braided beds on a buffer zone

Many technical reports exist on the Drac River and its riparian environments. Based on this data, terrestrial patrimonial species will be investigated to observe their evolution, according to inventories realized before restoration work. 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 and flora families. This will be investigated in 2018 during relevant period. The methodology will be defined with a recipient, possibly in a framework of research & development.

For the Drac, studies will be concentrated on population of the birds, riparian vegetation, macrophytes and bats (CLEDA, 2012, Matrices des indicateurs en fonction des scénarios d'évolution).

3.3.4. Summary of ecological monitoring on the Drac River

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

Ecological monitoring	*Agence de l'eau RMC (2016 to 2023) + AFB (1989 to 2017)*	*Département des Hautes-Alpes (2018 and 2019, data used since 2004)*
Hydrobiological monitoring	Invertebrate Macro Sampling, Diatom Sampling by Agence de l'Eau investigations	Water quality assessment by monitoring benthic invertebrate fauna according to quantitative and qualitative methods
Hydrology	*No investigation*	Four gaugings on 4 stations : Orcières, Pont du Fossé, Chabottes and Saint Bonnet en Champsaur 4 times a year.
Hydrogeology	Prior Hydrogeological Study around the restoration work area, Water level measurements of the groundwater by Agence de l'Eau investigations	*No investigation*
Thermal monitoring	*No investigation*	Aerial thermal investigation during low-water periods to define refugia zones for aquatic species on Drac River using a method developed by the CNRS + continuous monitoring for the temperature parameter on a control station (Drac In Pont du Fossé) and directly in the restored area (Drac in Saint Bonnet)
Physico chemical parameters	Measurements of physico-chemical parameters in situ, Macro Pollutant Analyzes by Agence de l'Eau	Punctual survey of all the physicochemical parameters (T °, O2, Conductivity and pH) on the 4 stations: Orcières, Pont du Fossé, Chabottes and Saint Bonnet en Champsaur each year + Continuous monitoring of those parameters at the control station and in

		the restored area.
Fishes inventory	Sampling fish stands by AFB Complementary measures on alluvial spawning grounds by AFB	Using AFB and Agence de l'eau investigations for the assessment of the evolution of the Drac River
Habitats and Riparian Dynamics	*No investigation*	mapping of the riparian habitats from Pléiades satellite images and aerial photographs field approach for definition of plant architecture monitoring of post-works biogeographic dynamics synoptic mapping of functional units of riparian strips. Diachronic analysis of riparian strips at the scale of functional units 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

4. References

Agence de l'Eau Rhône, Méditerranée, Corse, CCTP, Mise en place de suivis écologiques dans le cadre de projets de restauration de l'hydromorphologie de cours d'eau du bassin Rhône Méditerranée, Market to purchase order, 18 pp.

Agence VISU, 2012, Projet de restauration du lit du Drac en amont de Saint-Bonnet en Champsaur par recharge sédimentaire du lit mineur, Expertise écologique, CLEDA, 210 pp.

Agence VISU, 2012, Projet de restauration du lit du Drac en amont de Saint-Bonnet en Champsaur par recharge sédimentaire du lit mineur, Notice d'incidence NATURA 2000, CLEDA, 298 pp.

Agence VISU, 2012, Projet de restauration du lit du Drac en amont de Saint-Bonnet en Champsaur par recharge sédimentaire du lit mineur, Étude d'impact faune/flore, CLEDA, 298 pp.

Burgéap, 2012, Le Drac en amont de Saint Bonnet en Champsaur, Projet de restauration du lit du Drac par recharge sédimentaire, MISSION 1 – Études préliminaires complémentaires et diagnostic, Unpublished technical report, 141 pp.

CLEDA, 2012, Matrices des indicateurs en fonction des scénarios d'évolution, technical evaluation grid.

Département des Hautes-Alpes, 2016. Suivi de la qualité des cours d'eau. Unpublished technical report, 92 pp.

Lallias-Tacon, S., Liébault, F., Piégay, H., 2014. Step by step error assessment in braided river sediment budget using airborne LiDAR data. *Geomorphology*, 214(0): 307-323.

Lane, S.N., Westaway, R.M., Hicks, D.M., 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. *Earth Surface Processes and Landforms*, 28: 249-271.

Laval, F., and 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).

Liébault, F., Piégay, H., 2002. Causes of 20th century channel narrowing in mountain and piedmont rivers of Southeastern France. *Earth Surface Processes and Landforms* 27, 425-444.

Liébault, F., Laronne, J.B., 2008. Evaluation of bedload yield in gravel-bed rivers using scour chains and painted tracers: the case of the Esconavette Torrent (Southern French Prealps). *Geodinamica Acta*, 21(1-2) : 23-34. DOI : DOI: 10.3166/ga.21.23-34

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.

Mandlburger, G., Hauer, C., Wieser, M., Pfeifer, N., 2015. Topo-Bathymetric LiDAR for Monitoring River Morphodynamics and Instream Habitats—A Case Study at the Pielach River. *Remote Sensing*, 7(5): 6160.

Mao, L., Picco, L., Lenzi, M.A., Surian, N., 2017. Bed material transport estimate in large gravel-bed rivers using the virtual velocity approach. *Earth Surface Processes and Landforms*, 42(4): 595-611. DOI:10.1002/esp.4000

Marteau, B., Vericat, D., Gibbins, C., Batalla, R.J., Green, D.R., 2017. Application of Structure-from-Motion photogrammetry to river restoration. *Earth Surface Processes and Landforms*, 42(3) : 503-515. DOI :10.1002/esp.4086

Mondy, C.P., Villeneuve, B., Archaimbault, V., Usseglio-Polatera, P., 2012. A new macroinvertebrate-based multimetric index (I_2M_2) to evaluate ecological quality of French wadeable streams fulfilling the WFD demand: a taxonomical and trait approach. *Ecological Indicators*, 18 : 452-467.

Montjuvent, G., 1978. Le Drac : morphologie, stratigraphie et chronologie quaternaires d'un bassin alpin. Unpublished Thesis, Université de Grenoble II.

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.

Piégay, H., Alber, A., Slater, L., Bourdin, L., 2009. Census and typology of braided rivers in the French Alps. *Aquatic Sciences* 71, 371-388.

Tamminga, A., Hugenholtz, C., Eaton, B., Lapointe, M., 2015. Hyperspatial Remote Sensing of Channel Reach Morphology and Hydraulic Fish Habitat Using an Unmanned Aerial Vehicle (UAV): A First Assessment in the Context of River Research and Management. *River Research and Applications*, 31(3): 379-391. DOI:10.1002/rra.2743

Vázquez-Tarrío, 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: 94-105, 10.1016/j.geomorph.2017.01.039.

Wawrzyniak V., Piégay H., Allemand P., Vaudor L., Grandjean P., 2013., Prediction of water temperature heterogeneity of braided rivers using very high resolution thermal infrared (TIR) images (French Alps)

Wawrzyniak V., Räpple B., Piégay H., Michel K., Parmentier H., Couturier A., 2017, Analyse multi-temporelle des marges fluviales fréquemment inondées à partir d'images satellites Pléiades

Woodget, A.S., Carbonneau, P.E., Visser, F., Maddock, I.P., 2015. Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry. *Earth Surface Processes and Landforms*, 40(1) : 47-64. DOI :10.1002/esp.3613