Quantifying discharges and fluxes of matters in rivers

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L'HABILITATION À DIRIGER DES RECHERCHES

Spécialité : **Terre, Univers, Environnement**

Présenté par

Jérôme LE COZ

préparé au sein de **l'unité de recherche Hydrologie-Hydraulique de l'Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture (Irstea), Lyon-Villeurbanne, France**
dans l'Ecole Doctorale **Terre, Univers, Environnement**

Quantifier les débits et les flux de matières dans les cours d'eau

Habilitation soutenue publiquement le **29 novembre 2017**,
devant le jury composé de :

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ゆく 河 の 流れ は 絶えず して、しかも もとの 水 に あらず。

よどみ に 浮かぶ うたかた は、かつ 消え かつ 結びて、久しく とどまりたる ためし なし。

世の中 に ある 人 と すみか と、また かくの ごとし。

Le courant de la rivière qui s'écoule ne s'interrompt pas et pourtant l'eau n'est pas la même eau qu'auparavant. La mousse qui flotte sur les eaux stagnantes, qui disparaît, qui réapparaît, ne reste jamais la même très longtemps. De même en va-t-il avec les gens et les abris de ce monde.

The current of the flowing river does not cease, and yet the water is not the same water as before. The foam that floats on stagnant pools, now vanishing, now forming, never stays the same for long. So, too, it is with the people and dwellings of the world.

Kamo no Chōmei (鴨長明, 1155–1216)
Incipit du Hōjōki (方丈記, 1212), *La cabane de dix pieds carrés.*
Opening sentences of Hōjōki (方丈記, 1212), *The ten foot square hut.*

Ce document est dédié aux nombreuses personnes qui ont contribué aux recherches qui apparaissent ici sous mon seul nom, ainsi qu'aux arpenteurs d'eau qui, partout dans le monde et depuis des siècles, se consacrent avec passion à prendre le pouls de la Terre.

This document is dedicated to the many people who contributed to the research that appears here under my name alone, as well as to water surveyors around the world who, for centuries, have enthusiastically dedicated their time to taking the pulse of the Earth.

Contents

Quantifying discharges and fluxes of matters in rivers

1 Introduction

1.1 Importance and evolution of streamflow monitoring networks

How much water and associated matters are transported by rivers and streams is arguably the most important measure in hydrology. Discharge is indeed a fundamental variable for hydrology as it temporally and spatially aggregates the response of a river catchment to climatic forcing and anthropogenic pressure. Other hydrological fluxes like rainfall, snow, evapo-transpiration, groundwater and subsurface flows are spatially variable throughout the river catchment, thence more difficult to measure with similar accuracy as discharge at the outlet of the catchment. Streamflow time series serve as the basis of most studies and policy decisions related to water resources, flood risk, pollution, ecological habitat, among others. Dissolved and solid matters associated with streamflows, including bed material load, determine a river's morphological evolution and its ecological quality. Long, continuous and accurate time series of instantaneous fluxes of water and associated matters are necessary to establish volume and mass budgets at event or annual time intervals, to describe the flow, sediment, nutrient and pollutant regimes of a river through statistical indicators, and to calibrate and validate numerical models of the river network or the river catchment. Streamflow time series are the basis for any assessment of the impact of global change and anthropogenic pressure on rivers and inland water bodies.

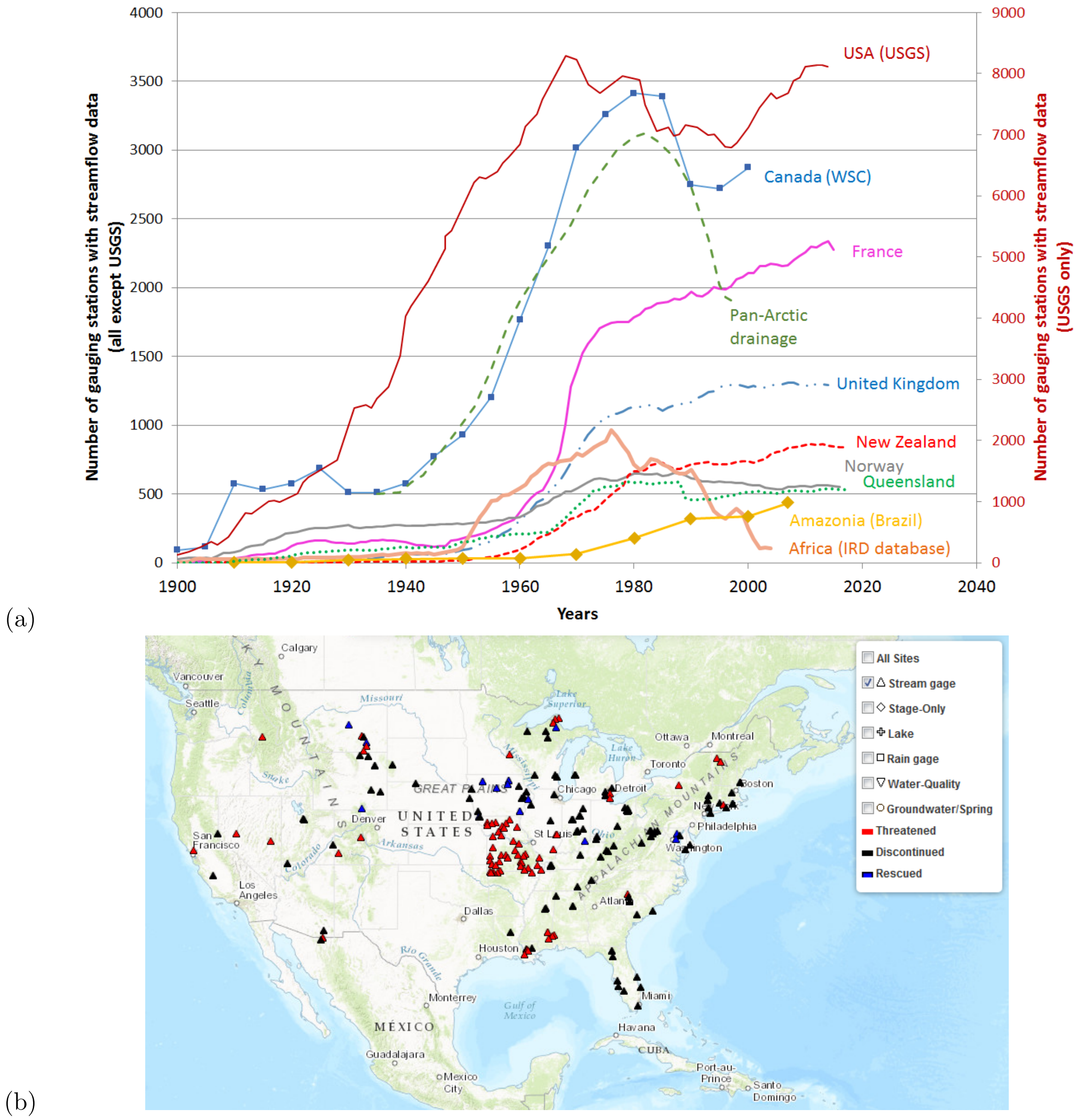

Figure 1: Evolution of hydrometry networks around the world: (a) number of operative streamgauging stations over the years in: UK's National River Flow Archive (Muchan, 2017, pers. comm.), France's national database Banque Hydro (Puechberty and Baillon, 2017, pers. comm.), Norway's NVE database (Florvaag-Dybvik, 2017, pers. comm.), New Zealand's national SIMS database (Henderson, 2017, pers. comm.), Queensland, Australia* (Maynard, 2017, pers. comm.), the Brazilian Amazon basin (National Water Agency ANA**), the Water Survey of Canada network (Mishra and Coulibaly, 2009), the Pan-Arctic drainage basin (Shiklomanov et al., 2002), the IRD database for Africa (Jouve et al., 2014), and the USGS network*** (USA); (b) dynamic map of the threatened, endangered, discontinued and rescued USGS streamgauging stations due to lack of funding****.

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* ©The State of Queensland (Department of Natural Resources and Mines) [2017]
** `http://arquivos.ana.gov.br/infohidrologicas/RHAmazonica.pdf`
*** `https://water.usgs.gov/nsip/trends9.html`
**** `https://water.usgs.gov/networks/fundingstability/`, accessed 12 April 2017.

In spite of increasing water-related crises and growing concern about the impacts of climate and land use changes on water resources and risks, the numbers of rain and streamflow gauges in some regions of the world have slowly or rapidly declined since the 1980s and 1990s (Stokstad, 1999). The decline can be dramatic in developing countries as reflected by the recession in streamflow data collected by the *Institut de Recherche pour le Développement* (IRD[1]) from various agencies in Africa (cf. Fig. 1a). For instance, Alsdorf et al. (2016) report that "*before 1960, there were more than 400 stream gauges throughout the Congo Basin, whereas today there are only about 10 operating stations*". To improve the situation in less advanced countries, the World Meteorological Organization (WMO) launched the World Hydrological Cycle Observing System (WHYCOS), a global capacity building programme: Jouve et al. (2014) reported on the French contribution to regional programmes Niger-HYCOS, Congo-HYCOS and Mekong-HYCOS. Beyond national hydrological databases, large-scale river flow archives like that operated by the WMO Global Runoff Data Centre (GRDC) are valuable for providing harmonised datasets of long-term streamflow time series across international boundaries (Hannah et al., 2011).

Tightening of networks has affected some rich countries as well, but it seems that the decline has often been stabilised or compensated by the development of locally-operated hydrometry networks. The network of the United States Geological Survey (USGS) continuously grew and included more than 8 000 stream gauges around 1970. Then it decreased in some years and remained with about 7 000 open stations before another increase to 8 000 in the 2000s (cf. Fig. 1a, right axis). However, depending on federal budget allocation, between 20 and 150 stations with 30 or more years of record have been shut down every year between 1980 and 2005. This equates to a cumulative loss of more than 2 200 long-record stations in the USA (USGS, 2007; Lins, 2008). The USGS provides a dynamic map of the endangered, discontinued and rescued stations because of funding issues (Fig. 1b). In the State of Queensland, Australia, there was a pronounced increase in gauging stations after World War II, an even larger increase in the mid-1960s driven by Federal Government funding, then a pronounced network reduction in 1988, which was to fund the installation of dataloggers and their sensors (cf. Fig. 1a). In mid-2002, many of the government-operated sites went to the hived-off organisation SunWater. In Canada too, due to restrictions in federal and provincial budgets the number of stream gauges operated by the Water Survey of Canada decreased in the 1990s and early

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[1] French Research Institute for Development. In spite of data availability issues and on-going updates, the number of stations in the IRD database appears to reflect the real trends in operative stream gauges in Africa, unfortunately (Jouve et al., 2014).

2000s to stabilise at 60% of its size in the 1980s (Water Survey of Canada, 2010). The figures reported by Mishra and Coulibaly (2009) reflect this trend but with a smaller decrease (cf. Fig. 1a), and the decrease was partially compensated through gauges operated locally, especially by various conservation areas across the country. Again, a major concern is that long hydrologic records have been discontinued in the process. According to Hannah et al. (2011), "*from 1987 to 2007, a total of 467 Canadian gauges having >30 year records were closed*". Furthermore, this was also the point at which sediment monitoring by Water Survey Canada stopped. The situation in European countries is more contrasted. For instance, in the last decades the number of operative gauges in the UK National River Flow Archive has remained fairly constant, while it has decreased in the NVE[2] database (Norway) and increased in the *Banque Hydro*, the French national database (cf. Fig. 1a). The vast majority of stations that are held on these three databases are operated by governmental organisations.

Such gross numbers may however hide important evolutions as some national archives gather data produced by various agencies and as the length and quality of streamflow records are not reflected. In that respect, the example of New Zealand is interesting, as important changes in the structure of the network occurred while the total number of stations has grown continuously (Le Coz, 2017). In 1993-1994, 60 of the 290 stations of the National Hydrometry Network of New Zealand – the governmental network operated by NIWA[3], were closed after a rigorous selection of the most valuable stations, hydrologically speaking (Pearson, 1998). This corresponded to a 20% cut in the governmental budget dedicated to streamflow monitoring. However, figures from the SIMS[4] database (Henderson, pers. comm., 2017) indicate an older and more contrasting trend in the general hydrometric network, with a marked growth slowdown as soon as the early 1980s, and a small but steady increase since then (Fig. 2a). The figures show that the evolution of New Zealand's hydrometric network is related to changes in the funding mode of the stations (Fig. 2b). Research-funded stations, including the National Hydrometric Network, have been continuously decreasing since 1980 following the primary boost during the International Hydrological Decade (1965-1974), well before the 'optimisation' of 1994 reported by Pearson (1998). This reflects both the contraction of the National Hydrometric Network and the closure of experimental research basins. Since 1975, the stations operated by local authorities (regional councils and district councils) have expanded

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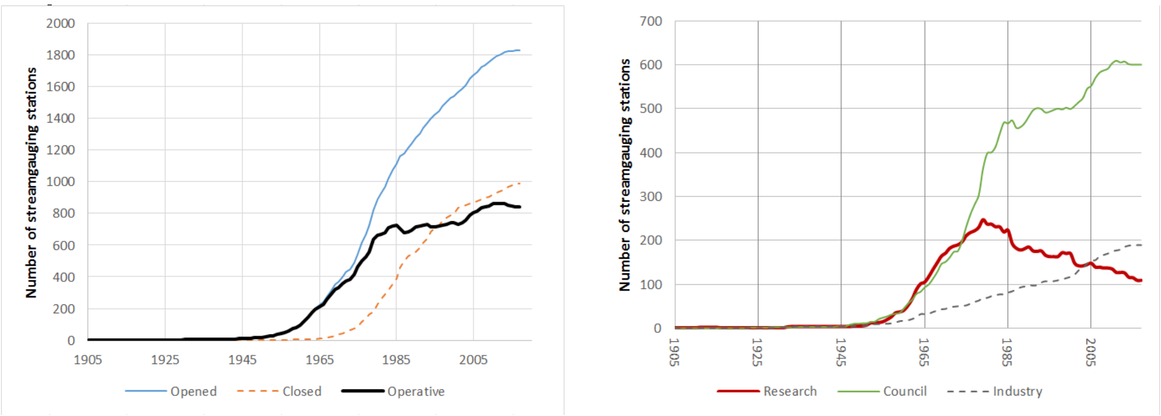
[2] The Norwegian Water Resources and Energy Directorate, `https://www.nve.no/english/`.

[3] National Institute of Water and Atmospheric Research

[4] `SIMS:StationInformationManagementSystem,NIWA(https://sims.niwa.co.nz/).`

with decentralised responsibilities for water resources management and flood forecasting (with the advent of the Resource management Act, 1991). Some formerly NIWA-operated stations were passed to councils and the total network has kept growing. The number of stations funded by the industry (hydroelectricity, irrigation, etc.) has increased slowly but continuously and they have become more numerous than those funded by research in the early 2000s. A large part of these are actually operated by the NIWA through commercial contracts.



(a) (b)

Figure 2: Evolution of the hydrometry network of New Zealand (Henderson, pers. comm., 2017, Le Coz, 2017): (a) cumulative numbers of opened, closed and active streamgauging stations since 1905 in the SIMS database; (b) cumulative numbers of active streamgauging stations by types of funders (about 2.5% stations are double counted).

Climate change impact research may be threatened by the disruption of stations located at remote but critical locations like the pan-Arctic region (cf. Fig. 1a). Between 1986 and 1999, the gauge densities of pan-Arctic river catchments decreased from 15 to 9 gauges per 100 000 km^2 in both Russia and North America (Shiklomanov et al., 2002). The most severe cuts were in the Province of Ontario and the Far East of Siberia where 67% and 73% of the streamgauging stations were closed, respectively. What Shiklomanov et al. (2002) conclude for the Arctic may also stand for other regions of the world, like sub-Saharian Africa: "*The decline of river monitoring is occurring at a critical time in Earth's history. We are losing the capacity to witness and understand these changes*". However, the evolution of the streamflow monitoring network of the Amazon basin is not as alarming, thanks to the development of national hydrologic services and international cooperation programs like the HyBam observatory. Costa et al. (2009) showed a clear but stabilised decline of the number of gauges after the rapid expansion in the 1970s and early 1980s. However, data from Brazil's national water agency (ANA) show a steady increase in the Brazilian part of the Amazon basin (cf. Fig. 1a). In recent years, the increase is mainly due to the inclusion of gauges operated by agencies other than ANA, that were less than 10 until 2005 and around 100 in 2007. Nevertheless, there are still fewer streamflow gauges in the Brazilian Amazonian basin than in Norway, and about three times and five times fewer than in UK and France, respectively.

Inland watercourses are the main sources of sediment and contaminant delivered from the continents to the global ocean, but the monitoring of their fluxes is even scarcer than the monitoring of water discharges. In their global, river-by-river study, Syvitski et al. (2005) were able to find observational data on sediment delivery to the sea for less than 10% of the world's rivers. They say "*Of the rivers that have been monitored, most have had their sediment-gauging activities terminated*". Nevertheless, they were able to estimate that the global flux of sediment (excluding bedload) would have been increased from 14 to 16.2 billion tons per year due to human activities (e.g. deforestation), but actually decreased to 12.6 billion tons per year due to sediment trapping in large (20%) and small (6%) reservoirs. They also estimate that the total global discharge of freshwater to oceans would be 40 000 km^3 if 6% of human-induced losses of water were not withdrawn.

In contrast with the paucity of sediment and contaminant flux data at the global scale, some successful and on-going flux monitoring networks are reasons for hope. Especially worth citing are the following examples of integrated observation networks of suspended load and contaminant fluxes. The USGS-operated National Stream Quality Network (NASQAN[5]) is a long-term programme that was established in 1973 for monitoring the concentrations and fluxes of sediment and chemicals in the largest rivers in the US: Mississippi, Columbia, Colorado, Rio Grande, and Yukon (cf. Horowitz et al., 2001). The HyBam[6] observation service provides flux data in the Amazon, Orinoco and Congo basins thanks to cooperation between academics and national hydrological services (cf. Martinez et al., 2013; Armijos Cardenas, 2015; Armijos et al., 2017). More recently (since 2009), the Rhône Sediment Observatory (OSR[7]) has become the most developed sedimentary monitoring network in France with streamflow, turbidity and suspended particulate matter (SPM) sampling stations distributed along the Rhône River and at the outlets of its main tributaries, from lake Geneva to the Mediterranean Sea (Launay, 2014; Le Bescond et al., 2017).

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[5] `http://water.usgs.gov/nasqan/`

[6] `www.so-hybam.org`

[7] `https://bdoh.irstea.fr/OBSERVATOIRE-DES-SEDIMENTS-DU-RHONE/`

1.2 Challenges and opportunities of modern hydrometry

Producing observational data of discharges and fluxes of matters in rivers is difficult, costly and sometimes unsafe. But most field hydrologists would also tell you that it is rewarding and quite exciting, especially during floods. The modern challenges and opportunities for monitoring the fluxes of water and matters in rivers and streams include determining:

- how to maintain the long-term quality and continuity of records while measurement technologies and procedures have changed at an increasingly fast pace;
- how to quantify, reduce and communicate the data uncertainty (a scary issue!);
- how to adapt hydrological monitoring networks to the increasing diversification of financial and administrative constraints, of dissemination media, of data producers, and of additional parameters like sediment transport and water quality.

New measurement technologies: progress or disruption? From the beginning of organised hydrometry networks in the end of the nineteenth century to the 1990s, hydrometric technologies were fairly stable for decades, with a reduced range of methods and instruments gradually improving with the advances of mechanical, electrical and electronic techniques. The vast majority of streamgaugings were achieved using floats or mechanical current-meters. The vast majority of stage measurements were recorded on paper from the position of a float in a stilling well. The vast majority of rating curves were hand-drawn on graph paper using French curves (until 2010 and 2006 at Water Survey of Canada and the USGS, respectively). The vast majority of hydrometric stations are still based on stage-discharge rating curves rather than modern velocity or discharge recording systems, in spite of the enthusiastic prophecy of André et al. (1975) in their hydrometry manual[8]: "*In 1975 it is not unreasonable to consider that river flows could be recorded by a direct measurement process*[9] *well before the year 2000. It will then no longer be necessary to record this intermediate variable, which is the water stage, and which is in non-linear relation with the flow only in an approximate, not always one-to-one and most often unstable manner.*" The traditional techniques have been continuously automated and computerised, and modern technologies for data

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[8] "*En 1975, il n'est pas déraisonnable d'envisager que bien avant l'an 2000 les débits des rivières pourront être enregistrés par un procédé de contrôle direct. Il ne sera alors plus nécessaire d'enregistrer cette variable intermédiaire qu'est la hauteur d'eau et qui n'est en liaison, d'ailleurs non linéaire, avec le débit que de façon approximative, pas toujours biunivoque et le plus souvent instable.*"

[9] They hoped that radioactive and fluorescent tracer dilution stations would be commonly used for measuring river discharges continuously.

storage and telemetry allowed extending the streamgauge networks in the decades after World War II (cf. Fig. 1a). Application efficiency was dramatically increased but the basic principles of operation remained the same.

Since their first applications to streamgauging around 25 years ago (Gordon, 1989), acoustic Doppler current profilers (ADCP) have revolutionised the practices of most hydrological services around the world. Typically, Despax (2016) showed that the streamgauging techniques used by EDF-DTG[10] hydrometry staff changed from 74% mechanical current-meter and 26% tracer dilution in 1990-1992 (1544 gaugings) to 58% ADCP, 31% mechanical current-meter and 11% tracer dilution in 2012-2014 (1799 gaugings). The use of ADCPs is even more dominant in French hydrometry services that monitor fewer mountainous streams and more lowland rivers than does EDF-DTG. Around the world, most of the gaugings are still performed using mechanical current-meters, but results of surveys launched by the World Meteorological Organization (WMO ProjectX[11]) in 2009 and 2014 show that ADCPs are increasingly used. Participation in the survey increased from 28 to 40 countries from 2009 to 2014 with a similar overall geographical distribution. Reported uses changed from 68% mechanical current-meters, 16% ADCP and 16% other techniques in 2009, to 46% mechanical current-meters, 27% ADCP and 27% other techniques in 2014. ADCPs offer unprecedented efficiency for gauging large rivers, including the largest rivers of the world, in the Amazonian basin for instance. However, hydroacoustic instruments are not the best streamgauging technique for a range of site conditions, including shallow flows, low velocities, rough free-surface or very clear waters, and they should not always replace other techniques. The use of ADCPs brought new challenging issues and new opportunities that have garnered attention from many research groups and operational agencies in order to estimate their uncertainties and validate them against other measurement techniques (Oberg and Mueller, 2007). More recently, fixed hydroacoustic profilers have been installed at gauging stations, usually pointing horizontally across the river (side-looking ADCPs, or H-ADCPs) but sometimes pointing vertically from the bed or from the free-surface (vertical ADCPs, or V-ADCPs). H-ADCPs are particularly suited for tidal rivers (Hoitink et al., 2009) or at sites affected by other types of variable backwater, such as confluences, lakes or dams (Le Coz et al., 2008a).

After hydroacoustic technology, hydrometry has experienced another revolution more recently with the emergence of two contactless, or non intrusive, velocimetry techniques: video imagery (Fujita et al., 1998, 2007; Hauet et al., 2008; Muste et al., 2011) and surface velocity radars (Costa et al.,

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[10] Électricité de France, Division Technique Générale.

[11] `http://www.wmo.int/pages/prog/hwrp/Flow/index.php`

2006; Welber et al., 2016). Modern non intrusive streamgauging techniques are similar in principle to one of the oldest streamflow measurement techniques: measuring the travel distances and times of floats, as done by Leonardo da Vinci (1452-1519) or by Pierre Perrault (1611-1680) in the Seine at Paris, for instance (L'Hôte, 1990). Compared to intrusive velocity-area gauging techniques using current-meters or ADCPs which also measure flow depths, the discharge uncertainty is increased due to potential bed evolution between the cross-section survey and the velocity measurements, and due to the conversion of surface velocities to depth-average velocities. The latter is usually done using a surface velocity coefficient, which can be estimated through theoretical and empirical considerations (Le Coz et al., 2007b, 2010a; Welber et al., 2016). Non intrusive streamgauging techniques are generally more suitable for flood discharge measurements in fast-flowing, highly turbulent flows, especially when intrusive techniques cannot be deployed in a safely and timely manner. They provide less accurate discharge measurements than conventional gaugings, but field operations are much safer, faster and they can be automated through permanent video or radar systems. Non-contact measurements of water levels, flow depths and velocities in rivers can even be conducted from manned or unmanned air vehicles (UAV, or drones). Fujita and Kunita (2011) pioneered air-borne image velocimetry using helicopter-borne videos of the 2002 flood of the Yodo River, Japan. Very recently, Detert et al. (2017) provided a bibliographic review of air-borne image velocimetry and demonstrated the feasibility of measuring the surface velocity field, bathymetry, and flow discharge in a small river using image sequences recorded by an off-the-shelf outdoor camera mounted to a low-cost quadcopter. Remote sensing from UAVs is a very promising avenue for hydrometry and more generally for river studies (Rhee et al., 2017), especially as image orthorectification is not necessary for vertical viewpoint from a drone (scaling is enough) as Hauet et al. (2017) showed.

The question of taking even more distance from the river has been given much attention with the development of remote sensing from satellites. Pros and cons have been reflected upon in a debate between Famiglietti et al. (2015) and Fekete et al. (2015) published in Science in 2015 and entitled *Watching water: From sky or stream?* According to Famiglietti et al. (2015), satellites "*provide the big picture*" as the stream levels, slopes and even discharges (cf. e.g. Paris et al., 2016) can now be measured from space. This capacity would be particularly interesting to efficiently gather streamflow time series throughout large transboundary catchments where data are very scarce due to the lack of resources and skills, political instability, poor international cooperation, and/or difficult access and poor infrastructure in remote areas. The main problem with satellite hydrometry is that it is often seen as a possible replacement for ground stream gauging stations instead of an added tool. While satellite remote sensing provides a lot of valuable large-scale observational data, e.g. throughout the surfaces of oceans, continents and ice sheets, it cannot provide the same hydrological information as traditional hydrometric stations (Fekete et al., 2015). Indeed, satellite-based streamflow measurements are currently limited to large rivers (about 100 m wide at least) with very limited time resolution (overpasses every week or less often, cf. Durand et al., 2014) and much larger measurement uncertainties, especially because no measurements of velocities and depths are done below the water surface. And the validation of satellite-based discharge estimates has very seldom been done using accurate ground discharge measurements.

Even if these issues were overcome technically, it would be unlikely that traditional streamflow time series could be discontinued and replaced by satellite data without disruption of the data quality. The necessary budgets should be put in the balance: a lot of training, equipment and maintenance for ground hydrometry stations could be funded with a small fraction of the budget of satellite missions... Of course it is less attractive for funding organisations to pay for installing and maintaining staff gauges and developing rating curves on graph paper, or to have endless negotiations with national hydrological services, than to contribute to high-tech programs. However, satellite missions will not replace the ground observation capacities that have collapsed in many developing countries. As already mentioned (Alsdorf et al., 2016), there are only about 10 gauging stations left in the immense Congo catchment area (3 680 000 km^2, the second largest river by mean discharge in the world), only a handful of which are actually operational... Despite all the difficulties, satellite technology should not be an excuse for circumventing the local services of those countries and discontinuing capacity building to help them take ownership of their network and produce reliable hydrological data.

Uncertainty analysis: a problem or a solution? Despite the importance of streamflow time series in hydrologic studies and water policies, they are usually provided without quantitative uncertainties (Hamilton and Moore, 2012). Uncertainty analysis of sediment or contaminant fluxes is even less common in spite of some methodological advances (e.g. Navratil et al., 2011; Moatar et al., 2013). Hamilton (2014) demonstrates the importance of assessing and communicating the quality of hydrometric data, especially in the new paradigm of many disparate data providers with a diversity of practices and procedures. It is therefore important to promote quality assurance through the

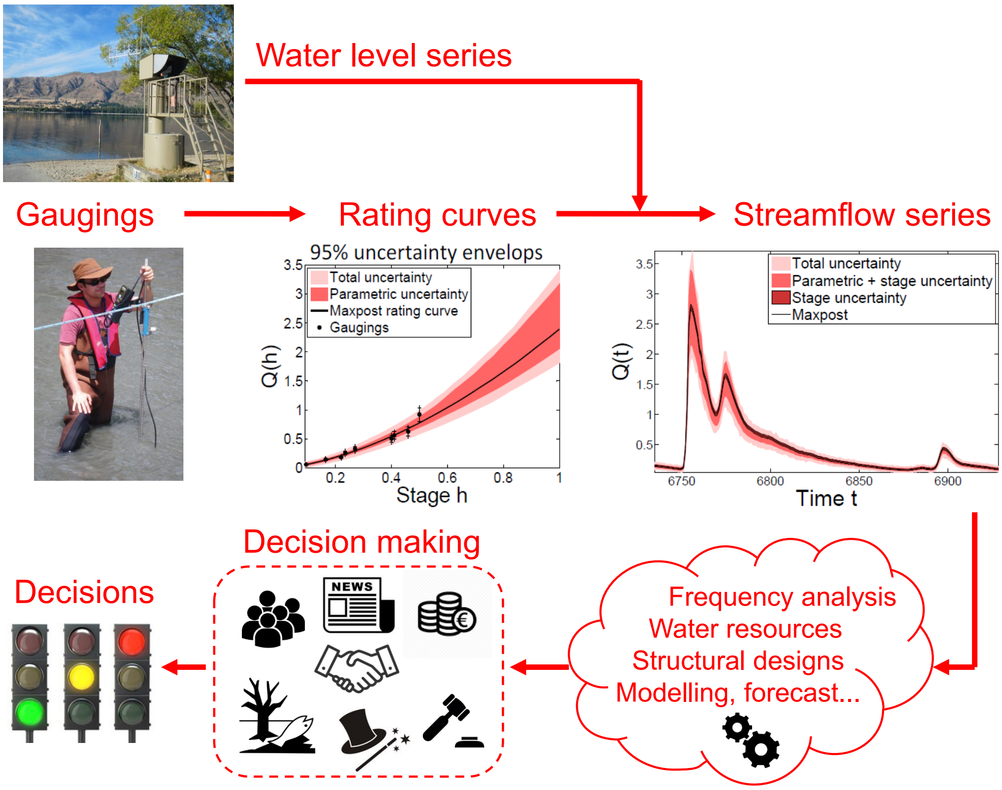

Figure 3: Uncertainty analysis of streamflow data from field measurements to a range of end uses of the published hydrological data and their contribution to decision making.

standardisation of quality codes and data exchange formats like the WaterML 2.0 standard. As we pointed out however (Yorke et al., 2014), this is not enough as uncertainty analysis of hydrometric data should also be undertaken in a systematic manner. Through real examples in several countries, McMillan et al. (2017) showed "*how uncertainty analysis of streamflow data can reduce costs and promote robust decisions in water management applications*".

Unfortunately, uncertainty analysis in hydrometry remains problematic due to the complexity of the error propagation chain, from field measurements (gaugings and water level series) to streamflow time series and statistical indicators, and passing through discharge models like stage-discharge rating curves (cf. Fig. 3). In-situ measurements of stage and discharge are affected by substantial site, flow and operator-specific errors that are difficult, if not impossible, to model. Only the instrument performance can be certified and traced to national and international standards, and the majority of the discharge uncertainty budget cannot be checked. As expressed by Hamilton (2014) for hydrometric data, "*It is relatively easy to quantify uncertainty for data for which the uncertainty is uninteresting, and it is extremely difficult to accurately quantify uncertainty for data* *acquired under unique or extraordinary conditions (...) for which an understanding of uncertainty is essential*".

As a consequence, quantifying the uncertainties of hydrometric data is still an active research area. In recent years, several uncertainty propagation methods for velocity-area gaugings have been proposed (cf. Despax et al., 2016b for a review) in order to overcome the limitations of the standardised approach (ISO748:2009, 2009). There is still much research to be done to improve these methods, extend them to all the existing gauging techniques, and to compare them with the results of interlaboratory experiments (Despax et al., 2016a; Le Coz et al., 2016a). The same can be said for every step in the hydrometric chain (cf. Fig. 3), especially the development of stage-discharge rating curves. More than 10 original methods for computing rating curve uncertainties have been published in the past decade, since Moyeed and Clarke (2005) published the first Bayesian approach of the problem. Kiang et al. (2017) compared 7 of them (see Reitan and Petersen-Øverleir, 2008; Sikorska et al., 2013; Le Coz et al., 2014b; Morlot et al., 2014; Coxon et al., 2015; McMillan and Westerberg, 2015) plus the traditional one proposed in ISO and WMO standards. Beyond the difficult comparison and validation of rating curve uncertainties, it is important to realise that each method actually relies on assumptions for developing rating curves. Practically, rating curve development is not a mere curve fitting exercise but it is also guided by expert knowledge and even modelling of hydraulic controls and processes at the site (Réméniéras, 1949; Di Baldassarre and Claps, 2011), especially for extrapolating the stage-discharge relation below and above the range of gauged flows. Beyond 'simple' stage-discharge rating curves, the uncertainty analysis must be extended to a range of ad-hoc complex rating curves with additional input variables, such as stage at an auxiliary station, the stage gradient or an index velocity, depending on site-specific flow conditions and the available instrumentation. Furthermore, the measurement errors of all the input variables, primarily stage, must be quantified and propagated to the final streamflow time series.

In spite of methodological issues, quantitative uncertainty analysis is a solution rather than a problem, as the data provider and the data user can make more robust, transparent and cost-efficient decisions (Pappenberger and Beven, 2006). First of all, the rating curve development is facilitated when both expert knowledge (or modelling) and the information content of gaugings can be combined in a fair way, i.e. relatively to their uncertainties. This solves the traditional conflict between both sources of information and allows for semi-automated calibration procedures. As a result, the assumptions behind the rating curve development are easier to explain and document for peer-reviewing and future updates. Second, understanding the error sources and their propagation, and establishing uncertainty budgets provide an objective basis to improve the measurement process and negotiate the necessary resources. Last but not least, the probabilistic information provided to the data user is more transparent and complete than quality codes alone. The data users can then make their own decisions with respect to their intended uses of the data more precisely than they can with poor/fair/good grades. Of course, uncertainty analysis should be based on published methods that are stable over time and consistent with general uncertainty standards like the GUM (JCGM, 2008) and the Hydrometric Uncertainty Guidance (ISO/TS25377:2007, 2009).

Diversification of hydrometry networks: data quantity versus data quality? As shown previously (cf. Fig. 1a), national networks of stream gauges have experienced expanding, shrinking and stabilising phases over the past decades. Slowly but constantly, stream gauges are opened, closed, relocated, re-opened, etc. This evolution is a more or less organised response to increasingly diverse challenges and expectations. In worst cases, stations are directly threatened by funding cuts, which may result in an excessive focus on short-term and local needs and in the disruption of long-term hydrological records (cf. e.g. Lins, 2008). In best cases, decisions are made based on thorough audits of the network, seeking the best trade-off between data usefulness, quality and quantity/representativeness on the one hand, and the limited resources on the other hand. The hydrological information brought by a hydrometric station may be estimated through statistical analysis (Pearson, 1991). This should be supplemented by an assessment of the importance of the station for the geographical and hydrological coverage of the country or catchment, and for given purposes: general hydrologic regime, flood and drought knowledge and forecasting, water resources management or other specific purposes. Even so, the exercise remains challenging and discontinuing stations inevitably brings discontentment of the impacted data users (e.g. Pearson, 1998).

Nevertheless, due to limited resources, data quantity must be balanced with data quality, through the necessary quality assurance and quality control. It is therefore crucial to rate the streamgauging stations in a network according to their quality and importance for their main purposes. Typically, the best and most important discharge time series valid for trend and frequency analysis should be identified, based on expert judgement and on their length, continuity and homogeneity. The best and most important stations should be identified for other purposes as well, based on e.g. the robustness of measurements and real-time telemetry (for flood forecast), the sensitivity and accuracy of low flow controls (for droughts and water allocation), the location of the station below a dam or at regulatory nodal points in the river network, etc. Also, episodic gaugings can be used to supplement an existing hydrometric network of permanent stations, especially for the determination of low flow characteristic discharges through regionalisation methods (Sauquet et al., 2016).

An important evolution lies in the diversification of the data producers and the data sharing methods, which has been enhanced by the development of digital technologies, the internet and social media. Beyond the diversity of hydrometric data providers already discussed, crowdsourcing (Lowry and Fienen, 2013; Fohringer et al., 2015) is an emerging way of compensating for the scarcity of hydrological data, especially during flood events. New communication and digital image technologies have enabled the public to produce and share large quantities of flood observations. Such observations are often authored, timestamped, georeferenced and eventually shared through social media. Quantitative hydraulic data such as the extent and depths of inundated areas (Fohringer et al., 2015; Brouwer et al., 2017) or flow rate estimates (Fujita et al., 2013; Le Boursicaud et al., 2016) can be computed using communications, photos and videos from eyewitnesses and can help improve the understanding and modelling of flood hazards. As with other citizen sciences, citizen hydrometry allows engaging with the general public and also with local or professional communities about flood risks, streamflow measurements, and other water-related topics.

Another exciting avenue is the diversification of the parameters measured at hydrometric stations. The monitoring of sediment and contaminant fluxes potentially adds great value to the existing hydrometric networks and may help reinforce their long-term funding. Of course, monitoring bedload, suspended load and a range of water quality parameters brings additional challenges that go beyond the traditional expertise of field hydrologists. However, their knowledge of river sites and flow regime, and their skills in conducting field measurements and in managing environmental time series are absolutely necessary to the success of a sediment and contaminant flux monitoring network. The successful examples cited previously (USGS NASQAN, HyBam observatory, OSR) were made possible thanks to close cooperation between hydrologists, geomorphologists and chemists with supplemental skills. It is indeed necessary to develop monitoring strategies well-suited to the hydro-sedimentary regime and to the station network in a similar way as hydrological observation networks are designed and operated. The relation between the frequency of water sampling, the variability of the hydrological regime and the final uncertainties is particularly important (Moatar et al., 2013). Innovative techniques for measuring fluxes and sampling water and sediment still have to be developed, validated and implemented routinely. For instance, hydroacoustic technologies already used by hydrologists to measure streamflows have a great potential to improve the measurement of bedload (Jamieson et al., 2011) and sand fluxes (Thorne and Hurther, 2014) through proxies of bed velocities and suspended load concentrations, respectively. Turbidity-meters (optical backscatter or transmissivity sensors) calibrated with water samples now allow the continuous monitoring of fine suspended load, which vary over several orders of magnitude during flood events. Passive particle traps are a cost-efficient way to collect time-integrated suspended particulate matter (SPM) samples through a river network for further grain size and physico-chemical analyses. Beyond field measurement, hydrological concepts for sediment and contaminant fluxes in rivers still have to be developed, building on tools developed for water fluxes. This would result in a 'sedimentary hydrology'. Sediment rating curves or more complex catchment models should be used to fill the gaps in sediment and contaminant flux records. Statistical analysis of the occurrence and trends of these fluxes should be further developed. Last but not least, uncertainty analysis is also a pending task necessary to establish meaningful sediment and contaminant flux budgets at the river network scale and at event, annual and pluri-annual time scales.

1.3 Scope of this dissertation

This manuscript offers an overview of my research on these issues since the completion of my PhD ten years ago (2007) and also discusses some research perspectives for the next 5 to 10 years. The first section deals with new methods for measuring streamflows, especially handling new gauging techniques and engaging with the general public to document flows during floods. The second section presents the methods developed for computing and measuring the uncertainties of gaugings, and the Bayesian framework introduced to compute probabilistic rating curves and streamflow time series. The third section focusses on sediment and contaminant fluxes in rivers, from field measurements to flux budgets at the river network scale. Eventually, research prospects are introduced and the manuscript ends with some concluding comments.

2 Modern methods for measuring streamflows

2.1 Hydroacoustic Doppler profilers (ADCP)

When they emerged as a new tool, ADCPs required the development of dedicated documentation (Simpson, 2001), procedures, training and validation experiments (Oberg and Mueller, 2007), as part of quality assurance and quality control (QA/QC) of the produced streamflow data. The USGS has been a leader in supplementing and verifying the information and procedures provided by ADCP manufacturers. Since 2005, the French-speaking hydrometry technologists from several agencies and companies have united their efforts within the Groupe Doppler Hydrométrie, an informal but very active working group (Le Coz et al., 2007a). A technical guide (Le Coz et al., 2008b) was published and its update and revision are currently underway, with the involvement of agencies from other French-speaking countries (Switzerland's Federal Office of the Environment, Environment and Climate Change Canada, HydroQuébec).

Beyond QA/QC, the uncertainty analysis of ADCP gaugings through propagation methods has been an active research area in recent years (cf. Section 3.1). The observed repeatability of successive ADCP transects is also a valuable source of information on ADCP uncertainties, as investigated by García et al. (2012). More generally, an empirical approach to uncertainty analysis is the interlaboratory comparison (Le Coz et al., 2016a), i.e. repeated measures experiments which were implemented to quantify the uncertainty of ADCP gaugings conducted in contrasting site conditions (cf. Section 3.2 for details).

In France, a few horizontal ADCPs (also known as side-looking ADCPs, or H-ADCPs) were installed around 2006-2010 upstream of dams in the Rhône, Saône and Isère rivers, at sites where the stage-discharge relation is not unique due to variable backwater from the dams. The traditional method in such situation is to measure stages at a main gauge and at an auxiliary gauge and to develop stage-fall-discharge rating curves that use water slope as an additional input record. The Compagnie nationale du Rhône (CNR) was especially interested in reducing the relative discharge errors (in %) at low flows compared to existing twin gauge stations but H-ADCPs did not succeed in doing so. Most of them have been removed and replaced by ultrasonic transit-time systems due to disappointing errors in low flow conditions, because of low velocities (<20 cm/s typically) and low suspended solid concentration (<10 mg/L typically), inducing very low signal-to-noise ratio (SNR) and high instrument noise (Le Coz et al., 2008a; Moore et al., 2012). As a consequence, velocities

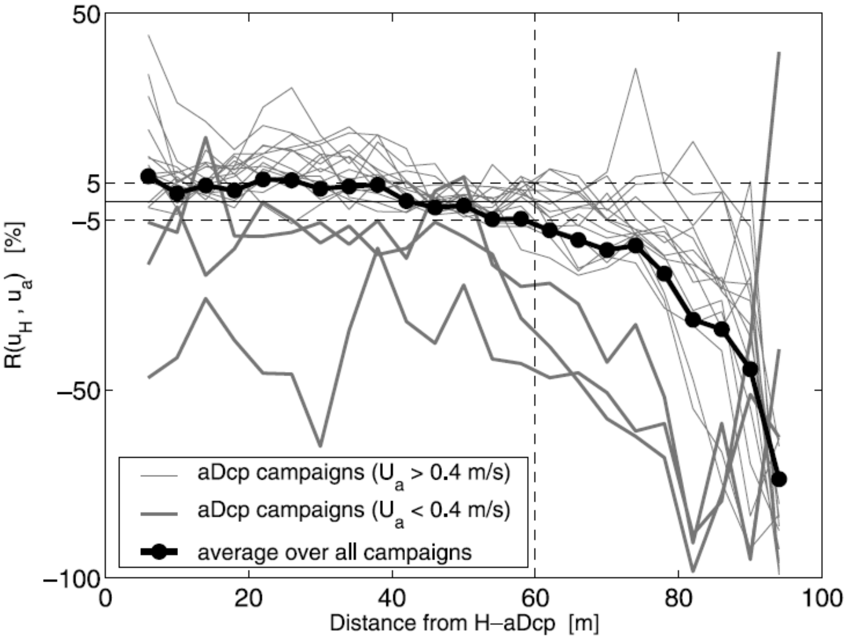

Figure 4: Comparison of point velocities u_H measured by the H-ADCP with corresponding ADCP velocities u_a, for 18 ADCP gaugings of the Saône at Lyon-St-Georges (figure taken from Le Coz et al., 2008a). Relative differences $R(u_H, u_a) = (u_H - u_a)/u_a \times 100$ are plotted versus the horizontal distance from the H-ADCP transducers.

were biased low (cf. Fig. 4), and this was difficult to correct through calibration. Other problems we had with H-ADCPs include attenuation for very high suspended load and long distances, and fixed echoes from bottom and free-surface (side-lobes), especially in shallow cross-sections. It was never possible to measure the velocity profile all across the river, up to the opposite bank, even in sections that were sufficiently deep according to manufacturer's specifications.

For sites equipped with permanent side-looking or up-looking ADCPs, the index velocity method (Levesque and Oberg, 2012) is the most commonly used to compute discharge. This method uses two ratings: cross-sectional average velocity vs. point or range-averaged ADCP velocity, and a stage-area rating derived from the bathymetry profile of the reference cross-section. However, other discharge computation techniques based on the calibration of vertical velocity profiles at each velocity cell have been investigated (Hoitink et al., 2009; Le Coz et al., 2007b, 2008a). Generally, no theoretical calibration is used without experimental verification and calibration; most experts agree that calibration gaugings are absolutely necessary to calibrate the index velocity method and other discharge computation techniques that use measurement obtained with fixed ADCPs, even at ideal sites. However, theoretical ratings obtained from hydraulic equations or hydrodynamical numerical modelling would be very useful for designing the shape of the index velocity-mean velocity rating, in terms of equations and number of segments. Both sources of information, i.e. prior knowledge and observations, could be combined through a Bayesian approach, similar to that developed for rating curves (see Section 3.3). The index velocity method is also gaining popularity at transit-time stations and surface velocity radar stations (Jacob, 2014), especially in rough mountain streams.

Hydroacoustic profilers enable the visualisation and computation of more than just streamflow. They can be used to visualise velocity fields (Kim and Muste, 2012; Parsons et al., 2013), longitudinal dispersion (Carr and Rehmann, 2007; Launay et al., 2015), bed shear stress (Vermeulen et al., 2013), apparent bed movement (Jamieson et al., 2011), backscatter intensity and suspended sediment concentration (Moore et al., 2013; Hanes, 2016).

2.2 Non intrusive streamgauging techniques

As non intrusive streamgauging techniques, video imagery and surface velocity radars require a model of the vertical velocity distribution below the free-surface where velocities are measured, in order to provide a discharge estimate. In practice, a value has to be assigned to the depth-average to surface velocity ratio, known as the surface velocity coefficient. Fig. 5 displays the values of the surface velocity coefficient measured in a large set of watercourses in Italy, Israel and France (Welber et al., 2016). Values measured at local positions (Fig. 5A and B) were found to be much more scattered than cross-sectional average values (Fig. 5C), especially for shallow flows and greater relative roughness. In both cases, the mean is close to the usually accepted default value, 0.85. The cross-sectional average values typically range from 0.80 to 0.90 with a general decrease with greater relative roughness.

The most popular image-based technique for hydrometry is LSPIV[12] which was originally adapted from laboratory experiments to streamflows by Fujita et al. (1998); Creutin et al. (2003); Hauet et al. (2008). I have contributed to the development and application of the LSPIV technique to the quantification of streamflows: applications to fast, seeded flows (Jodeau et al., 2008), to recirculating flows in river side-cavities in the field or in physical models (Le Coz, 2007; Le Coz et al., 2010b), to floods using mobile or fixed stations (Le Coz et al., 2010a), to the high-flow extension of rating curves (Dramais et al., 2011), to crowd-sourced flood videos (Le Boursicaud et al., 2016; Le Coz et al., 2016c); estimation of velocity uncertainties; development of executables, scripts for operating

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[12] Large Scale Particle Image Velocimetry

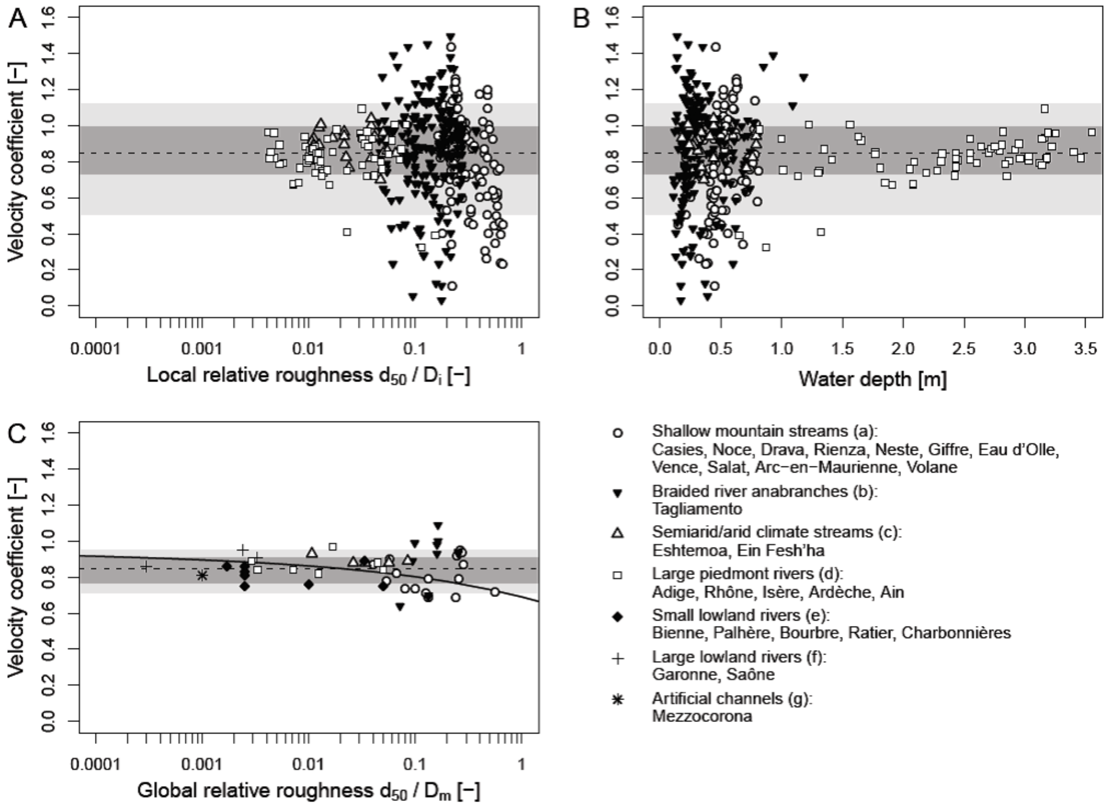

Figure 5: Empirical values of the depth-average to surface velocity ratio (surface velocity coefficient) measured in a large set of watercourses in Italy, Israel and France (from Welber et al., 2016): variation of local measurements with relative roughness (A) and water depth (B); variation of cross-sectional average measurements with relative roughness (C). The dashed line is the default value (0.85) and the solid line is the theoretical value (see Welber et al., 2016). The interquartile range is shaded in dark grey; the 10th-90th percentile range is shaded in light gray. Local values are unavailable for some sites.

permanent stations, and implementation in the free, user-friendly Fudaa-LSPIV software (Le Coz et al., 2014a).

I also worked on the application and verification of portable surface velocity radars (SVR) for gauging floods, with a first prototype adapted from a heavy, fixed SVR (around 2010-2012), then with light, commercially available handheld SVRs (Welber et al., 2016). Procedures and field forms in French and in English have been produced and shared with hydrological services in France and in other countries. I have contributed to the implementation of SVR gaugings in BARÈME, the in-house software developed by Pierre-Marie Bechon (DREAL[13] Auvergne-Rhône-Alpes) and used by the French hydrological services. The SVR technology is now commonly available to field hydrologists and has allowed them to gauge floods that they had never been able to gauge in the

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[13] Direction régionale de l'environnement, de l'alimentation et du logement (DREAL): Regional environment agencies of the French government, operating the national hydrometry network.

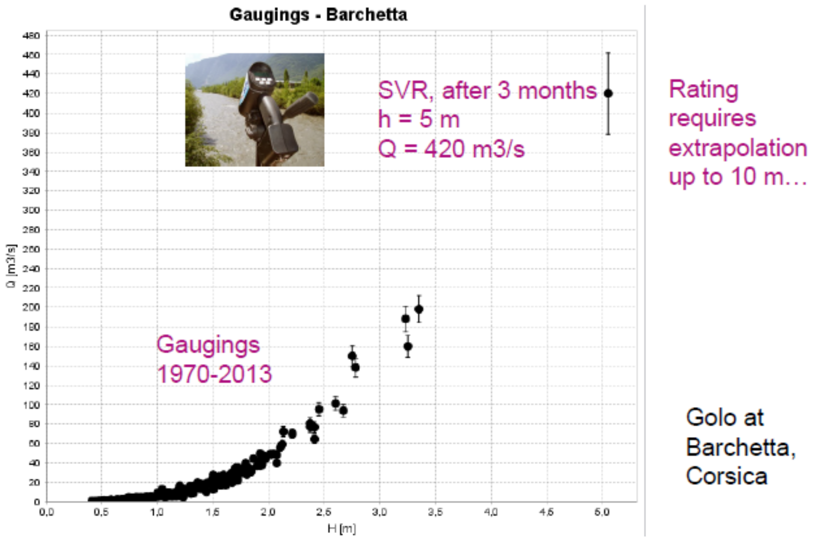


Figure 6: Example of the advantage of non intrusive streamgauging techniques for a Mediterranean catchment, the Golo at Barchetta, Corsica, France: the first flood discharge measured using the surface velocity radar (SVR) three months only after it was purchased is twice the highest of the intrusive gaugings in more than 40 years.

past (cf. Fig. 6), hence reducing the uncertainties of the extrapolated top ends of the stage-discharge rating curves.

Surface velocity radars have also been increasingly installed permanently in mountainous streams to apply the index-velocity method at stage/velocity radar stations, with usually good performance (Thollet et al., 2017). Compared with conventional stage-discharge ratings, the main advantages of the index-velocity method are that changes in the stage-discharge relation are directly visible through the measured stage-velocity relation, and that the velocity-velocity rating is less sensitive to bed evolution than is the stage-discharge relation. The stage-area rating is affected by changes to the bed but it can be quickly updated after a single topography survey of the reference cross-section, whereas building a new stage-discharge rating requires a set of gaugings over the range of measured flows. However, the velocity-velocity relation may be more difficult to predict than the stage-discharge relation as the distribution of the velocities throughout the cross-section may be complex and may vary with discharge.

2.3 Citizen science for flood measurements

Using a video of a pulsed flash-flood flow in a mountainous torrent shared on YouTube, we investigated the troubles and potential of applying the LSPIV technique to flood videos recorded under non-ideal conditions (Le Boursicaud et al., 2016). Simple solutions for correcting lens distortion

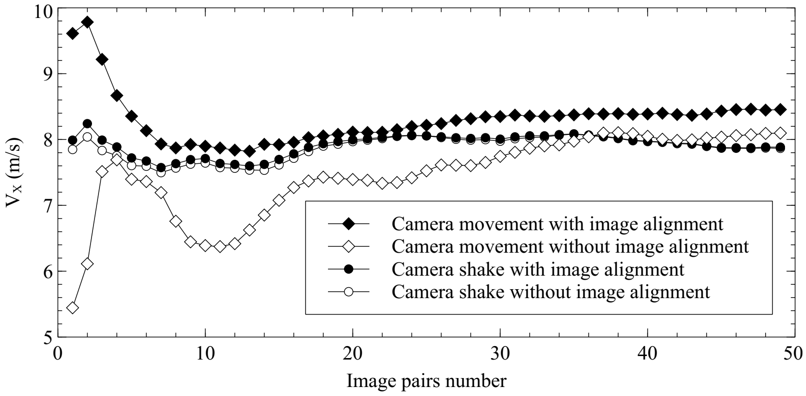


Figure 7: Impact of image alignment for coherent (steady) and incoherent (shake) camera movements on the LSPIV cumulative average velocity estimates (from Le Boursicaud et al., 2016).

(fisheye) and limited incoherent camera movement (shake) through image alignment were successfully applied, and the related errors were reduced to a few percent (cf. Fig. 7). Testing the different image resolution levels offered by YouTube showed that the difference in time-averaged longitudinal velocity was less than 5% compared with full resolution for all available resolutions. The indirect determination of the water level was found to be the main source of uncertainty in the results. Video-based measurements provide useful information on the velocities and the temporal dynamics of the flow, which is usually lacking in conventional post-flood surveys (Gaume and Borga, 2008). For such a pulsed, unsteady flow, the conventional slope-area method based on high-water marks created by the highest waves would have overestimated the time-averaged flow rate. It was shown that it could be more accurately estimated using LSPIV results.

Le Coz et al. (2016c) reported on three projects typical of emerging citizen science initiatives for crowdsourcing flood hydrology data: a photo-based flood mapping project (RiskScape, New Zealand) and two video-based flow estimation projects (Flood Chasers, Argentina, and FloodScale, France). Compared to other similar projects, they involved similarly simple procedures for the public, but more advanced data processing and reviewing by the scientists (cf. Fig. 8). An exciting perspective would be to combine such 'measurement-oriented' and 'citizen hydrologists' approaches with the powerful tools developed in other projects for data mining the social media contents and conducting the spatial analysis of volunteered geographic information.

The three projects illustrate the great potential of citizen science initiatives for improving flood risk assessment in interaction with the local communities. Key drivers for success appear to be: a clear and simple procedure, suitable tools for data collecting and processing, an efficient communication plan, the support of local stakeholders and authorities, and the public awareness of natural hazards. Beyond the technical and communication challenges, this is an efficient way to enhance the culture of flood risk and make people more engaged collectively.

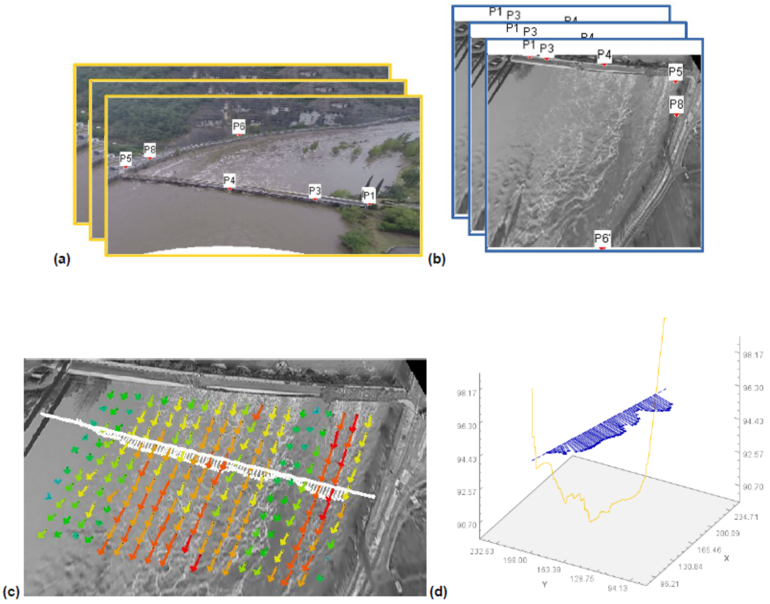


Figure 8: Applying Fudaa-LSPIV software to a drone video of the Ardèche River at Sampzon Bridge, France, shared on YouTube after 2014 floods (from Le Coz et al., 2016c): raw image sequence with ground reference points (a), same images converted to grey scales and ortho-rectified (b), time-averaged surface velocity field (up to 4 m/s) and depth-averaged velocities interpolated at the transect used for discharge computation (c), 3-D view of the transect (d).

3 Uncertainty analysis of streamflow data

3.1 Streamgauging uncertainty propagation

A large part of the discharge measurements (streamgaugings) conducted in open-channels are performed using the velocity-area method, which consists of sampling flow velocity and depth throughout the cross-section for summation of discharge. This technique is described in the ISO 748 standard (ISO748:2009, 2009), a fundamental standard in hydrometry. However, the application of the uncertainty analysis framework proposed in the ISO 748 standard to the diversity of velocity-area discharge measurements made by hydrometry services is problematic. For ideal conditions and procedure, the computed uncertainty usually lies between ±5% and ±7%. However, for many measurements done in non-ideal conditions, the uncertainty values obtained with this method appear to be irrelevant because they are too high.

More precisely, the drawbacks of the ISO 748 uncertainty analysis method are mainly due to uncertainty components that are missing in the uncertainty propagation equation, or are difficult-to-estimate. Missing uncertainty components relate to the discharge extrapolations in the near-surface, near-bed and near-edge areas of the cross-section, the time-integration in the case of varying discharge, position, inclination and orientation of the instruments, and bed changes when bathymetry is not measured simultaneously with velocities, which is typical of surface velocity gaugings. Several uncertainty components that are included in the uncertainty propagation equation are difficult-to-estimate for each specific situation, especially those regarding the vertical and transverse integration of velocities and depths, and the systematic instrument errors after calibration.

In the past decade, several alternative uncertainty computation methods have been published, most of them attempting to improve the estimation of the uncertainty components related to the spatial integration of velocities and depths. A bibliographic review can be found in Despax et al. (2016b), including the application of the GUM by Muste et al. (2012), the Q+ method I proposed (Le Coz et al., 2012, 2015), the IVE method (Cohn et al., 2013, USGS), and the Flaure method to which I contributed through the work of Despax et al. (2016b).

Sharing common principles, the Q+ and Flaure methods solve some of the ISO 748 method issues and they both aim at accounting for the distribution of the verticals throughout the cross-section and the complexity of the bed and velocity horizontal profiles. The equation issued from the $Q+$ method is expressed as:

$$u^2(Q) = u_s^2 + \frac{\displaystyle\sum_{i=0}^{m+1} Q_i^2 \left\{ u^2(B_i) + u^2(D_i) + u_p^2(V_i) + u_m^2(D_i) + u_m^2(V_i) + \frac{u_{c,e}^2(V_i)}{n_i} \right\}}{\left(\displaystyle\sum_{i=1}^{m} Q_i \right)^2} \tag{1}$$

with u representing standard uncertainties, Q discharge, B_i, D_i, V_i, n_i, Q_i widths, depths, velocities, number of velocity points and discharges, respectively, of each subsection i around each of the m verticals ($i = 0$ and $i = m + 1$ correspond to near-edge subsections). The elemental standard uncertainties are related to systematic errors of the instruments after best calibration (u_s), non-systematic errors of width, depth and velocity measurements ($u(B_i)$, $u(D_i)$, $u_{c,e}(V_i)$, respectively), vertical velocity integration errors ($u_p(V_i)$), transverse depth integration errors ($u_m(D_i)$) and transverse velocity integration errors ($u_m(V_i)$).

The main differences with the ISO 748 method are that the $u_p(V_i)$ term accounts for spacing between velocity points and for discharge extrapolations in the top and bottom layers, and that uncertainties due to transverse integration of depths $u_m(D_i)$ and of depth-averaged velocities $u_m(V_i)$ throughout the cross-section are computed separately, and include discharge extrapolations to the edges. To compute $u_m(D_i)$ and $u_m(V_i)$, the user has to define the maximum transverse slope angle α as representative of the maximum depth errors due to interpolation between verticals. The merit of this approach is to make the error computation physically explicit, however estimating the value of α is somewhat subjective and the final uncertainty is very sensitive to α when the aspect ratio (i.e. width-to-depth ratio) is high. Despax et al. (2016b) showed that an automatic calibration of α as the discharge-weighted mean of the measured bed angles produced reasonable results, in fair agreement with the Flaure method they introduced. The Q+ method and its automatic calibration have been implemented by Pierre-Marie Bechon (DREAL Auvergne-Rhône-Alpes) in the operational BARÈME software used by the French national hydrologic services to compute discharges from gaugings and develop rating curves.

In his PhD work, Aurélien Despax (2016) developed the novel Flaure method, which differs from Q+ method in the way the transverse integration uncertainty terms u_m are computed. Initially, u_m was computed from the known errors of a set of high-resolution reference gaugings collected in France, New Zealand and other countries; the u_m uncertainty of a given gauging was an average of the u_m of the four reference gaugings that were found to have the most similar bed and flow horizontal profiles to those of that given gauging. The Flaure method has further been simplified: u_m is now estimated using a polynomial function of a sampling quality index (SQI, Despax et al., 2016b). The SQI more or less reflects the spacing between verticals and the variation of flow per unit width between two verticals. Though it is not a perfect indicator of the sampling quality, the SQI was found to be a more explanatory variable than the number of verticals. To relate the distribution of integration errors to the SQI, high-resolution reference gaugings were subsampled following an original technique that mimicks realistic selection of verticals by a field hydrologist, instead of traditional random sampling techniques.

The Flaure method was applied to thousands of gaugings from EDF-DTG and USGS databases with various flow conditions and the results were compared with those of other methods (cf. Fig. 9). Results show that Flaure is overall consistent with the $Q+$ method but not with ISO 748 and IVE methods, which produce much larger uncertainties for gaugings with less than 15 verticals.

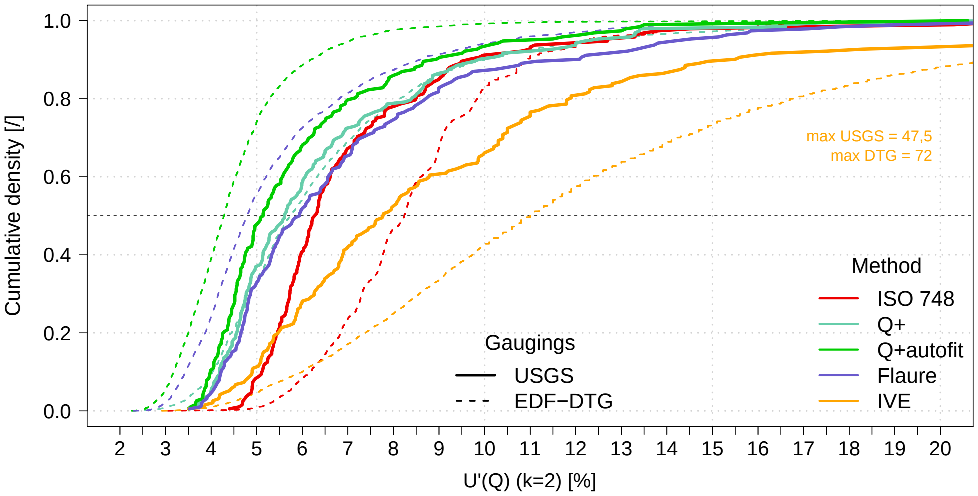


Figure 9: Cumulative densities of the expanded uncertainties (within 95% probability) computed with four uncertainty propagation methods (ISO748, Q+ with fixed or calibrated angle α, Flaure, IVE) applied to 192 gaugings of the USGS (solid lines) and 3930 gaugings of EDF-DTG (dashed lines). Maximum IVE uncertainty estimates are 47.5% and 72% for USGS and EDF-DTG gaugings (Despax, 2016).

Such uncertainty analysis opens the debate on the optimisation of field procedures, with contrasting strategies in France and in North America. In North America gaugings usually have more verticals (no less than 20) and fewer velocity points per vertical (usually 1 or 2, based on ISO 748 standard formulas), whereas French gaugings have a median number of verticals close to 10, with integration of a larger number of velocity points per vertical.

It may be argued that there is no one-fits-all best procedure but that the number and distribution of verticals and velocity points should be adapted to the aspect ratio of the cross-section, its geometric complexity, the flow uniformity and the flow steadiness. Quantitative uncertainty computation is clearly the most practical and objective way to optimise the sampling strategy, provided that all relevant uncertainty component are included, which still requires further development. For instance, using Q+ and Flaure methods, it has been possible to compute the amount by which the discharge uncertainty decreases when additional depth measurements are done between the traditional verticals, with negligible extra field work. Hence, this new procedure with additional depth measurements was promoted and included in the EDF (Jasmine) and French national hydrological services (BARÈME) software used to process velocity-area gaugings.

Since the 1990s, hydro-acoustic profilers (ADCPs) have become the first or second most frequently used technique for streamgauging, especially in large rivers. Their uncertainty analysis is therefore an operational necessity. ADCPs deployed in stationary mode, i.e. at fixed positions across the river, are similar to other velocity-area techniques, and uncertainty analysis developed for current-meters may be applied (Muste et al., 2012). This is not the case with the most common mobile-boat ADCP gaugings, because the basic equation for computing discharge is different, as the boat velocity is now included in a vectorial cross-product with the water velocity, in the own reference system of the instrument beams.

Very recently, a range of uncertainty computation techniques have been developed for mobile-boat ADCPs, from the simple review of meaningful quality indicators (Qrev, USGS, Mueller, 2016) to Monte Carlo simulations (QUant, joint work by Water Survey of Canada and the USGS, Moore et al., 2016) and comprehensive application of the first-order Taylor series expansion approach of the GUM (JCGM, 2008) as proposed by González-Castro and Muste (2007); González-Castro et al. (2016). After the work by Dramais (2011), inspired by the Q+ method for the uncertainty analysis of current-meter gaugings (Le Coz et al., 2012), the Oursin method was developed by the Compagnie nationale du Rhône (Pierrefeu et al., 2017). Oursin is a simplified GUM-based uncertainty propagation approach similar to the ISO748 or Q+ uncertainty methods for velocity-area measurements. Its complexity is arguably in between that of the QRev uncertainty estimation which has similar principles but more values fixed through expert judgement, and that of QUant (MonteCarlo simulations), not speaking of full-fledged applications of the GUM to the complete ADCP data reduction equation. There are also differences in how the uncertainty of multi-transect discharge measurements is computed and in how systematic errors are dealt with. Perspectives for the validation of the Oursin method and its implementation in QRev will be discussed later.

3.2 Streamgauging uncertainty estimation from interlaboratory comparisons

While the application of uncertainty propagation methods to hydrometry is still challenging, in situ collaborative interlaboratory experiments have proved to be a valuable tool for empirically estimating the uncertainty of discharge measurement techniques. Thanks to the experience of large-scale ADCP intercomparison events organised by the Groupe Doppler Hydrométrie in 2009, 2010, 2011, 2012 and 2016, Le Coz et al. (2016a) demonstrated the applicability of in situ collaborative interlaboratory experiments to quantify the uncertainties of streamgauging techniques under specific site conditions. We introduced a procedure for acquiring and processing the results according to authoritative ISO standards (cf. Fig. 10). The repeatability standard-deviation s_r and the interlaboratory standard-deviation s_L are estimated from the repeated measurements of the same discharge by various participants, or 'laboratories'. The two standard deviations are combined to compute the final uncertainty of a discharge measurement, or of the average of N discharge measurements from P laboratories, using the equations in Fig. 10.

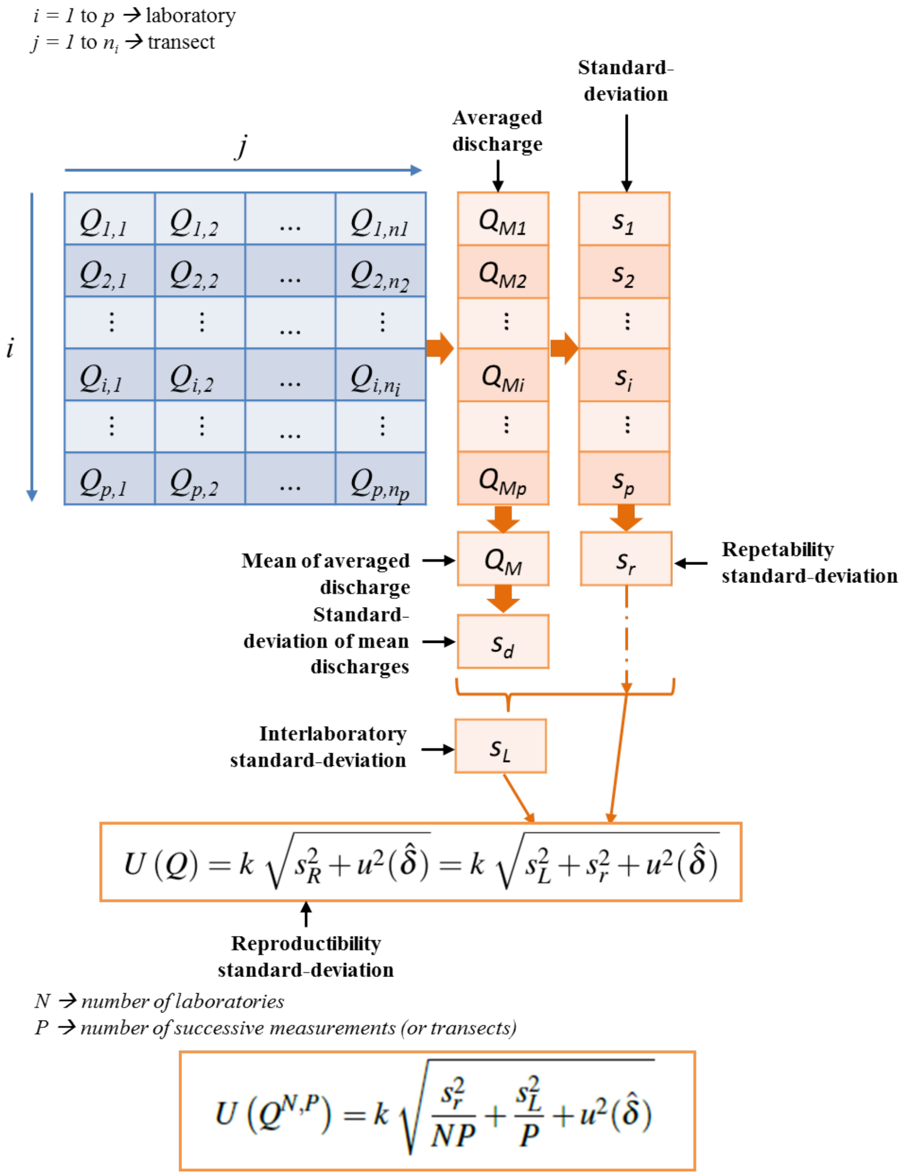


Figure 10: The main steps to compute the inter-laboratory uncertainty. From Despax et al. (2017a). The uncertainty of the bias estimate, $u(\hat{\delta})$, has to be estimated separately. The first equation gives the average uncertainty $U(Q)$ of the discharge measurements from any single transect of any single laboratory. The second equation can be used to compute the uncertainty $U(Q^{N,P})$ of a mean discharge computed as the average of N transects repeated by P laboratories.

Beyond the costs and difficulties related to their organisation, including the requirements of steady discharge and similar conditions and procedures for all participants, interlaboratory experiments are feasible at many river and canal sites using the proposed method. The results are always affected by statistical limitations. Since the number of participants and repeated measurements is limited, samples are usually small and it is not relevant to consider small differences in uncertainty results. The uncertainty of the uncertainty results can be estimated using some simple equations as a function of the numbers of participants and repeated measurements and of the reproducibility-to-repeatability ratio.

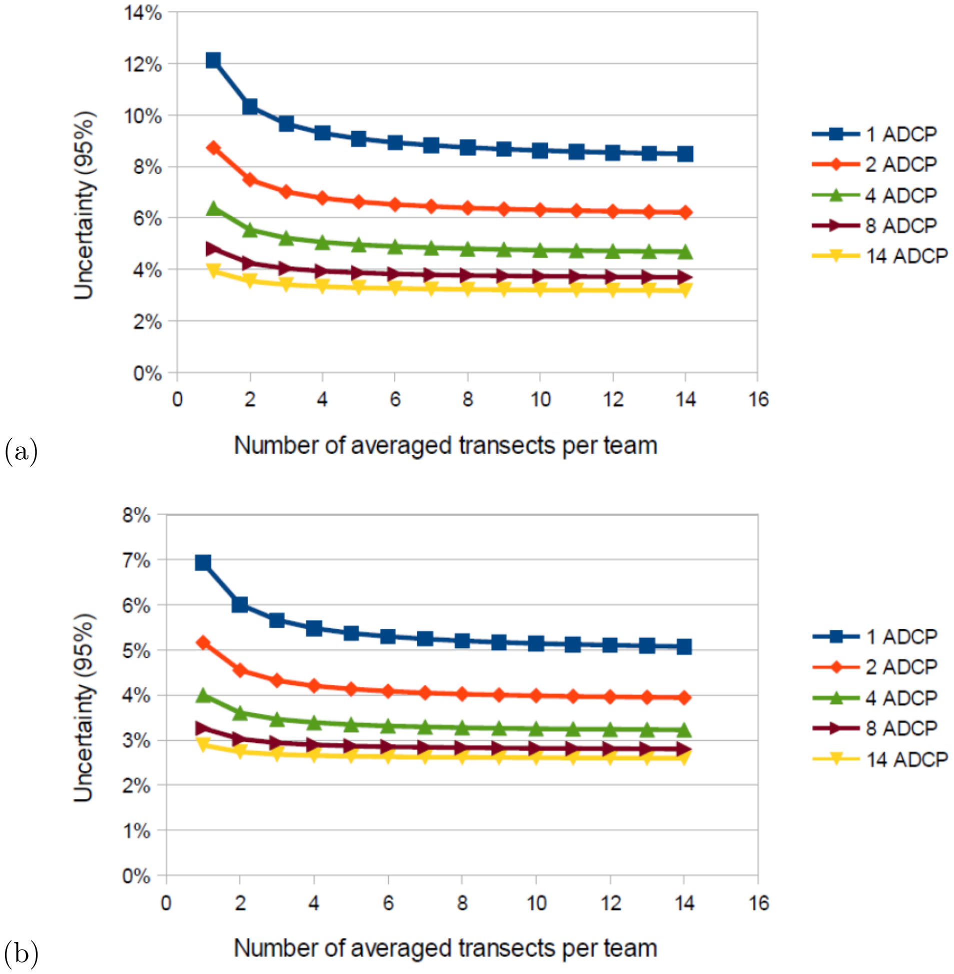


Figure 11: Expanded uncertainty in discharges measured as the average of N transects from $P = 1, 2, 4, 8, 14$ ADCPs at both sites of the Génissiat 2010 interlaboratory experiments: GE site with adverse conditions (a) and PY site with favourable conditions (b). Expanded uncertainties are expressed with a probability level of 95%.

Typically, the Génissiat 2010 ADCP comparison event held on the Rhône River yielded different results at two sites with adverse (Fig. 11a) or favourable (Fig. 11b) measurement conditions (Le Coz et al., 2016a; Muste et al., 2017). nterlaboratory experiments are a quantitative way to estimate how the uncertainty varies with the site, the number of averaged repeated measurements (ADCP transects), and the number of averaged laboratories (instruments, operators, cross-sections...).

Other interlaboratory experiments have been conducted to study different streamgauging techniques such as ADCP, surface velocity radars and current-meters mounted on wading-rods or suspended from cables. Interlaboratory experiments can provide a useful end-to-end uncertainty analysis approach to characterise a subset of elemental sources of errors acting at the time of the experiments. The covered error sources include site selection, environmental, operator-related and field procedure effects which are highly difficult to predict numerically.

Quantifying the uncertainty due to the bias of a streamgauging technique, i.e. the systematic error that is common to all participants, would require a streamflow reference measurement with a much lower demonstrated uncertainty, typically by one order of magnitude, than that of the studied streamgauging technique. This is almost always missing in field situations. There are also some limitations due to the large number of sources of error which may significantly contribute to the combined uncertainty. It may then be very difficult, if not impossible, to isolate and quantify the individual effects of each error source using dedicated experiments. Repeating the experiments after permutation of the instruments, operators and/or measuring locations may be a way to discriminate the source of the observed interlaboratory variability, as recently attempted with the Chauvan 2016 ADCP comparison event (Despax et al., 2017a).

Collaborative interlaboratory experiments conducted in natural watercourses would be very welcome for documenting a wide range of measurement conditions. The uncertainty results would ideally be obtained with the same standardised methodology and could populate a world-wide open database. Such uncertainty values can help validate and improve methods for determining error propagation and the assumptions made on environmental errors. This has been investigated by Despax et al. (2016a) for velocity-area gaugings using ISO 748, IVE, Q+ and Flaure methods, and is planned to be done for mobile-boat ADCP gaugings using Oursin, Qrev, QUant and possibly other uncertainty propagation methods (cf. Section 3.1).

In turn, a GUM-based approach can be used to extend the uncertainty results to measurement conditions other than those of the interlaboratory experiments, especially the most extreme flood conditions. The definition of meaningful metrics and indicators to categorise interlaboratory experiments that could be used by end-users to select the uncertainty results that are representative of their gaugings is an important issue that remains to be tackled.

3.3 Bayesian analysis of rating curves and hydrological data

Streamgaugings are mainly produced to serve as calibration data to develop stage-discharge (or more complex) rating curves which in turn are used to compute discharge time series and other hydrological data from recorded water level time series. Building and maintaining rating curves however is not a mere curve fitting exercise, as the problem is usually underdetermined due to the limited amount of gaugings, especially in extrapolated parts of the curve for extremely high or low flows. The consideration of hydraulic controls, i.e. the physical features of the channel or the critical sections that determine the stage at the gauge for a given discharge, has long been recognised as an utmost necessity (Réméniéras, 1949). Nevertheless, practical methods for field hydrologists to equitably combine physical knowledge (or modelling) with calibration data (i.e. gaugings) were lacking until the development of Bayesian approaches in the last decade (Moyeed and Clarke, 2005). Thanks to a providential collaboration with Benjamin Renard and others and thanks to the support of operational partners (SCHAPI, CNR, EDF), we have been able to develop Bayesian tools for hydrometry technologists since 2010.

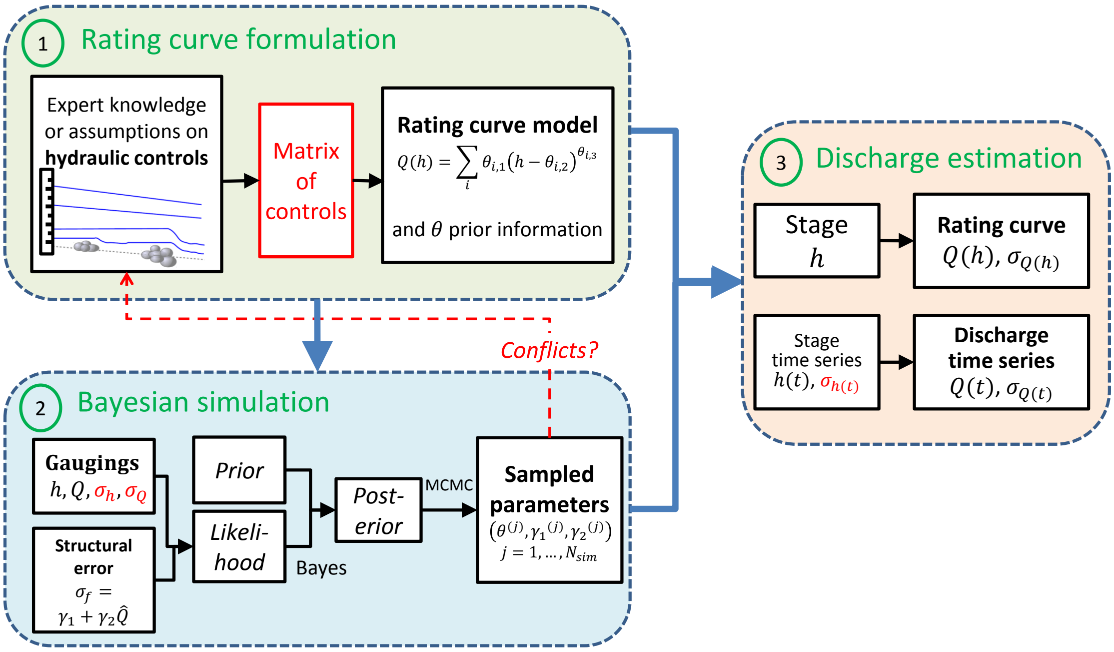


Figure 12: Principle of the BaRatin method for computing stage-discharge rating curves and the associated uncertainties. From Le Coz et al. (2016b).

BaRatin (Bayesian Rating curve) allows the construction of stage-discharge rating curves with uncertainty estimation, combining prior knowledge on the hydraulic controls and the information content of the uncertain gaugings (Le Coz et al., 2014b). The three main steps of the method are i) the rating curve formulation based on hydraulic controls, ii) the Bayesian simulation using the gaugings and iii) the discharge estimation (cf. Fig. 12). Uncertainties on both the discharge and stage measurements of the gaugings are considered as Gaussian distributions with mean zero. Typical discharge uncertainties are assumed based on the gauging procedure. Stage uncertainties may also be specified, e.g. in case of varying flow. The rating curve equation is derived from the combination of power functions for each of the assumed or known controls at the site. The user also defines the prior distributions of the physical parameters of the stage-discharge model, 'prior' meaning without looking at the gaugings further used in the Bayesian simulation of a large set of possible parameters and rating curves. Such Bayesian simulation is based on Monte Carlo sampling of the posterior distribution of the rating curve parameters inferred from the Bayes theorem. Any physical conflicts between the results and the assumed priors should be checked and should lead to questioning the rating curve model and the estimated uncertainties of the gaugings.

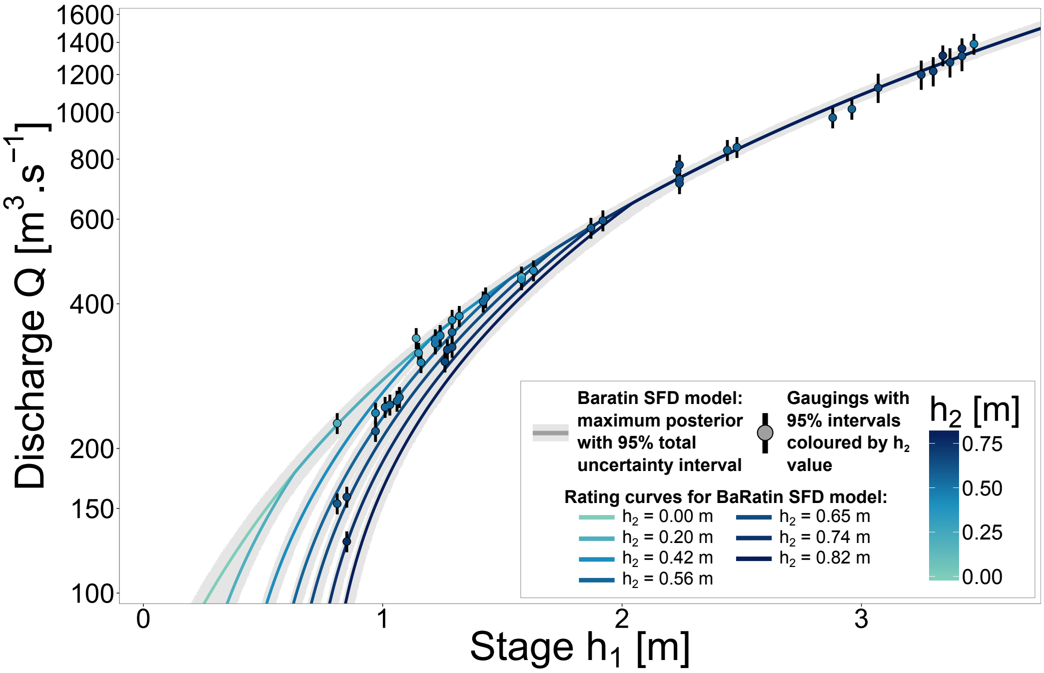
A large number of possible rating curves are simulated through the Monte Carlo sampling process. A statistical post-processing of this bunch of rating curves, or 'spaghetti', yields the uncertainty bounds of the rating curve and of the propagated discharge time series at any level of probability (95% usually). The total uncertainty combines the parametric uncertainty, derived from the spaghetti samples, and the remnant uncertainty accounting for the structural errors of the rating curve model. None of the parametric and remnant uncertainties include the measurement uncertainty. The remnant uncertainty may be modelled as a linear function of discharge (recommended option) or as a constant. Wide uniform distributions are used as reasonably non-informative priors for remnant uncertainty parameters that will be estimated to account for the mismatch between the observations (gaugings) and the model (rating curve) that cannot be explained by the uncertainties of the gaugings. The maximum a posteriori (MAP, or MaxPost) rating curve is computed using the set of parameters with the highest joint probability.

Research versions have been developed by Mansanarez (2016) in his PhD work for complex ratings, including stage-fall-discharge (SFD) models for twin gauge stations affected by variable backwater (Le Coz et al., 2016b; Mansanarez et al., 2016, cf. Fig. 13), stage-gradient-discharge (SGD) models to address hysteresis due to unsteady flows (cf. Fig. 14a), and stage-period-discharge (SPD) models to describe net rating changes due to bed evolution through a single, multi-period rating curve (cf. Fig. 14b). The BaRatin-SPD model developed by Valentin is based on a segmentation of stable periods of time delineated by rating changes: dates of rating changes are assumed to be known. Reach-scale bed evolution affecting both channel controls and section controls is distinguished from local bed evolution affecting section controls only. Compared to applying the conventional BaRatin method to each period independently, BaRatin-SPD usually provides more stable and more precise ratings (especially the top ends) because the gaugings from all the periods provide information to estimate the parameters of a single, multi-period model.

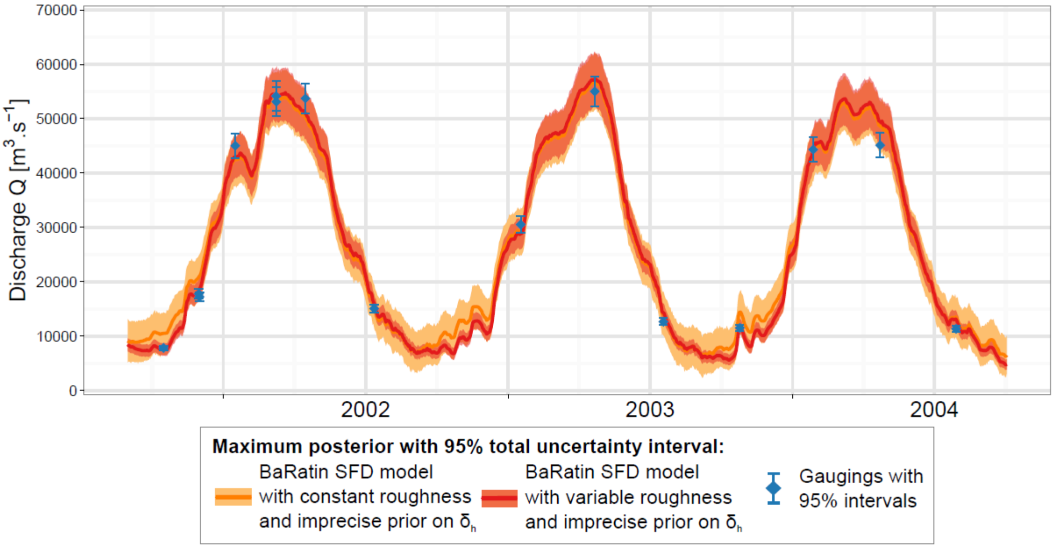
The propagation of rating curve uncertainties and stage series uncertainties to flow series uncertainties has been implemented. Horner et al. (2017) introduce an original method for propagating the measurement uncertainties of the stages of the gaugings, as well as the systematic and non-systematic (independent) errors of the stage time series. Non-systematic errors are mainly related to incoherent water waves and instrument precision, whereas systematic errors are mainly related to instrumental biases and drift over time. The error model is generic and applicable to any probabilistic method that provides a set of rating curve samples. The new method was applied to a panel of six contrasting hydrometric stations in France including the Blies at Bliesbruck (cf. Fig. 15) and the resulting uncertainty budgets were compared at various time intervals from hour to year. The results were found to be highly site-specific and sensitive to the systematic uncertainty component and to the recorder correction periodicity, especially for long-term flow averages.

The relative contributions of hydrometric uncertainties (rating curve and stage errors) and of sampling uncertainties (limited length of records) in the estimation of characteristic discharges (low, medium and high flows) have been investigated through Bayesian analysis by Horner et al. (2016). This is currently the longest chain of uncertainty analysis of hydrological data, from field measurements to statistical indicators, we have been able to study. It gives promising perspectives of integrated probabilistic approaches from the producer to the end users of the hydrological data.

BaRatin and its graphical environment BaRatinAGE have been released in French and English with a free, individual licence and detailed documentation (Renard et al., 2016). The computation of discharge time series is embedded. The tools have been adopted by the French national hydrological services (SCHAPI) and the Compagnie nationale du Rhône (CNR) for the operational management of their rating curves. They have also been tested by other agencies around the world, e.g. the USGS (Mason et al., 2016) and used by other research groups (Lundquist et al., 2016; Osorio and Reis, 2016; Storz, 2016; Zeroual et al., 2016; Ocio et al., 2017; Osorio, 2017).



(a)



(b)

Figure 13: Bayesian tools for complex rating models developed by Mansanarez (2016): (a) BaRatin-SFD (Stage-Fall-Discharge) for variable backwater applied to the Isère at Beaumont-Monteux, France (Le Coz et al., 2016b), (b) BaRatin-SFD with variable roughness applied to the Madeira at Fazenda, Brazil (Mansanarez et al., 2016).

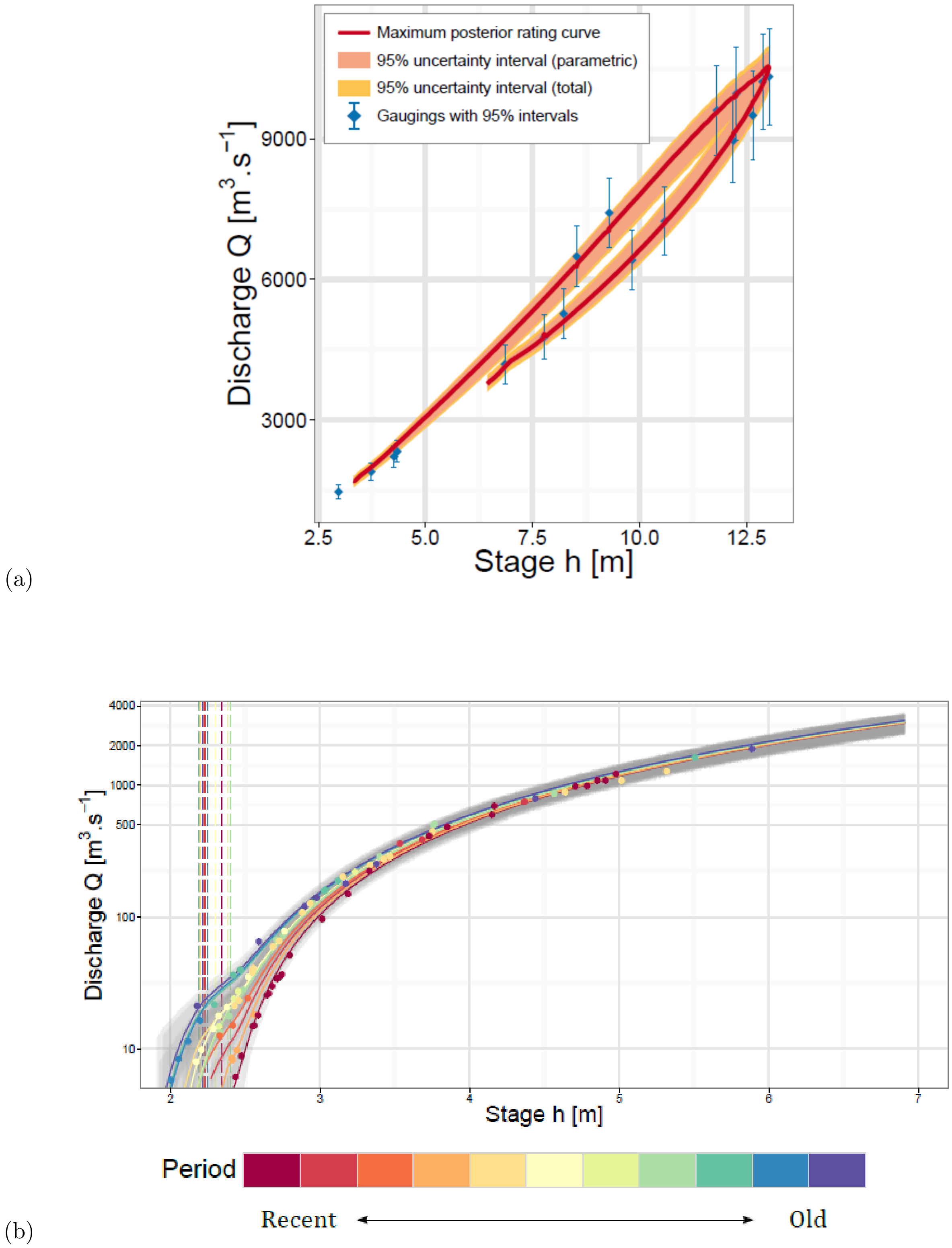


Figure 14: Bayesian tools for complex rating models developed by Mansanarez (2016): (a) BaRatin-SGD (Stage-Gradient-Discharge) for hysteresis during unsteady flows applied to the Ohio at Wheeling, USA, (b) BaRatin-SPD (Stage-Period-Discharge) for rating changes due to floods applied to the Wairau at Barnetts Bank, New Zealand.

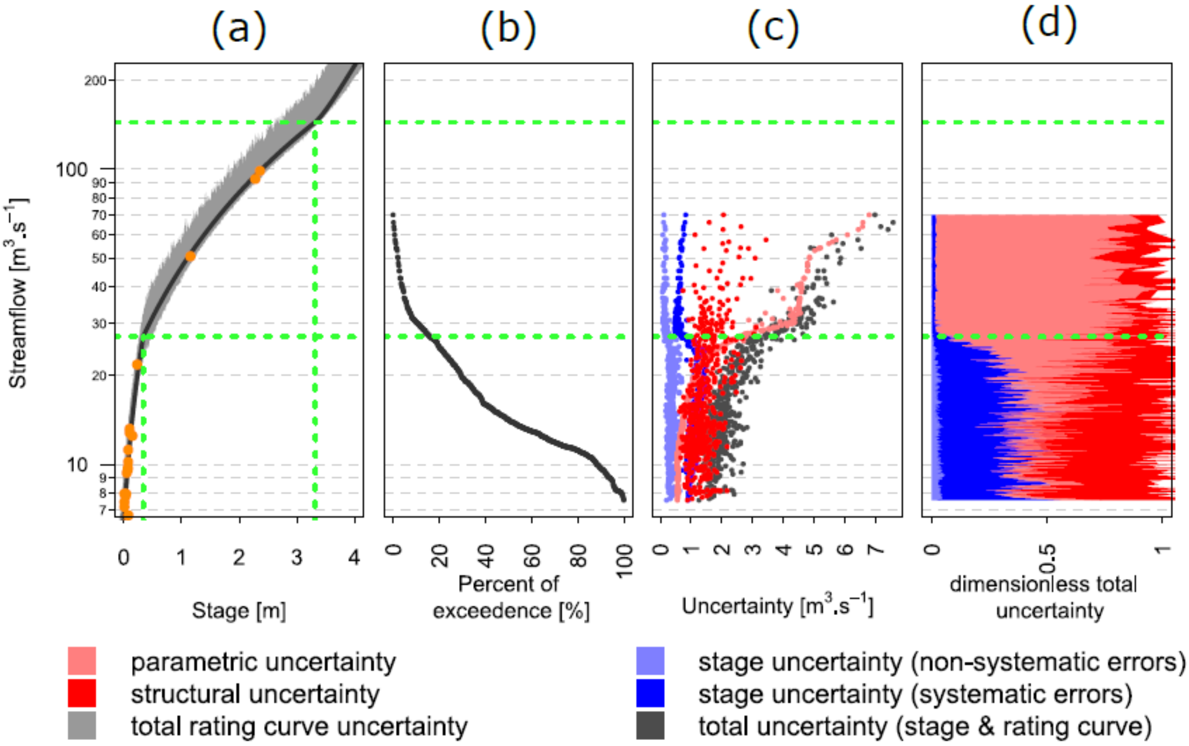


Figure 15: Uncertainty analysis of the streamflow data of the Blies at Bliesbruck: (a) the gaugings (orange dots) and the MaxPost rating curve with total (parametric and structural) uncertainty, (b) the flow duration curve of 2014 MaxPost daily streamflow data, (c) the distinct uncertainty components, computed as the half-lengths of 95% uncertainty envelopes, (d) the uncertainty budget. The green dashed lines show breakpoints between controls. From Horner et al. (2017).

4 Quantifying sediment and contaminant fluxes in rivers

4.1 Gravel and sand fluxes

Fluxes of coarse material drive the morphological evolution of rivers and the quality of the ecological habitat through erosion, deposition and infiltration processes. Sand and gravels are valued resources for construction but modifying their natural dynamics greatly affects the living conditions of fish and other species, human activities, navigation, bridges and other structures, reservoirs, etc. Such coarse material mainly originates from the stream bed and banks, and from upstream sources. Coarse particles can be transported as bedload (sliding, rolling, saltating) or graded suspension, with a strong vertical concentration gradient. Their actual fluxes are limited by the stream transport capacity, related to local shear stresses, and by the availability of sediment for transport. Many regulated and engineered rivers in Europe and elsewhere are ‘hungry rivers’ where bedload and sand fluxes are sediment-limited rather than capacity-limited, due to disconnection to sediment sources because of dams, bank protection, bed degradation and armouring, reforestation, etc.

With colleagues from river morphology, biology and hydraulics groups, I have been involved in several research projects addressing two major challenges related to gravel and sand fluxes in rivers: measuring them and restoring them. In some projects, 1-D and 2-D hydrodynamical models were used to predict the evolution of gravels injected in bedload-lacking rivers like the Lower Ain River, the by-passed Rhine between France and Germany (Béraud, 2012), and some sections of the Rhône River. Modelling results were sometimes used for ecological habitat assessment in cooperation with scientists in freshwater biology. In turn, the bed response to a sediment input provides valuable data for improving mobile-bed hydraulic models, especially through the description of grain-size processes (Béraud, 2012; Camenen et al., 2017a).

Through international cooperation, I was lucky enough to contribute to and work with coarse sediment fluxes in large rivers such as the Danube, Mekong and Amazon, in addition to experiments led by Benoît Camenen in the Arc-en-Maurienne and Rhône rivers in France. Bedload sampling is a difficult, costly and uncertainty measurement; sampling suspended sand is arguably even more difficult. As a result of data scarcity and of strong and difficult-to-predict gradients within a cross-section, along a reach, and over time, the measurement of coarse sediment fluxes in rivers produces quite uncertain results. Detailed bedload data measured in the Danube by the Slovak Water Institute were used to demonstrate how important it is to account for local transport conditions and grain-

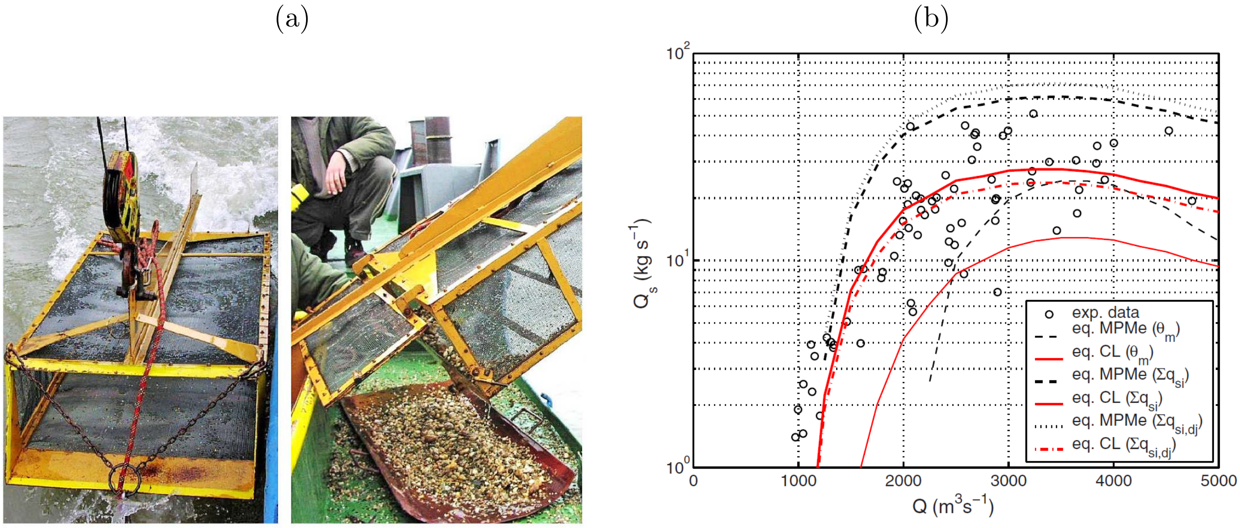


Figure 16: Sampling (a) and modelling (b) of the bedload flux through a cross-section of the Danube River downstream of Medvedov, Slovakia (Camenen et al., 2011). Meyer-Peter and Mueller (1948, MPMe) and Camenen and Larson (2005, CL) formulas were applied with mean bed shear stress (θ_m), or with local bed shear stresses using a single grain-size (Σq_{si}) or five grain-size classes ($\Sigma q_{si,dj}$).

size effects in a 1-D modelling perspective (cf. Fig. 16, Camenen et al., 2011). Such modelling can be implemented in a numerical code or in more simple rating curves relating sediment fluxes to discharge or stage, as developed to compute sand fluxes in the Rhône, Amazon and Mekong Rivers (cf. Fig. 17, Camenen et al., 2014). Though usually quite uncertain, such sediment rating curves appear as a promising way to compute the sediment flux time series necessary to establish annual sediment budgets and assess trends in response to human activities and climate change. Much research work remains to be done to improve the structure and calibration of sediment rating curves.

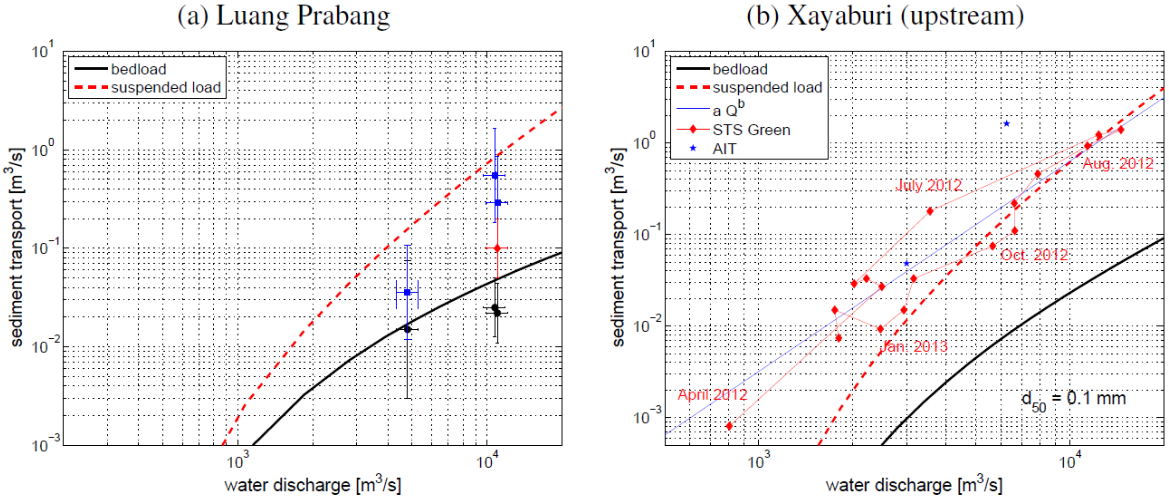


Figure 17: Sand flux rating curves developed for the Mekong at Luang Prabang and Xayaburi, Lao PDR (Camenen et al., 2014). Bedload measurements are displayed as black dots; other symbols are suspended load measurements from different operators and sampling techniques.

4.2 Hydroacoustic measurement of sediment transport

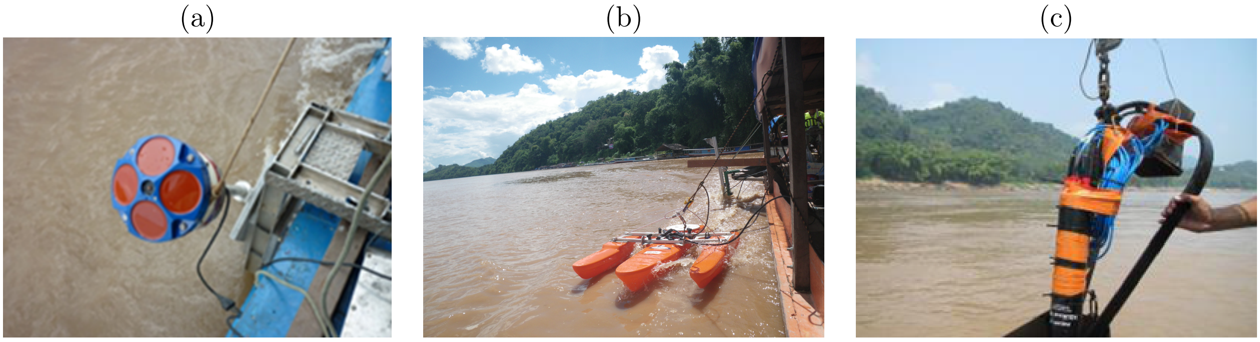
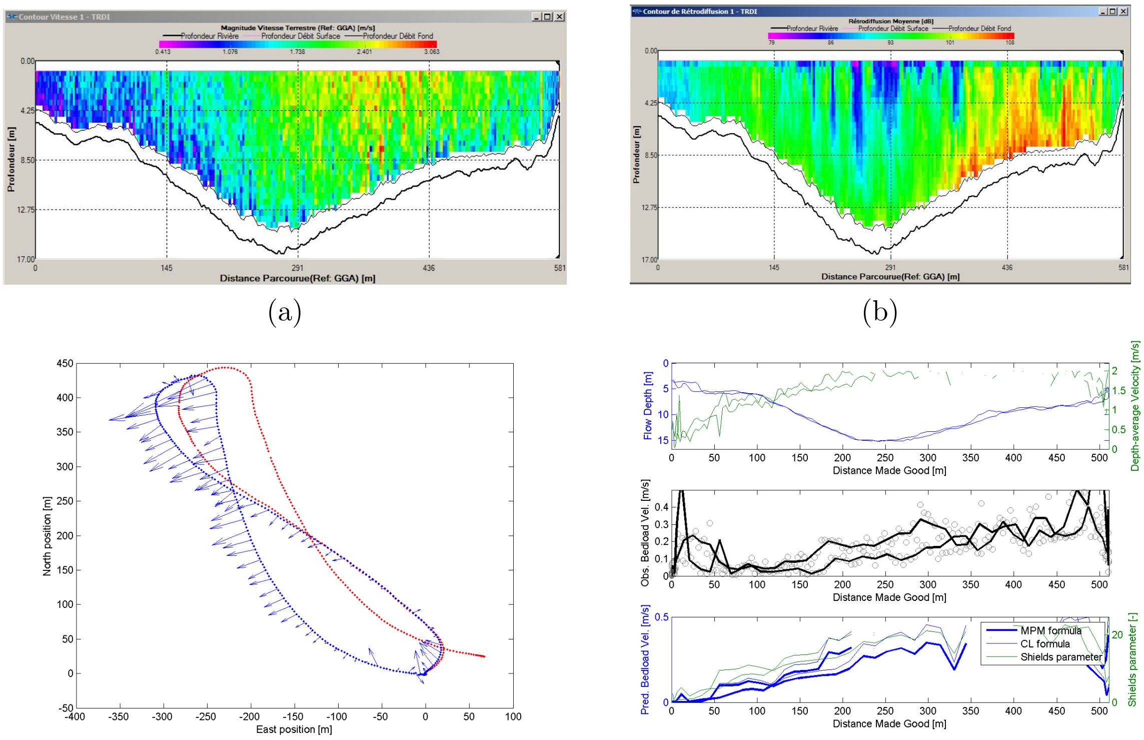

(a)
(b)
(c)

Figure 18: Hydroacoustic measurements of sediment transport: 600 kHz ADCP in the Amazon River at Manacapuru, Brazil (a), ADCP in the Lower Mekong River (b) and multi-frequency acoustic backscatter system (Aquascat) in the Lower Mekong River (c).

Hydro-acoustic instruments such as Acoustic Doppler Current Profilers (ADCP, Fig. 18a) or Acoustic Doppler Velocimeters (ADV) are now commonly used for measuring flow velocities and discharge in rivers. They may also provide information on bedload (Jamieson et al., 2011) and suspended load (Thorne and Hurther, 2014). In addition to 3D velocity measurements throughout a cross-section, an ADCP transect also records acoustic backscatter intensities which depend on the local suspended sediment concentrations (cf. Fig. 19ab). This proxy provides views on sediment transport in rivers with unprecedented spatio-temporal resolution. This is particularly interesting for estimating the fluxes of sands transported in graded suspension in rivers due to their high temporal variability and strong vertical (and lateral) gradients throughout the cross-section that cover several



(a)

(b)

(c)

(d)

Figure 19: Visualisation of flow and sand transport throughout a cross-section of the Mekong River at Luang Prabang, Lao PDR in 2013 using a 600 kHz ADCP coupled with a GPS (Dramais et al., 2015): velocity magnitudes (a), fluid-corrected backscatter intensity (b), apparent bed velocity as the difference between bottom-track and GNSS displacements (c) and its comparison with bedload capacity formulas (d).

orders of magnitude. However, the relation between concentration and backscatter is far from easy to predict due to the complexity of sound scattering and absorption by particles of different sizes and natures.

When the ADCP is coupled to a Global Navigation Satellite System (GNSS), the apparent bed velocity can be computed as the difference between bottom-track and GNSS displacements at each time step (cf. Fig. 19cd). Again, the spatial information is very valuable, especially for improving the computation of the total bedload through a cross-section. However again, converting this proxy to quantitative bedload flux values is not straightforward as the thickness of the moving sediment layer is unknown, as are the amounts of stationary material, bedload and near-bed suspended material that contribute to the bottom echo.

The theory of acoustic interactions with suspensions of solids has been developed mostly through marine and coastal studies. Computing the acoustic intensity received from a suspension is possible, provided that the transducer properties (frequency, size, directivity, sensitivity, etc.) and the sediment properties (size, shape, density, concentration, etc.) are known. As we want to solve the inverse problem, i.e. to compute the concentration and potentially the size of the particles from the backscatter intensity profiles, numerical solution techniques must be applied, all of which have different assumptions and convergence issues.

My first applications followed existing iterative solutions with calibration of the transducer and sediment properties using concentration samples, as implemented in commercial software like Sedi-View or the Plume Detection Toolbox of Aquavision. Through this work we obtained suspended concentration maps that were helpful for river studies, including the assessment of sediment distribution at confluences, in abandoned channels or through arms of the Danube Delta (Tiron Jugaru et al., 2009; Tiron Duţu et al., 2014). However, the agreement between concentrations from backscatter and concentrations from water samples was often quite poor and not at all robust: the calibration was site-specific, and sometimes time-specific.

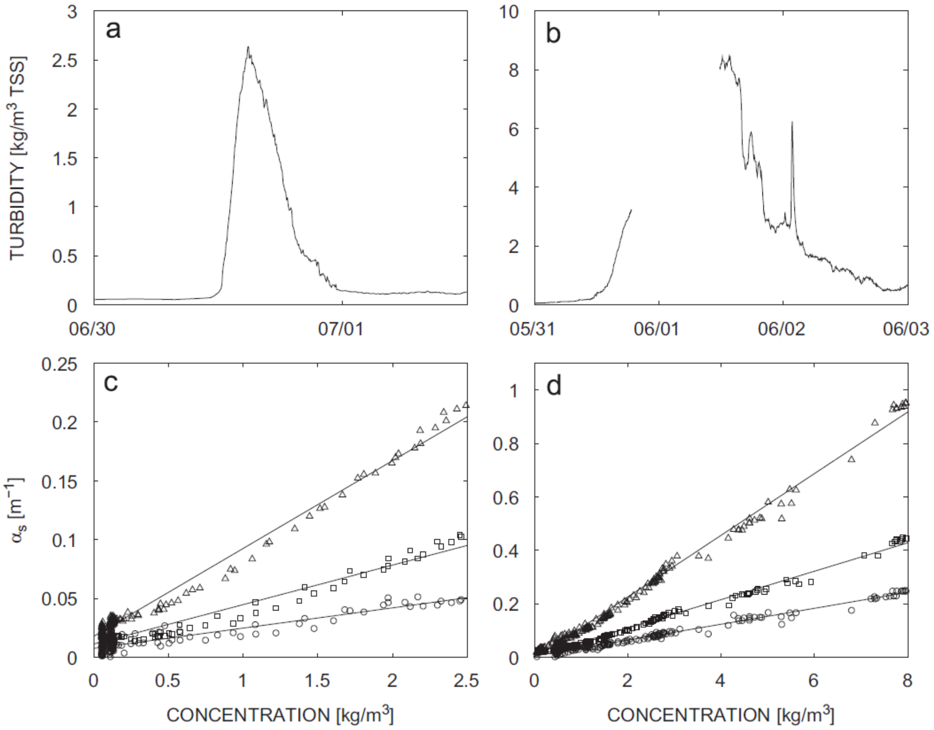


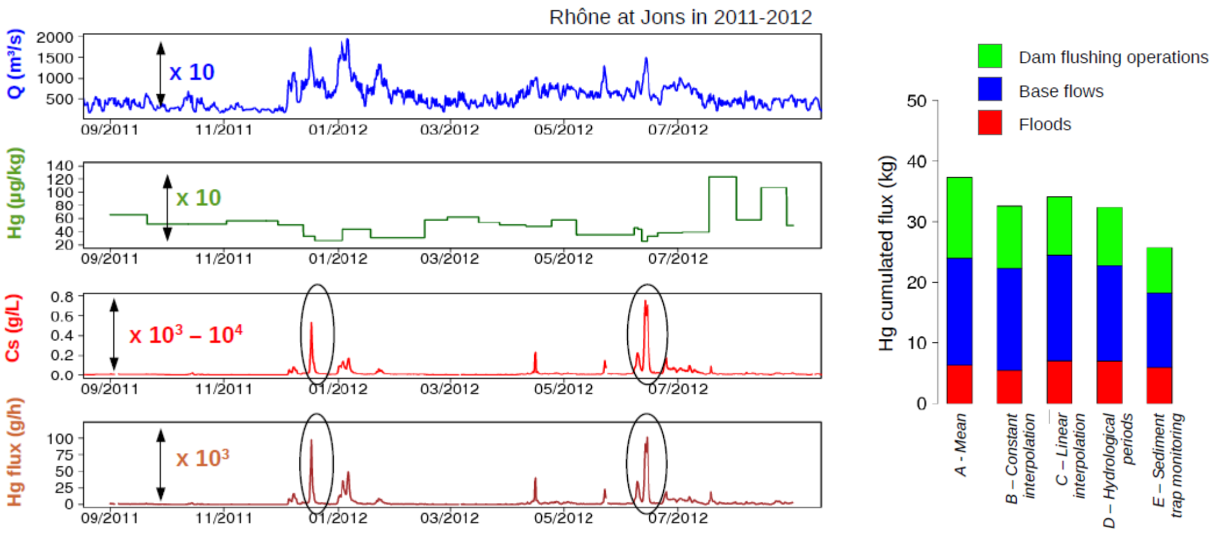
Figure 20: Deriving concentration from acoustic attenuation in the Isère at Romans (Moore et al., 2012): Turbidity time series for the attenuation events of (a) June 30, 2010 and (b) May 31-June 3, 2010. Relationship between particle concentration and sediment attenuation for the 300 kHz (circles), 600 kHz (squares), and 1200 kHz (triangles) H-ADCPs for (c) the June 30 event and (d) the May 31-June 3 event. Concentrations are computed as 0.96×turbidity and the least-squares linear fits to the data are shown.

In her PhD work on fixed side-looking ADCPs in the Rhône, Saône and Isère Rivers, Moore (2011) confirmed the advantages of hydroacoustic technologies for measuring marked spatio-temporal gradients of suspended load. She developed a method for estimating the concentration of a homogeneous suspension from the attenuation slope of fluid-corrected backscatter profiles, and successfully applied it to floods in the Isère River (Moore et al., 2012). In order to be more robust and less sensitive to calibration data, Stephanie made clear the interest of using multi-frequency systems and of developing more physical inversion methods that account for the grain size distribution of particle mixtures that occur in rivers (Moore et al., 2013). Indeed, a range of measurement campaigns in large rivers (Rhône, Mekong, Amazon) proved that developing solutions accounting for bimodal sediment mixtures, with distinction of fine homogeneous suspension vs. highly graded sand suspension, is required. This is usually less problematic in marine and coastal studies since attenuation due to fine sediment can be neglected and grain size distribution is quite homogeneous.

Adrien Vergne's PhD (2015-2018) aims at developing acoustic methods suitable for measuring river suspensions. Beyond, ADCP instruments commonly used for hydrometry, Adrien has studied a high-resolution multi-frequency backscattering system (Aquascat, Fig. 18b) we had first deployed in the Mekong River in 2012. The Aquascat does not measure velocities but it provides more information on acoustic backscatter as the transducer calibration is known, raw acoustic records are available, up to four transducers with frequencies can be used simultaneously and the bin sizes are small. The Aquascat has been deployed in the Rhône River, in a sediment tank at Irstea and better controlled conditions in the new sediment tank DEXMES recently built by Ifremer in Brest. A new and possibly severe issue raised by these experiments is the likely great contribution of air micro-bubbles to the backscatter signal, depending on the transducer frequency and the sediment size and concentration. Further experiments are planned to confirm the necessity of correcting the signal and to develop corrections.

4.3 Fine particles and contaminant fluxes

Fine suspended particles (clay and silt) are the main carriers of contaminant fluxes in river systems. For a given particulate substance, the instantaneous flux through a river cross-section is the product of three quantities: the water discharge, the suspended particulate matter (SPM) concentration, and the substance content in the SPM. The temporal variability of contaminant fluxes is high, spanning 3 or 4 orders of magnitude typically (cf. Fig. 21a). Such variability is mainly driven by the time evolution of SPM concentration, and to a lesser extent by the time evolution of water discharge and contaminant contents in the SPM. As discussed in the Introduction, monitoring networks of contaminant fluxes in river systems are scarce, and SPM concentrations and contaminant contents are very seldom sampled frequently enough to capture their temporal variability.



(a) (b)

Figure 21: Total mercury (Hg) flux in the Rhône River at Jons during the 2011-2012 hydrological year (Launay, 2014): temporal variability of the water discharge, Hg content in SPM, SPM concentration (C_s), and Hg instantaneous flux (a); cumulated annual fluxes depending on different methods for computing the Hg contents in the SPM (b).

In her PhD thesis on polychlorobiphenyls (PCB) and mercury (Hg) fluxes in the Rhône River, Launay (2014) compared several methods for monitoring or reconstructing SPM concentrations and contaminant contents to establish contaminant flux budgets. Marina showed that discharge-SPM rating curves could be used to reconstruct annual SPM fluxes with acceptable uncertainty, but that turbidity meters calibrated with water samples were an efficient technique to continuously monitor SPM fluxes at smaller time scales. As we found that the sensitivity of turbidity meters to SPM concentration was inversely proportional to the size of the particles (Thollet et al., 2013), it is preferred to check and (if need be) update the turbidity-SPM rating curve with frequent water samples, especially at sites where the particle size may vary according to their sources.

Unfortunately, there is no affordable way to monitor contaminant contents of SPM continuously. Using continuous flow centrifuge and integrative particle traps to sample sufficient amounts of SPM, Launay (2014) compared several methods to measure and reconstruct contaminant contents in the SPM (cf. Fig. 21b). The differences in annual fluxes was generally limited and actually negligible before the measurement uncertainties due to sampling representativeness and physico-chemical analyses. When frequent observational data are missing, using average contaminant contents for the whole period, or for the various hydrological conditions (base flow, flood, dam flush) was found to produce acceptable annual flux estimates. The best observation strategy would combine low-cost, time-integrative particle traps and punctual, flow centrifuge sampling (which is arguably more accurate) to document the contamination levels throughout the river network. Though they are often biased in grain size distribution or particulate organic carbon (POC) contents, particle trap samples showed contents in contaminants (PCB, Hg) similar to those in continuous flow centrifuge samples (Masson et al., 2017). In the Rhône River network, spatial variability is actually much higher than temporal variability as the mean contamination levels of the tributaries are much more different than their fluctuations over time. As for monitoring SPM concentrations, the homogeneity of suspended load throughout the cross-section must be assessed with distributed sampling campaigns, especially downstream of a confluence with a flooded tributary.

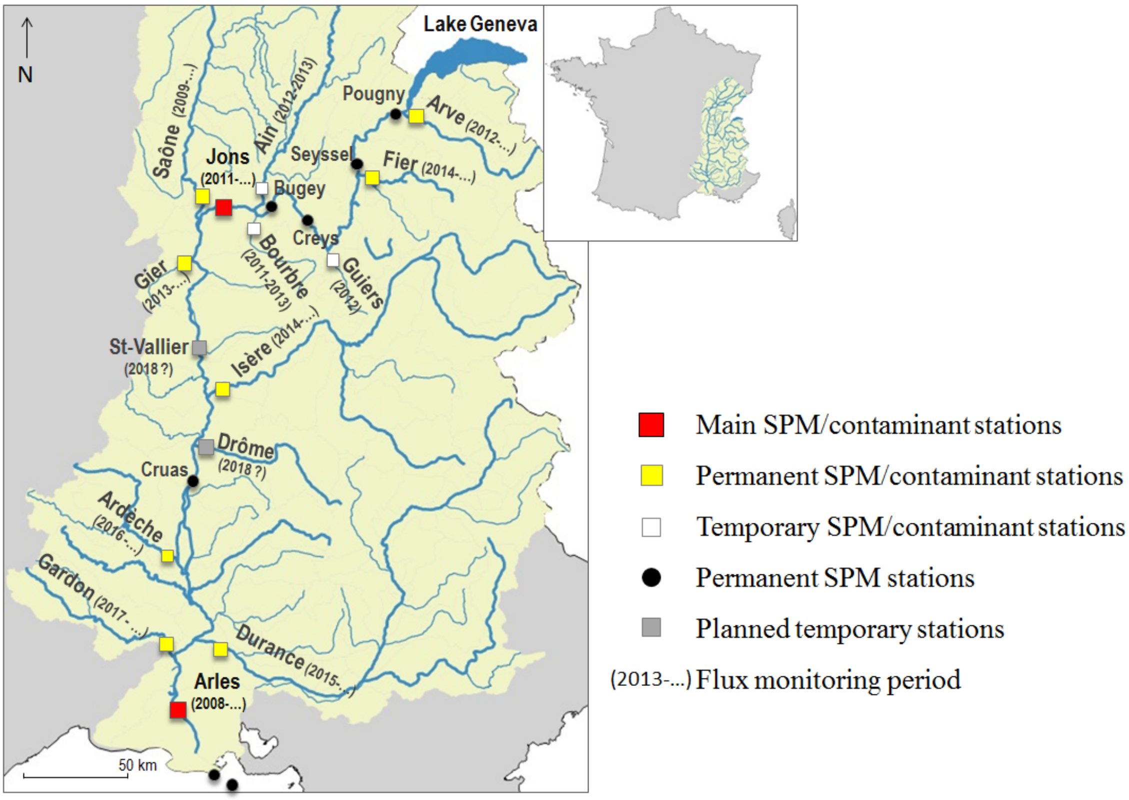
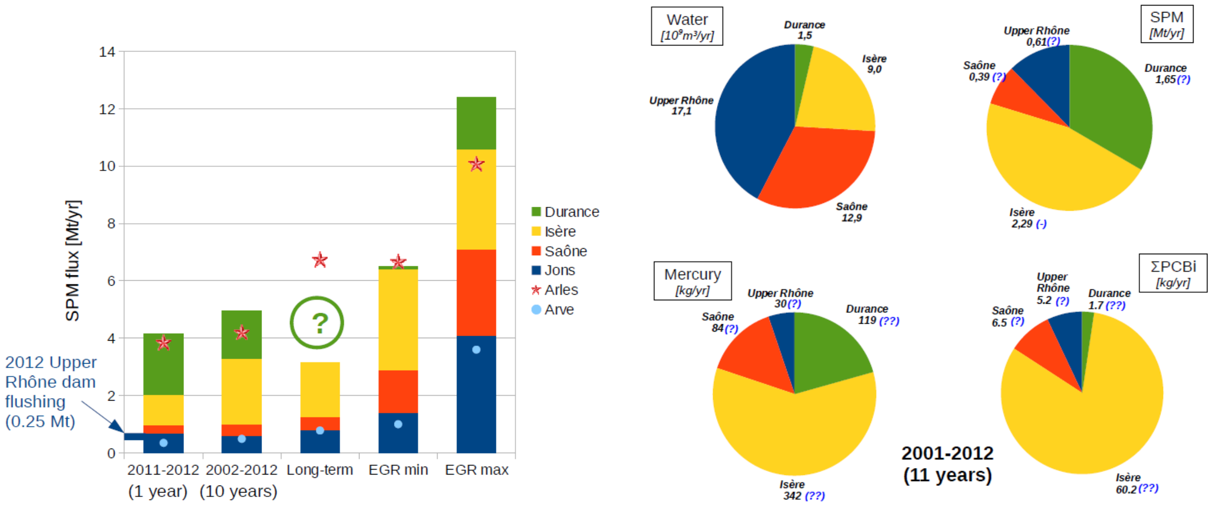


Figure 22: Suspended Particulate Matter (SPM) and contaminant flux monitoring stations of the Rhône Sediment Observatory (OSR) in March 2017 (Le Bescond et al., 2017).

Since 2009, the scientific and operational partners of the Rhône Sediment Observatory (OSR) have implemented this observation strategy to monitor the SPM and contaminant fluxes in the Rhône River and its main tributaries in Switzerland and France from Lake Geneva to the Mediterranean Sea, at time-scales ranging from a flood lasting for a few hours to annual or pluri-annual budgets

(Le Bescond et al., 2015). The Rhône River is a major river in Europe as it carries most of the SPM delivered from continental surfaces to the North Western Mediterranean Sea, together with numerous organic and inorganic contaminants. The OSR flux observation network (Fig. 22) is now composed of a number of permanent and temporary stations monitoring water discharge, SPM concentrations and their contaminants contents. At the two main stations at Jons and Arles SPM samples for chemical analyses are taken every two weeks and more frequently during floods and dam flushing operations. The major tributaries that make most of the annual SPM inputs to the Rhône (i.e. the Arve, Saône, Isère, Ardèche and Durance Rivers) are monitored with permanent turbidty meters and particle traps. The rating tables, the time series of measured parameters (e.g. stage, turbidity), the time series of computed parameters (e.g. discharge, SPM and contaminant fluxes) and their control points (measurements) are validated and made publicly available in the BDOH/OSR[14] database (Le Bescond et al., 2017). The Rhône Sediment Observatory (OSR) is part of the Long-Term Ecological Research (LTER) Rhône Basin (ZABR) and is connected to other SPM observatories in some subcatchments (Arc-Isère, Ardèche OHMCV, Draix-Bléone-Durance).



(a) (b)

Figure 23: Flux budgets in the Rhône from Lake Geneva to the Mediterranean Sea (Launay, 2014): SPM flux estimates over different periods of time compared to previous estimates of long-term averages from Etude Globale Rhône (a); contributions in water, SPM, mercury (Hg), and sum of indicator PCB (ΣPCBi) from the main tributaries during 11 hydrological years, 2001-2012 (b). Question marks indicate increasing levels of uncertainty.

Based on the observations of the OSR, annual and pluri-annual flux budgets in the Rhône River from Lake Geneva to the Mediterranean Sea were established (Fig. 23). The SPM budgets

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[14] https://bdoh.irstea.fr/OBSERVATOIRE-DES-SEDIMENTS-DU-RHONE/

are acceptably well balanced as the sum of the inputs approximately equals the output at Arles[15] (Fig. 23a). Long-term average SPM fluxes are lower than existing estimations (EGR, Etude Globale Rhône). Fig. 23b shows that the relative contributions of a given tributary in water, SPM and contaminant fluxes are not mutually proportional, because mean SPM concentrations and contaminant contents vary between tributaries. For instance, over 2001-2012 the Durance River brings only a few percent of the water budget but brings almost a third of the total SPM supply to the Rhône; due to contrasted levels of contamination, the corresponding mercury and PCB (7 indicators) inputs are about 20% and a few percent of the total, respectively. Such flux budgets at a large river network scale provide a better understanding of the river system and its particulate exports to the marine environment. Annual and event-scale budgets of cumulated fluxes allow mass balance assessments that highlight SPM storage and re-suspension processes in hydropower and navigation structures, as well as in river margins and dead zones. New observations are constantly used to update the flux estimates (Poulier et al., 2017). The reconstruction of past SPM and contaminant fluxes requires further investigation, especially using contaminant contents found in core samples taken in sedimentary archives.

Another collective achievement of the OSR is the development of a 1-D hydro-sedimentary numerical model of the Rhône River between Lake Geneva and the Mediterranean Sea (Dugué et al., 2015a). This Rhône 1-D model uses the code Mage for solving the 1-D transient shallow water equations over a looped river network including the regulation rules of hydropower structures (Dugué et al., 2015b). It also includes an advection-dispersion module (Adis-TS) for solute pollutants and suspended particulate matters with a mass exchange with the bed to reflect deposition and erosion (Guertault et al., 2016). Longitudinal dispersion coefficients have been calibrated following the experimental work of Launay et al. (2015) who concluded that the Iwasa and Aya formula (1991) was the closest to the results of fluorescent tracing experiments and ADCP surveys in the Rhône River in Lyon. The numerical simulations can be performed using several classes of sediment grain sizes, from clay to medium sand typically. Parameters related to SPM transport and erosion/deposition were calibrated by Guertault et al. (2016). The computational cost is optimised, which allows for both real-time and long-term simulations. Typically, on a usual laptop simulating a month of real fluxes takes 10 minutes approximately. Guertault et al. (2016) developed an additional module

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[15] using the total discharge of the Rhône measured at Beaucaire

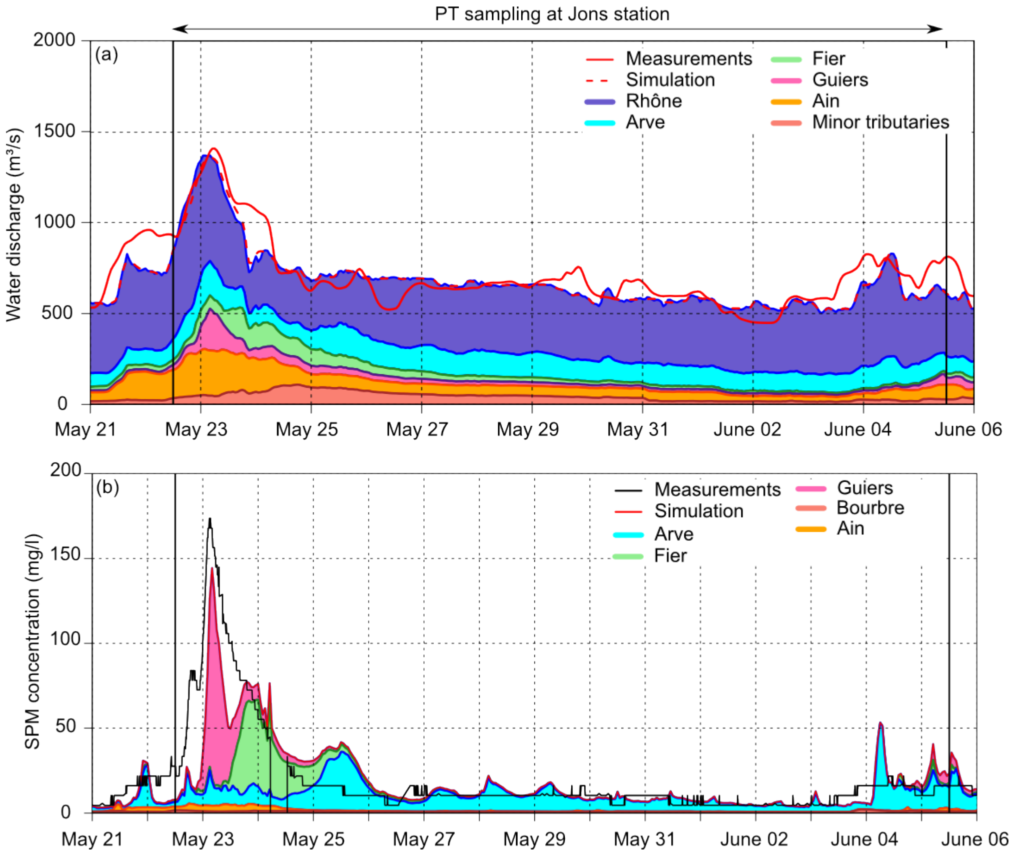

Figure 24: Numerical simulation of the Rhône River at Jons using the 1-D hydro-sedimentary model (Dabrin et al., 2017): (a) decomposition of water discharges, (b) decomposition of SPM concentrations. The investigated period (May-June 2012) corresponds to the particle trap sample JON_18 (cf. Fig. 25).

accounting for SPM releases from the gates and spillway of Génissiat Dam and successfully applied the model to simulate dam flushing operations in the French Upper Rhône River.

This model has proved to be very useful for propagating and reconstructing the flow, SPM and contaminant hydrographs at any point throughout the Rhône River network, given the upstream inputs. Using numerical tracers specific to each tributary, their respective contributions to the fluxes can be estimated, which is a useful output (Fig. 24). This numerical decomposition of SPM sources in particle trap samples was compared with a fingerprinting model based on the concentrations of major elements and trace metals analysed in the residual (conservative) fraction of SPM (Dabrin et al., 2017). Fig. 25 shows an overall good agreement between the two independent methods, with some minor inputs sometimes missed in the fingerprinting results, or interpreted as SPM from the Arve River. Results obtained with samples taken during dam flushing operations confirm that most of the re-suspended deposits in the reservoirs originate from the Arve River.

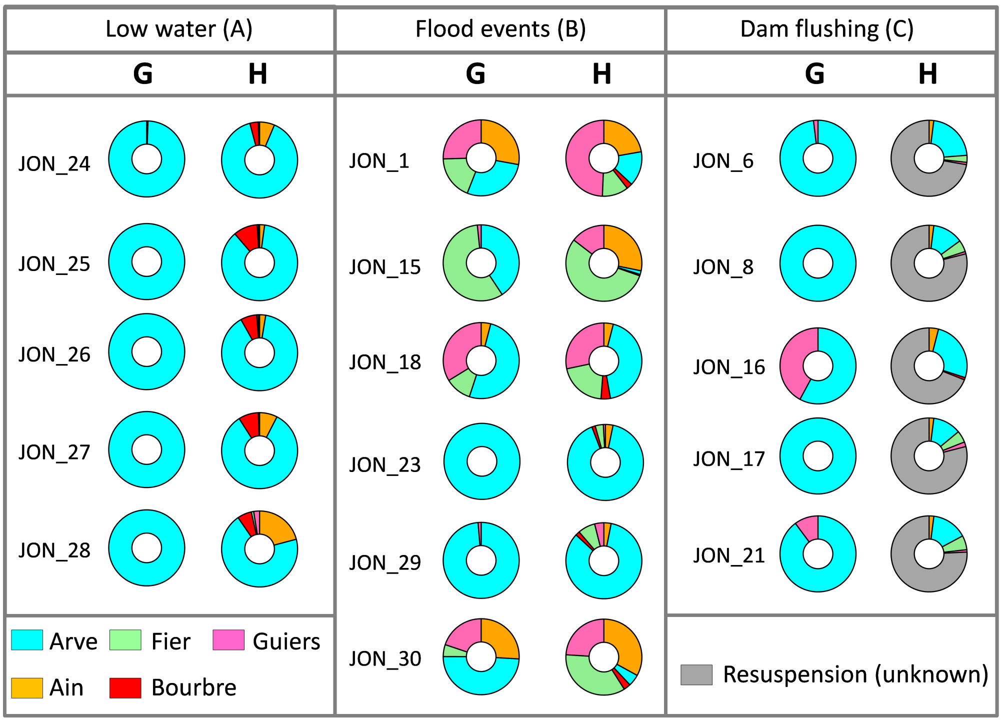

Figure 25: Comparison of the SPM sources estimated by the geochemical fingerprinting model (G) and the hydro-sedimentary model (H) in the Rhône River at Jons during periods of low flows (A), flood events (B) and dam flushing operations (C) (Dabrin et al., 2017).

Launay et al. (2017) applied the model to the extreme sedimentary event of May-June 2008, a combination of floods and dam flushing operations in the Durance and Isère Rivers, to better understand the sources of the SPM export to the Mediterranean Sea. The mass balance was also investigated and intense deposition in some Rhône reaches was computed, in agreement with field observations. In addition to boundary conditions (water discharges and SPM concentrations), the model is sensitive to grain size distributions which are not known precisely. In spite of its limitations and uncertainties, the 1-D model provides high-resolution views of the sedimentary processes that are valuable for improving the understanding and the management of such a complex regulated river network.

5 Research prospects

5.1 Improving and increasing streamflow observations

There is still much research to do to make river discharge measurements more accurate, more efficient and more widespread. In the next 5 to 10 years, I plan to continue the development and validation of new measurement technologies and procedures.

The development of image-based hydrometry and its dissemination to practitioners through the Fudaa-LSPIV free software will remain an important part of my research activities, in close collaboration with EDF (Alexandre Hauet, Magali Jodeau) and Irstea colleagues (Jean-Baptiste Faure, Lionel Pénard). In addition to my interest in LSPIV, I have been interested in alternative image velocimetry techniques, such as STIV-Space Time Image Velocimetry (Fujita et al., 2007), optical flow (cf. PhD of Musaab Mohamed, 2014-2017), LSPTV-Large Scale Particle Tracking Velocimetry (cf. Brevis et al., 2011, and PhD of Antoine Patalano, 2017). Such alternative image velocimetry techniques may help cover an extended range of image, flow and tracing conditions, not only for floods but also for other applications in environmental hydraulics, e.g. low flows with few tracers, laboratory experiments (Jodeau et al., 2017; Piton et al., 2017), debris flows, lahars, dam or dike breaks, etc. The image acquisition would also benefit from improvements: in 2017 we will install and test a FLIR (Forward-Looking Infra-Red) thermal camera at one of our stations in the Ardèche catchment for day and night measurements.

The non-intrusive measurement of flow depths remains a rather frustrating frontier, as this would allow for fully non-intrusive discharge measurements. Following the GPR (Ground Penetrating Radar) tests reported by Costa et al. (2000), there was little advance in the validation of this difficult measuring technique until the promising results published very recently by Hong et al. (2017). Furthermore, Detert et al. (2017) published encouraging results of flow depth estimation from the turbulence scales of the surface velocity field. I am sure this issue will be actively investigated in the coming decade, and I look forward to pursuing this research.

In addition to non-intrusive image-based techniques for discharge measurements, it is also worth paying attention to alternative stream gauging techniques, often based on old principles revisited using modern technologies. The POEM-Pressure Operated Electronic Meter (Smart, 1991; Magirl et al., 2009) is a brilliant example of one such successful instrumental metamorphosis, as it is the modern version of the Pitot tube improved by Darcy for the use of the French hydrological services in the middle of the 19th century. I would like to test and possibly enhance this and other smart methods proposed by my fellow researchers, focussing on low-cost techniques which may improve discharge measurements in specific site conditions and/or would be more affordable for training, developing countries or remote regions. For example, the transparent head rod introduced by Fonstad et al. (2005) and modified by Pike et al. (2016), based on older head rod models (Wilm and Storey, 1944; Drost, 1963) may be a cost-efficient option for wading gaugings. The solid steel spheres used as pendulums by Storz (2016) may be a low-cost and safe alternative to suspended current-meters in tough flood conditions. Last but not least, I believe the rising bubble technique (Hilgersom and Luxemburg, 2012; Wilding et al., 2016) may provide the most accurate velocity measurements in slow and possibly weedy streams. It also has the advantage of providing direct measurements of the discharge per unit width.

Crowd-sourced hydrometry is an exciting way to extend the observation of streamflows at higher spatial and temporal resolution. Crowd-sourced texts, images and videos have a great potential not only for flood hazard mapping and post-disaster surveys (Le Coz et al., 2016c), but also for low flows and drought observations (cf. Hydropop project launched by Pierre-Alain Ayral, Ecole des Mines d'Alès). Our past projects showed the limits of manually mining social media and video sharing platforms and indicated a need for the automation of video and text selection, which requires the development of efficient software tools (Fohringer et al., 2015; Brouwer et al., 2017). Also, interdisciplinary projects including social sciences would be necessary to improve the general public engagement and the flood damage assessment and mapping. International cooperation will help unite the diverse skills and experiences needed to set up an integrated analysis of crowd-sourced hydrological data, as initiated through informal networking with active colleagues in Argentina (Carlos Marcelo García, Antoine Patalano, Universidad Nacional de Córdoba), Italy (Milanesi et al., 2016), Germany, and the United Kingdom.

Whereas calls for flood images and texts have been successful and the general public have provided them spontaneously, calls for flood videos have been much less successful and actually most of the crowd-sourced videos have been searched and found by the scientists themselves. Amongst other possible reasons, I think this is because the final use of videos to quantify flood velocities and discharges is less intuitive. The best would be to provide free, easy-to-use tools to the general public for their own video-based streamflow measurements. Recently, several smartphone apps have been developed by research groups for that purpose (Lüthi et al., 2014; Yu and Hwang, 2016; Tsubaki, 2017) and we also plan to develop a smartphone version of Fudaa-LSPIV. The key point is to make their use by anyone as easy as possible. A major limitation is the accuracy and convenience of the image orthorectification step. Implicit camera calibration as in Fudaa-LSPIV usually requires a number of Ground Reference Points (GRP) with accurate coordinates, which is usually not achievable by non professional users. On the other hand, explicit camera calibration may be done from data provided by the operator (elevation above water, camera specifications), the sensors of the smartphone itself (GPS for position, inclinometers for pitch-roll), or through grid calibration tests. However, the resulting orthorectification errors may be large, depending on the accuracy of the input data. I am currently working on a Bayesian method (BiM for Bayesian Image) combining both approaches to quantify and reduce the uncertainties (see next Section). The camera calibration would then account for the uncertainties of the input data, which in practice would allow for more uncertain GRP positions and a much easier use of the image velocimetry technique.

Recently, the French International Office for Water (OIEau) has launched an international project on the use of altimetry data from the future Surface Water and Ocean Topography (SWOT) satellite mission for measuring discharge at several stations throughout the Congo River catchment. Irstea colleagues (Pierre-Olivier Malaterre and Igor Gejadze) are involved in this project and plan to apply variational data assimilation techniques they have developed using a 1-D numerical model (Gejadze and Malaterre, 2017). I think that it would be interesting to also apply the Bayesian methods we have developed for hydrometric stations, especially the stage-fall-discharge model for variable backwater (Mansanarez et al., 2016), to satellite-based records of water stages, which could be seen as a simplified version of the Bayesian approach of Durand et al. (2014). This approach may help bridge the gap between traditional hydrometry and satellite remote sensing by applying the same method to both kinds of stage measurements and accounting for their respective uncertainties, and by assimilating the same kind of field observations (gaugings, topography data). The uncertainty of the output discharge data would be computed using the same procedure as for the traditional discharge time series so that the quality of satellite-based discharge time series could be compared more directly.

Beyond improving and increasing future streamflow observations, I am convinced that the reconstruction of past discharge time series deserves attention. There have been a number of studies that aimed at reconstructing historical flood discharges using hydrodynamical models and available data including water levels, flood marks, gaugings and topography surveys (Naulet et al., 2005; Balasch et al., 2010; Di Baldassarre and Claps, 2011). Reconstructing discharge time series with their potentially large uncertainties at sites where historical water level time series exist but no or limited discharge measurements and no rating curves are available is obviously challenging but the results would be of great interest for assessing the long-term evolution of flow regimes in relation to climate and land use changes. The historical station of the Rhône at Beaucaire is an exciting and important study case as it is located near the outlet of a large river catchment with diverse climatic and orographic characteristics. Irstea (Michel Lang) and Hydro-Consultant (Antoine Bard) are currently updating the flood frequency statistics of that station by reconstructing the annual discharge maxima and their uncertainties since the beginning of daily stage records in 1816. It would be interesting to go further and try to reconstruct the daily discharge time series and its uncertainties by modelling the evolution of the stage-discharge relation using a hydrodynamical model and observed or estimated riverbed topography, in cooperation with fluvial geomorphologists working on the Rhône such as colleagues from Lyon (Hervé Piégay) and Aix-Marseille (Michal Tal) universities.

5.2 Producing probabilistic streamflow data

The long-term aim of this research theme is to complete the toolbox to cover the whole chain of streamflow uncertainties, from field measurements to the streamflow times series delivered to end-users.

First of all, I will continue investigating the potential of interlaboratory experiments (Le Coz et al., 2016a) for estimating the uncertainty of streamgauging techniques empirically. This standardised approach can be seen as a one-way repeated measures analysis of variance (ANOVA) that can be generalised as an N-way ANOVA for well-balanced experiment designs (Despax et al., 2017b). This was first achieved through the Chauvan 2016 ADCP experiments (Despax et al., 2017a) with a well-balanced experiment design: two groups of 24 teams (or ADCP/operator couples) were circulated over two groups of 12 cross-sections, respectively. The Chauvan 2016 ADCP experiments were organised by EDF and the Groupe Doppler Hydrométrie (GDH) in collaboration with other hydrological services from Czech Republic, Norway, South Korea, Spain, Sweden, the United Kingdom and the USGS. Such experiments make it possible to separate the effects of the identified factors and to quantify difficult-to-estimate uncertainty components such as cross-section selection, operator choices, instruments, deployment bias (such as the direction of ADCP transects, i.e. left to right bank versus right to left), etc. This was the main objective of the postdoctorate position of Aurélien Despax (2016-2017) I supervised in collaboration with EDF and SCHAPI.

Repeated measures experiments provide uncertainty estimates for the given site, flow, operator, instrument conditions covered in the experiments. Therefore, it is important to conduct similar experiments in different conditions. A practical problem is how to document the most adverse conditions, which are the most problematic (and the most interesting) while keeping a good design for the uncertainty estimation. This would certainly be possible in a man-made white-water paddling facility for instance, or in a very slow, potentially weedy section, provided that there is a constant inflow from an upstream artificial structure such as a gate or a weir. Artificial rivers like the River Experiment Center in Andong, Korea, operated by the KICT[16] offer controlled conditions for such experiments, with more or less steep channel slopes and a range of meander curvature indices. I would like to contribute to such experiments through the cooperation of Irstea, KICT and Dankook University and the WMO ProjectX (international hydrometry expert panel). Inter-agency cooperation is very important to document streamgauging uncertainties over a wide range of conditions. Common procedures and analyses should be promoted through international experiments like the Chauvan 2016 ADCP experiments, standardisation (WMO, AFNOR/ISO, inter-agencies) and ideally the development of a database to share experimental data and uncertainty estimates.

Improving the computation of streamgauging uncertainties is another long-lasting research task that benefits from the outputs of uncertainty experiments. The new IVE (Cohn et al., 2013), Q+ (Le Coz et al., 2012) and Flaure (Despax et al., 2016b) methods have brought important improvements to the ISO748 standardised method for computing the velocity-area gaugings. However there is no consensus on which method is the best, and decisive improvements are still pending. Despite the recent developments, the computation of velocity and depth integration errors still requires improvements, especially the u_m component reflecting the limited number of verticals. I would like to introduce a clearer definition of the angle α of the $Q+$ method, as the maximum deviation of the bed profile from the linear interpolation of measured depths, instead of the horizontal. And this angle, or the u_m component should be related to metadata describing the site conditions, as initiated by Despax et al. (2016b) using analogous high-resolution gaugings. The data reduction equation needs to be refined to include all relevant error sources, especially velocity time-averaging errors and biases related to the deployment (e.g. angle errors) and to the vertical velocity model. Increasing the complexity of uncertainty computation methods must be balanced by additional help to the end-user through improved software and easier specification of the inputs and data processing. This topic has important consequences for the improvement of hydrometric procedures and international standards, as the different methods have different sensitivities and compute different levels of uncertainties, especially regarding the number and spacing of the depth and velocity positions.

The computation of moving-boat ADCP discharge uncertainty is another important topic I am working on, through cooperation between French agencies and the USGS on the Oursin method and

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[16] Korea Institute of Civil Engineering and Building Technology

its possible implementation in QRev software (Mueller, 2016). Most of the French agencies involved in the GDH hydrometry network (the national services, EDF, CNR, Irstea) have decided to cooperate to finalise and evaluate the Oursin method for the uncertainty analysis of moving-boat ADCP discharge measurements. Our plan is to stabilise the uncertainty computation method implemented in the Oursin software developed and freely released by CNR, compare the uncertainty results obtained with a range of ADCP measurements (especially from comparison experiments like Chauvan 2016), document the method and publish an international research paper. We would also like to compare the Oursin uncertainty estimates with the outputs of other methods, namely QRev, QUant and possibly others. We in France also acknowledge the need for improving our QA/QC procedures, for making ADCP file formats and discharge computation more homogeneous and independent from equipment providers, and for using common pieces of open software to this end. QRev looks like the perfect tool for this. EDF have managed the issue of a French version of QRev and their field hydrologists have adopted QRev for their routine reviewing of ADCP gaugings. We expect that its use will become widespread in France in the near future, as it is already in other countries. While the existing Oursin software remains useful for testing the uncertainty computation method we are proposing, it has important limitations compared to QRev: no QA/QC tests, WinRiver discharge computation only, reads ASCII files from TRDI ADCP with constant bin size only, French version only, among others. As we think Oursin is an acceptable trade-off between statistical rigour and engineering applicability, we have proposed to cooperate with the USGS in implementing the Oursin uncertainty computation in QRev, perhaps amongst several options.

Most of these uncertainty propagation methods, including ISO748, IVE, Q+, Flaure, QRev and Oursin, are based on the first-order Taylor series expansion (FOTSE) approach proposed by the GUM (JCGM, 2008). As done by Muste et al. (2012), the comparison of FOTSE results with more costly Monte Carlo simulation is interesting to validate the restrictive assumptions that are made in the FOTSE approximation. This comparison of methods will be made possible using the QMSys uncertainty calculator which is currently in development as a task of WMO ProjectX. Though their computation schemes are slightly different, QUant and Oursin results could provide such a comparison too.

Beyond velocity-area and moving-boat ADCP, the uncertainty of other streamgauging techniques should also be computed, starting from their own data reduction equations and elementary uncertainty inputs. This notably includes surface velocity gaugings (a specific case of velocity-area gaugings) and tracer dilution gaugings, for which EDF-DTG have already proposed an uncertainty computation method. I have worked on substantial uncertainty sources of surface velocity gaugings, due to the surface velocity coefficient (Le Coz et al., 2010a; Welber et al., 2016) and due to possible scour-fill of the alluvial bed, which is sometimes observed to span over several metres. During my scientific stay at NIWA[17] Christchurch, New Zealand in 2015-2016, I tried to set up an equation for estimating the magnitude of the bed response to a flood wave but I was not successful. I would like to try again, as an estimation of the change to the bed that results from a flood wave is necessary to quantify the uncertainty of surface velocity gaugings conducted during floods. I am also working with Benjamin Renard on a Bayesian approach (BiM) to camera calibration which provides an estimation of image orthorectification errors that can be propagated to velocity fields and discharges. This would be a significant advance towards the uncertainty analysis of image velocimetry gaugings, as orthorectification errors are likely to be a dominant uncertainty component.

In addition to the proposed work described above, it is clear that the development of uncertainty methods for rating curves and streamflow time series will keep me busy during the next decade(s). The probabilistic approach of the BaRatin method (Le Coz et al., 2014b) has proved to be a firm basis for the development of a complete toolbox addressing the main methods and issues of hydrological data production and use. Several tasks are already on the agenda for my next years of research. Benjamin Renard, Michel Lang and I will supervise a second PhD student (2017-2020) to extend BaRatin for addressing rating changes in real-time (or as soon as possible), as this is a very important operational issue, particularly for flood forecasting and water resource regulation. The PhD work will focus on the detection and estimation of rating changes based on prior information, especially the stage time series, estimated bedload volumes and other measured parameters or expert-based information. Time-evolving rating curves, i.e. stage-time-discharge (STD) models will need to be set up so their parameters and structural errors will be estimated using the information content of the gaugings, as soon as available, to update the rating curve and reduce its uncertainty envelope. STD models will address bed evolution, either net changes (cf. the SPD model developed by Mansanarez, 2016) or gradual scour-fill processes, and cycles of growth and decline of aquatic vegetation. Other interesting rating change processes include temporary dams built by swimmers, beavers, or other artificial alterations of the bed or operation of hydraulic structures, and the roughness evolution of ice sheets that cover cold-water rivers. Ice-influenced flows account for 18.7% of the hydrometric

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[17] The national institute of water and atmospheric research (New Zealand).

data published by the Water Survey of Canada, for example (Hamilton, 2003). The associated high uncertainties are not quantified, thereby compromising water balances in the northern regions (Hamilton, 2004).

As a continuation of the PhD work of Mansanarez (2016), the extension of BaRatin for complex ratings will be continued and implemented in the BaRatinAGE operational interface, using the BaM (Bayesian Models) engine developed by Benjamin Renard. Amongst other specific discharge models, index velocity ratings have been increasingly developed for velocimetric stations, using fixed ADCPs or fixed velocity radars, typically. The index velocity model will therefore be interesting to include and test in the Bayesian framework. Furthermore, an extension of the Stage-Fall-Discharge (SFD) model for twin-gauge stations (Mansanarez et al., 2016; Le Coz et al., 2016b) to transient flows in tidal rivers has been initiated through encouraging applications of the modified model to the Saigon River, Vietnam, and the Seine River, France, by Camenen et al. (2017b).

Our recent works on the computation of probabilistic streamflow time series (Horner et al., 2017) highlighted the need for a better understanding of measurement errors in the input variables of the discharge models. Notably, we should develop methods for specifying stage measurement errors based on testing experiments, expert knowledge, QA/QC procedures, etc. The measurement errors of any other input variables of complex rating curves, such as velocity in the index velocity method, should be studied and quantified thoroughly. Importantly, Horner et al. (2017) demonstrated the importance of accounting for systematic stage measurement errors, as non-systematic (time-independent) errors rapidly vanish as streamflows are time averaged. Accounting for all kinds of systematic errors is a key challenge for computing realistic streamflow uncertainty estimates. We plan to let BaRatin users define ‘families of gaugings’ for which the errors are not mutually independent, if they share the same instrument, the same cross-section, the same discharge extrapolation coefficients, or were successively conducted over a short period of time, etc. We also plan to implement better remnant (structural) uncertainty models with a systematic dependence on time and/or stage.

The advantage of producing probabilistic streamflow time series as ensembles of realisations is that their propagation to any kind of model or application is more straightforward and transparent for the end-users of the hydrological data. Personally, I am interested in cooperation with co-workers who would propagate streamflow data through hydrodynamical models (cf. e.g. MonteCarlo simulations using the fast-computing MAGE 1-D model following the uncertainty analysis by Souhar and Faure, 2009), hydrological signatures (Westerberg et al., 2016, and the PhD of Ivan Horner, 2017-2019, supervised by Flora Branger and Isabelle Braud), hydrological models, data assimilation for flood forecasting, among other uses of streamflow series.

5.3 Developing a hydrological approach to sediment and contaminant fluxes

In my opinion, what has limited the development of the hydrological analysis of sediment and contaminant fluxes in rivers is the scarcity and the uncertainty of times series at resolution high enough to capture the spatio-temporal variability of such fluxes. Due to additional measurement issues, observation has been traditionally limited to occasional sampling, sometimes over long periods of time but often with discontinuous field and laboratory procedures. Flux balance estimation and statistical analysis are therefore difficult to conduct without large uncertainties. I believe that the cooperation of hydrologists and hydrometry technologists with chemists and sediment experts is the way to fill the gap and build efficient flux observation strategies similar to what is done for streamflows, as initiated through the Rhône Sediment Observatory (OSR, Launay, 2014; Le Bescond et al., 2017) and its flux database, BDOH/OSR[18]. The Rhône catchment is a wonderful laboratory for developing a sedimentary hydrology and I hope it will be integrated in future research programmes like the future Danubius European Research Infrastructure[19]. The following perspectives are focussed on the Rhône catchment but I will certainly keep working on other rivers too, through existing (e.g. HyBAM Amazonian observatory) and future collaboration opportunities.

Through the new OSR5 programme (2018-2020), the flux observation network of the Rhône River will be maintained and extended to new stations. We want to obtain at least 10 years of continuous records, and potentially make some of the stations perennial. We will also improve the reconstruction of past fluxes of suspended particulate matter (SPM) and of associated contaminants, using discharge-SPM rating curves or other models and comparing modern fluxes with historical records from sediment cores (Desmet et al., 2012; Mourier et al., 2014). In addition to geochemical fingerprinting (Dabrin et al., 2017), we would like to apply the 1-D hydrodynamical model to past water and SPM fluxes to relate the deposition layers in a sediment core to successive flood events. Then, the sources of the particles (tributary of origin) and their storage and re-suspension in the river network could be assessed.

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[18] `https://bdoh.irstea.fr/OBSERVATOIRE-DES-SEDIMENTS-DU-RHONE/`

[19] `http://www.danubius-ri.eu/`

An important limitation of our 1-D model, as of most 1-D models, for computing SPM fluxes through river networks is the assumption of complete, instantaneous mixing at confluences. River cross-sections actually have very large width-to-depth aspect ratios and transverse mixing takes very long downstream distances to be achieved, typically tens of kilometres in the Rhône River (Launay et al., 2015). The incomplete mixing of waters and SPM fluxes must be accounted for in the model at each junction with a notable tributary or effluent and at each bifurcation and junction of the numerous hydropower structures along the Rhône river network. The on-going PhD of Sébastien Pouchoulin (2016-2019), co-supervised by Nicolas Rivière, Emmanuel Mignot, Gislain Lipeme-Kouyi (INSA Lyon) and I aims at developing and validating a parametric formula for mixing downstream of confluences that could be further implemented in 1-D hydrodynamic model. Sébastien has carried out the physical and numerical simulation of simple geometry cases, using pH tracing experiments in the INSA physical model of street crossings (Bazin et al., 2017) and RANS[20] and LES[21] 3-D numerical modelling. We also plan to conduct temperature surveys throughout cross-sections in the Rhône River, downstream of confluences with tributaries bringing colder or hotter waters like the Ain or the Isère Rivers for instance. Such experimental data on river mixing would be useful to test the application of the new parametric formula to real river cases.

A long-term objective would be the development and application of hydrological methods to fine sediment (SPM, washload) and contaminant fluxes, in order to develop not only a 'sediment hydrometry' but a 'sediment hydrology'. First of all, I would like to extend the BaRatin Bayesian framework developed for streamflows to compute probabilistic SPM and contaminant fluxes and their uncertainty envelopes. This will require implementing suitable 'rating curves', computing the discharge/SPM/contaminant contents product, and specifying all relevant uncertainty components, including water/SPM sampling uncertainties and physico-chemical analysis uncertainties. As for stage-discharge rating curves and streamflow time series, assessing systematic errors in the whole process will be necessary and challenging. In particular, we are working on how to reflect the systematic errors due to episodic rating changes in the turbidity-SPM relations and in the discharge-SPM rating curves used to establish measured and reconstructed SPM time series, respectively. SPM/contaminant flux time series open exciting perspectives for new hydrological applications, including flux frequency analysis, influence of floods and dam flushing operations on flux budgets, implementation in hydrological models such as the spatially-distributed model of the Rhône catch-

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[20] Reynolds-averaged Navier-Stokes equations

[21] Large eddy simulation

ment (MDR[22] project using the J2000 code, Krause and Kralisch, 2005) coupled with the 1-D hydrodynamical model of the Rhône River, and assess the effects of climate and land use changes on SPM and contaminant fluxes. Numerical modelling would especially help understand the impact of urbanisation, forest growth or glacier retreat on SPM generation, the potential re-suspension of historical contaminants (such as PCB, heavy metals) from sediment stocks, the long-term evolution of fluxes in response to pollutant regulation and mitigation policies, and the fate of SPM and contaminants delivered to the Mediterranean Sea throughout the Gulf of Lion (Cossa et al., 2014; Le Fouest et al., 2015). I think that connecting the observational and modelling efforts which exist throughout the Rhône catchment and the Gulf of Lion in a joint research project would be very productive. I would like to contribute to the preparation of such an ambitious programme, which would integrate multi-disciplinary approaches to studying SPM dynamics from source to sink at various spatio-temporal scales, in the same way as the FloodScale project (2012-2015) addressed flash-flood dynamics (Braud et al., 2014; Nord et al., 2017).

Other fluxes of matters in rivers could be investigated from a hydrological perspective: solute fluxes of course, but also bedload and bed material suspended load, i.e. fluxes of sand in graded suspension. The PhD of Guillaume Dramais (2016-2020), cosupervised by Benoît Camenen and I, aims at improving the establishment of sand flux time series and budgets in large rivers such as the Rhône, the Mekong and the Amazon. There is a huge demand for sand suitable for construction around the world (around 40 billions tons per year[23]). Sand has been or is still being mined in river channels, legally and illegally, creating important environmental concerns for ecological habitat, land and infrastructure stability, and flood hazard. However, sand flux data are usually scarce and sand budgets are affected by large uncertainties that are seldom estimated. In his PhD, Guillaume Dramais plans to improve field procedures for sand flux measurements and quantify their uncertainty, build sediment rating curves to calculate sand flux time series, and compute sand flux time series and annual budgets. Ideally, sand rating curves should not rely on discharge and the local transport capacity alone, but also on the non necessarily limited sediment supply from upstream, and its changes with seasonality, flood rise/recession, long-term trends, etc. Again, we plan to implement such models in the Bayesian framework to produce probabilistic time series and quantify the uncertainty bounds.

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[22] Modélisation hydrologique distribuée du Rhône (spatially-distributed hydrological modelling of the Rhône River catchment).

[23] `https://en.wikipedia.org/wiki/Sand`

Actually, the hydrological approach could be generalised to any quantity transported by rivers that can be monitored continuously over time, either directly or through a model or surrogate measurements such as stage, discharge or other variables that can be monitored continuously. For instance, such a proxy for gravel bedload could be the weight of trapped gravel in pits (Habersack et al., 2017), the sound intensity measured by hydrophones (Geay et al., 2017), or the impacts of gravels against plates or bars measured by geophones (Rickenmann and Fritschi, 2017). Surrogate techniques for monitoring suspended load continuously are based on bulk optic (turbidity), laser optic, pressure difference, and acoustic backscatter principles (Gray and Gartner, 2010). Satellite optical remote sensing (Martinez et al., 2015) can even be used to measure SPM concentrations in large river systems (Espinoza Villar et al., 2012). And beyond sediment and contaminant, it may be possible to develop the observation and modelling of other substances transported by rivers, such as drift wood (MacVicar and Piégay, 2012) and waste, oils and other buoyant pollutants, heat and water temperature, etc.

6 Concluding comments

In a recent post of his Hydrology corner blog[24], Stu Hamilton described me as "*the Chuck Yeager of hydrometry. He is pushing the envelope of conventional limitations on the measurement of water. His research is leading to better understanding of hydrometric uncertainty, developing new methods to actively reduce the uncertainty of extreme flow and to change the way rating curves are developed to better represent expert knowledge and quantify resultant uncertainties*". While the comparison with Chuck Yeager is obviously undeserved, the definition of my research aims is accurate, if extended to stream fluxes other than water, beyond pure hydrometry. Pushing the envelope is definitely exciting but at the end of the day a basic question remains: is it useful research? Through innovation and research, I have been trying to bring practical solutions to long-lasting problems in the form of new methods, technologies and paradigms. Between equipment providers and operational agencies, scientists have a key role to play to harness the power of new measurement technologies and avoid disruption in the quality of hydrological data. Scientists can also help the general public be more aware of and even contribute to hydrometry networks by making the most of digital technology and social media.

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[24] `http://aquaticinformatics.com/blog/hydrology/international-hydrometry-workshop/`, accessed 22 June 2017.

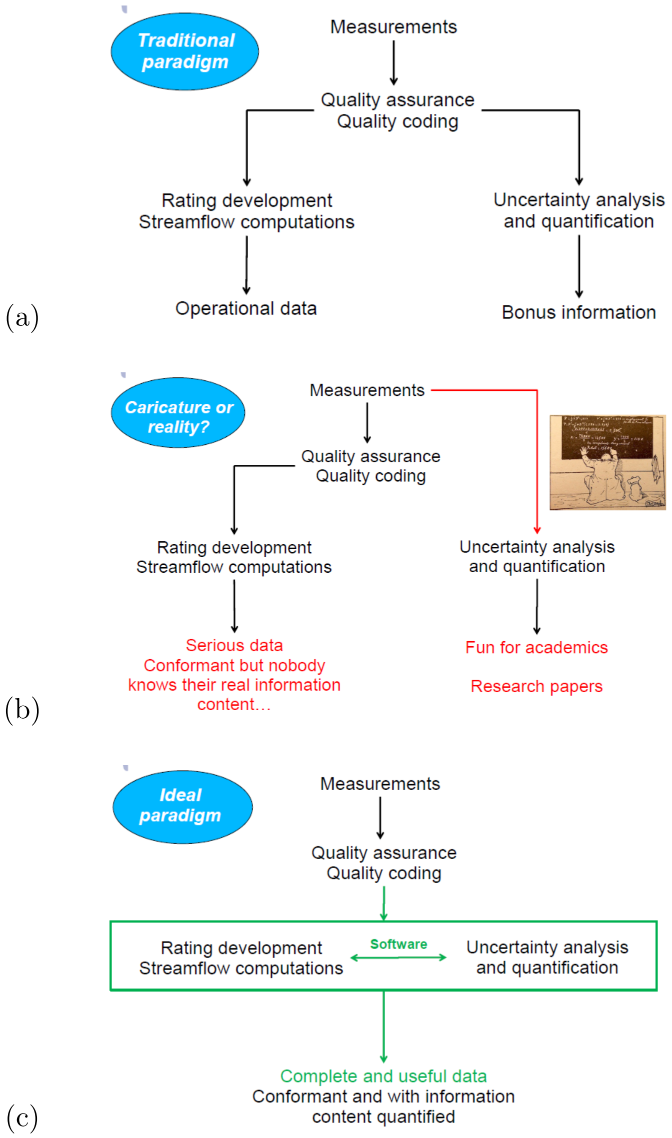

Figure 26: Paradigm shift on the uncertainty analysis of streamflow data: the traditional paradigm (a), the real situation? (b) and the ideal paradigm (c).

Bringing uncertainty analysis to the core of streamflow data production is an important paradigm shift that will take years if not decades to be achieved (Fig. 26). Uncertainty analysis has long been seen as an additional, often tedious exercise, better to be left to academics outside of the operational data flow. Pappenberger and Beven (2006) dispute seven common arguments against the use of uncertainty analysis in hydrological and hydraulic modelling and argue that the main obstacle is the lack of guidance on methods. Actually, uncertainty analysis is not a goal in itself, rather it is a powerful method for producing better hydrological data and avoiding a lot of difficulties. The problem is streamflow series are modelled, not measured. This is not always obvious to everyone, and some managers or data users sometimes think or believe that there should be no subjective input from the data producer and that rating curves should be generated by the same robot at every site. In my opinion, subjective judgement and intuition are and will remain absolutely necessary to develop and review rating curves, as it is an underdetermined problem.

Simple stage-discharge rating curves as well as more complex ratings can be seen as inverse hydrodynamic models, as discharge is the input and water stage, slope, velocity are the outputs of hydrodynamic models. Hence any field hydrologist is a modeller who has to build a model, calibrate it with a limited number of uncertain observations (the gaugings) and review it. Ideally, such models must be robust and have the lowest complexity, in agreement with the well-known principle of Parsimoni (1753): "*Of two models of equal beauty always choose the simplest*[25]". Nevertheless, using a hydraulically interpretable model rather than any flexible fitting curve has decisive advantages. First, you can interpret the parameters physically, check the consistency of the results with prior assumptions, and assess those you would expect to change or remain constant over time and during floods. Second, it is much easier to comment and explain your assumptions to others; this is the main function of a model, in my opinion, as a model represents a set of assumptions on the driving processes, not the real world. Last, you can apply automatic calibration techniques that are guided to keep the results within realistic bounds, which usually makes substantial difference in the extrapolation of extreme low and extreme high flows. The Bayesian framework makes this approach possible and efficient. We do not mean to suppress subjectivity in the art of building rating curves and computing hydrological data, rather we want to make subjective decisions appear clearly in a consistent form, so that they can be defended, reviewed and possibly revised.

Technological transfer is a demanding but also rewarding task. I am happy when other people succeed in using tools I have helped develop, and I am even happier when they find them useful. Once tested and validated, new methods need to be encapsulated in software with user-friendly interfaces and full documentation. The common idea behind BaRatinAGE (Fig. 27) and Fudaa-LSPIV (Fig. 28) software is to make new methods accessible to the widest range of practitioners. I am also happy to contribute a bit to exciting software developing projects like BDOH (Branger et al., 2014), a database developed by Irstea for publishing hydrological time series and fluxes from research observatories, and BARÈME developed by Pierre-Marie Bechon (DREAL Auvergne-Rhône-Alpes), the in-house software used by the French national hydrological services for managing

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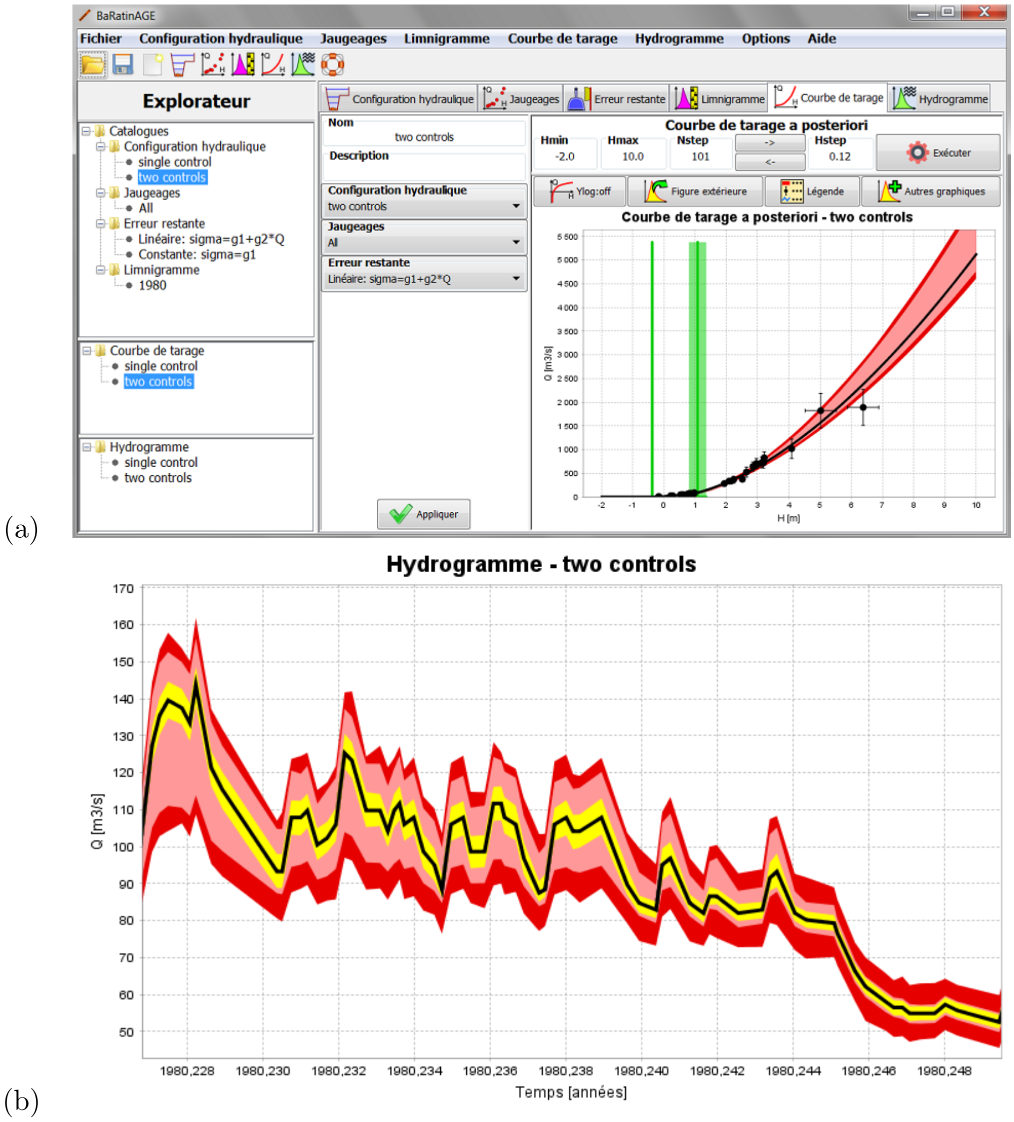
[25] *"Inter duas aequa pulchritudine formulas semper eligere simplicissima"*, Giacomo Parsimoni (1725-1755) cited by Olivier Mestre, MétéoFrance.



Nom: two controls

Description

Configuration hydraulique: two controls

Jaugeages: All

Erreur restante: Linéaire: sigma=g1+g2*Q

Hmin: -2.0

Hmax: 10.0

Nstep: 101

Hstep: 0.12

Figure 27: Snapshots of the BaRatinAGE software interface: computation of a rating curve (a) and a streamflow time series (b), and their uncertainties.

their gaugings and rating curves. This experience has made me more aware of the importance of the validation and transparency of data processing procedures. Open-source and fully documented software and open data with standardised file formats are key to improving the procedures and enhancing international cooperation. Sharing new methods and tools eventually calls for dedicated training. Beyond training sessions focussed on specific software or measurement technology, my collaborators and I have strived to explain the statistic principles and methods behind uncertainty analysis in hydrology by setting up a new training programme in 2015-2017 (Renard et al., 2015).

Combining academic research and operational practices is a long-term task which requires time, team work, substantial amounts of freedom, and supportive colleagues and partners. The BaRatin

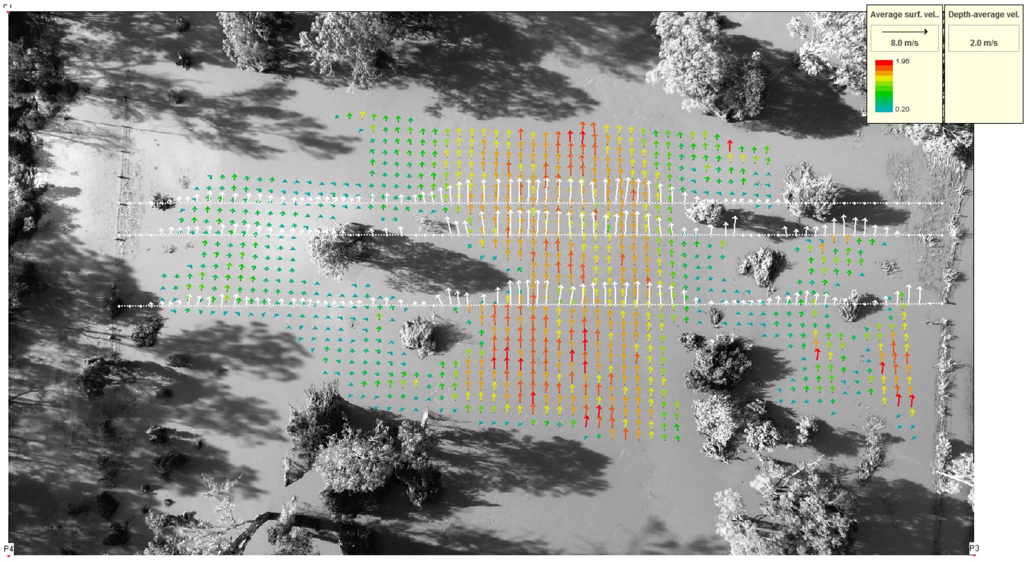


Figure 28: Snapshot of the Fudaa-LSPIV software interface: computation of surface velocity field and discharges from a drone-borne video of the Logan River in Australia during cyclone Debbie (data provided by Mark Randall, Queensland government).

project history provides a good example of this. Starting in 2010 from an informal discussion between two scientists in river hydraulics and hydrological statistics, it was developed and tested thanks to a series of contracts with several French hydrological services (SCHAPI, CNR). It has then been a team project involving up to 10 people including 2 PhD students, a computer programmer, hydrologists and engineers. The main products have been a first version of the graphical interface in 2013 (BaRatinAGE v1), then a new one issued in 2016 (BaRatinAGE v2), dozens of training sessions (generally organised by Laurent Bonnifait), 2 research papers on the BaRatin method (Le Coz et al., 2014b; Mansanarez et al., 2016 and three others in preparation), and 5 research papers (Lundquist et al., 2016; Mason et al., 2016; Osorio and Reis, 2016; Zeroual et al., 2016; Sikorska and Renard, 2017) and 2 Master dissertations in Switzerland (Storz, 2016) and Brazil (Osorio, 2017) that present results obtained with the BaRatin method. Of course, the development of BaRatin has been well integrated in scientific projects (e.g. the ANR[26] FloodScale project) and is aligned with Irstea's objectives, but I am convinced that this kind of initiative cannot be successful if scientists are not allowed to freely rub shoulders with one other and decide on the direction of their research. I feel lucky that Irstea and our partners have let this possible to happen. I hope that the importance and usefulness of spontaneous, and even serendipitous research will not be forgotten in spite of increasing administrative constraints designed for commercial rather than scientific activities.

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[26] Agence nationale de la recherche (French National Agency for Research).

A major reason for hope in the advances of hydrometry and stream flux quantification is international cooperation between agencies and research groups. We are lucky enough to have active professional associations (the Groupe Doppler Hydrométrie and the new Hydrometry Section of the Société Hydrotechnique de France I am leading, the Yammer International Hydrometry Network, the North-American Association of Stream Hydrographers, the Australian Hydrographers Association, the New Zealand Hydrological Society, etc.) and a number of international working groups dealing with hydrological measurements: the WMO ProjectX, the regional sections of the WMO CHy, the International Streamflow Rating Curve Project, the USGS SurfBoard (surface velocity measurements), the IAHS MOXXI Hydrology Working Group (Measurements and Observations in the 21st Century), the EGU working group on rating curve uncertainty analysis, etc. I personally feel that the European community of hydrometry technologists could be enhanced in the near future. Standardisation committees in hydrometry (ISO TC113, CEN TC318, AFNOR X10C commission and other national committees) are also very active and interagency cooperation on joint procedures is heightening. For instance, the Water Survey of Canada and the US Geological Survey now share common procedures. In France, the various agencies recently revised their common quality assurance guide (Puechberty et al., 2017). The global community of hydrometry has increasingly shared procedures, free software (e.g. QRev, Extrap, BaRatin, Fudaa-LSPIV, Oursin, etc.), and ideas through seminars and conferences, international training, e-learning videos (e.g. by NIWA and the USGS) and streamgauging comparison events (e.g. organised by GDH, NASH, NZHS, etc.). All these efforts are very positive as they stimulate a sense of belonging to the international community of stream field hydrologists. This is made easier by new communication technologies, but also by the enthusiasm of water surveyors for their noble, useful and exciting mission.

With this *Habilitation à Diriger des Recherches* (HDR) title, I expect that my research activities will further expand through the supervision of students, the cooperation with other research groups and operational partners, and the leadership in research projects and academic communities. As an HDR of the Earth-Universe-Environment graduate school of the Grenoble-Alpes University, I will strengthen my cooperation with the academic community of Grenoble, in which my main research topics fit very well. That said, I will not neglect my cooperation with colleagues from the University of Lyon and my other academic and operational partners. My research is also well integrated in the agenda of the new RIVERLY research group that will unite my current Hydrology-Hydraulics research group and other freshwater biology and water quality research groups of Irstea Lyon-

Villeurbanne after January 2018. This new RIVERLY research group has a consistent focus on the processes and ecological status of inland waters, rivers in particular, through a multi-disciplinary approach and many experimental sites throughout the Rhône catchment and elsewhere. This looks like the perfect community for developing the research prospects I have presented in this HDR manuscript, as quantifying water discharges and fluxes of matters in river systems is crucial for assessing their processes and their ecological status.

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Quantifier les débits et les flux de matières dans les cours d'eau

Jérôme Le Coz

Résumé :

Ce mémoire propose une mise en perspective de mes travaux de recherche sur la quantification des débits et des flux de matières dans les cours d'eau et leurs incertitudes, ainsi qu'une prospective pour les 5 à 10 prochaines années. Nouvelles technologies de mesure (moins intrusives) et sciences participatives permettent des avancées importantes pour améliorer les mesures de débit, en crue notamment. Elles posent cependant de nouveaux problèmes méthodologiques. Ceci peut se généraliser aux mesures de flux de sédiments et de contaminants, avec la nécessité supplémentaire de caractériser les propriétés et les origines des particules solides. Enfin, de nouvelles méthodes d'analyse des incertitudes visent à couvrir toute la chaîne de production des données de flux, depuis les opérations de terrain jusqu'à la publication et l'utilisation des données. Bien avancée pour les séries hydrologiques (débits des cours d'eau), la démarche pourra être étendue aux flux de sédiments et de contaminants, en intégrant les incertitudes propres aux mesures du transport solide (charriage et suspension) et des teneurs en contaminants (échantillonnage et analyses au laboratoire). Une telle analyse des incertitudes ne doit pas être considérée comme un traitement fastidieux supplémentaire, ou un simple bonus pour l'utilisateur des données. Elle est au contraire indissociable des processus opérationnels de production des données et de gestion de leur qualité qu'elle permet de revisiter et d'améliorer.

Mots-clés : rivière; cours d'eau; débit; hydrométrie; flux; matières en suspension; incertitudes.

Quantifying discharges and fluxes of matters in rivers

Abstract:

This thesis offers an overview of my research on the quantification of discharges and fluxes of matters in rivers along with their uncertainties, as well as research perspectives for the next 5 to 10 years. New (less intrusive) measurement technologies and citizen sciences allow important advances in improving flow measurements, in particular for floods. However, they bring new methodological issues. This statement can be generalised to sediment and contaminant flux measurements, with the additional need to characterise the properties and origins of solid particles. Finally, new methods for analysing uncertainties are intended to cover the whole production chain of hydrological data, from field operations to the publication and use of data. The approach which is well advanced for hydrological series (streamflows) could be extended to sediment and contaminant fluxes, including the uncertainties associated with sediment transport (bedload and suspension) measurements and contaminant levels (sampling and analyses in the laboratory). Such uncertainty analysis should not be seen as a tedious additional processing, or as a simple bonus for the end-user of the data. It is, on the contrary, inseparable from the operational processes of data production and quality management which it serves to improve.

Keywords: river; discharge; hydrometry; flux; suspended particulate matter; uncertainty.