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Assessment of freshwater discharge into a coastal bay through multi-basin ensemble hydrological modelling

A. de Lavenne^{a,b,*}, C. Cudennec^a

^aUMR SAS, AGROCAMBUS OUEST, INRA, 35000 Rennes, France

^bNow at SMHI, Norrköping SE-601 76, Sweden

Abstract

Coastal basins of the Brittany peninsula (France) are hydrological hot spots. A high level of nutrient pollution affects many of these basins and causes algal blooms in several coastal bays; nine have been a specific focus of the European Commission since 2007. The flux of each contributing basin flowing into these bays must be examined to assess the conditions and explore mitigation options. However, this task encounters a large lack of data since most of the basins are ungauged. In this context, this study developed a method which facilitates transposition of hydrographs from gauged basins to ungauged neighbouring basins of interest. Inverting a simple geomorphology-based transfer function of the gauged basin which describes travel time through channels enables the net rainfall time-series to be estimated from the discharge time-series of donor basins. To estimate the net rainfall of a given ungauged catchment, several net rainfall time series of gauged catchments are averaged. The resulting net rainfall is then transposed onto the ungauged target basin and convoluted by its own transfer function to estimate the hydrograph. This allows the transposition of as many hydrographs as there are different donor basins. This ensemble prediction enables the proportion of prediction uncertainty that is due to the heterogeneity in hydrological behaviour to be estimated. Moreover, the time-series of the donor basins are combined to estimate the ungauged net rainfall time-series. This provides a discharge prediction which values all available measurements. The method was applied to the highly controversial Saint Brieuc Bay, where it was possible to quantify the contribution of each coastal basin, even those influenced by dams, and ultimately the entire volume of fresh water entering the bay at an hourly time step. This work opens perspectives to additionally refine estimation of the associated nutrient fluxes.

Keywords: Coastal bay, Ensemble prediction, Geomorphology, Streamflow, Transposition, Prediction in ungauged basins

1. Introduction

The increase in nutrient delivery into the ocean is an important issue that occurs in many French coastal basins in Brittany. This pollution, essentially driven by agriculture (Fovet *et al.*, 2015), is responsible for green tides caused by coastal eutrophication and algal blooms (Ménésqueu and Piriou, 1995; Smetacek and Zingone, 2013; Le Luherne *et al.*, 2017; Ménésqueu and Lacroix, 2018; Le Moal *et al.*, 2019), and the issue prompts many studies and discussions with stakeholders involved in managing the bays and upstream activities (Diaz *et al.*, 2013; Moreau *et al.*, 2013; Narcy *et al.*, 2013; Gascuel *et al.*, 2015; Desmit *et al.*, 2018). This particular ecohydrological situation is an example of actual crises resulting from changes and intensification of hydrological and anthropogenic pressures (Brondizio *et al.*, 2016; Ceola *et al.*, 2016; McMillan *et al.*, 2016; Di Baldassarre *et al.*, 2018). Since 2007, the

European Commission has identified nine coastal bays in Brittany that have significant nutrient fluxes. Assessing these nutrient fluxes requires knowledge about the hydrological behaviour of these catchments, especially essential data about discharge at their outlets. To understand all fluxes flowing into one bay, the discharge must be estimated at the mouths of the rivers (*Ménesguen et al.*, 2018; *Ménesguen and Lacroix*, 2018). However, most coastal basins are poorly gauged at these points or not gauged at all because of network density and of tidal influence.

Assessing water discharges at every coastal river mouths and so along the coastal interface of a bay is a particular challenge (*Cudennec et al.*, 2015; *Ménesguen and Lacroix*, 2018) in the frame of the PUB (Prediction in Ungauged Basins) perspective (*Blöschl et al.*, 2013; *Hrachowitz et al.*, 2013), with a particular topological target made of the set of outlets along a line, instead of the single outlet usual approach. Beyond the bay approach identified here, the challenge is generic and can be identified for any water body receiving freshwater and associated fluxes from a population of convergent basins such as an estuary, reservoir, lake, or closed sea (*Ludwig et al.*, 2009, 2010; *Dürr et al.*, 2011; *Aouissi et al.*, 2015; *Yalçın et al.*, 2017; *Ménesguen and Lacroix*, 2018); and in contrast to populations of divergent basins (*Cudennec and Fouad*, 2006).

We developed a method which facilitates the transposition of hydrographs from one or several gauged basins to an ungauged basin. The approach uses geomorphology-based modelling, which can be performed easily for any gauged or ungauged basin, to describe water transfer through the river network. Inversion of this transfer function then allows the net rainfall time-series of the gauged basin to be calculated from the discharge measured. This net rainfall is then transposed onto the ungauged basin, thanks to similarity, regardless of its scale, to estimate the hydrograph.

de Lavenne et al. (2013) previously demonstrated the potential of this method in Brittany, which was then generalized over a larger data set over the Loire River basins (*de Lavenne et al.*, 2016), using gauged basins and leave-one-out validation to imitate ungauged situations. We extend this method by following ensemble modelling approaches (See for instance, *Thirel et al.*, 2008; *Cloke and Pappenberger*, 2009). This combination of multiple sources of information facilitates its application to truly ungauged sites by improving the robustness of simulations.

This study aims to estimate the discharge of each coastal basin and so ultimately the whole flux of freshwater into Saint Briec Bay, Brittany, one of the bays affected by a high frequency of green tides (*CEVA*, 2014; *Le Luherne et al.*, 2017) with implications for ecology, aquaculture, public health, tourism, upstream-downstream governance and conflict management, design of agricultural and territorial transitions.

2. Materials and Methods

2.1. Catchments studied and data

Many coastal basins contribute to the outflow of Saint Briec Bay (figure 1). The four largest basins are: the Ic River (85 km² at the ungauged mouth U20; 79 km² at gauged point G7), the Gouët River (250 km² at the ungauged mouth U13; 136, 27 and 197c km² at gauged points G4, G5 and G6), the Gouessant River (425 km² at the ungauged mouth U7; 244 km² and 139 km² at gauged points G1 and G2) and the Urne River (59 km² at the ungauged mouth U11; 43 km² at gauged point G3).

These basins are located on Armorican bedrock with a high drainage density, few aquifers and a rapid response to rainfall. The western portion (Gouët, Ic) is topographically defined by deeper valleys than those in the eastern

55 portion (Gouessant). Two dams are impacting the hydrology of those rivers: at the station G6 on the Gouët River
 56 (7 Mm³ for energy production and drinking water supply) and at the river mouth U7 of the Gouessant river (1
 57 Mm³ for energy production).

58 This study aimed to estimate the volume of freshwater and the relative contribution of each coastal basin
 59 flowing into Saint Brieuc Bay. Discharge was estimated at the mouth of each river, where no monitoring station is
 60 available. In this manner, the study aimed to estimate the discharge for 21 truly ungauged basins. This study also
 61 took advantage of seven monitoring stations located upstream from the four main basins in the bay. Streamflow
 62 discharge measurements were extracted from the French Banque HYDRO database (www.hydro.eaufrance.fr) at a
 63 variable time step and converted into a one-hour time step. Simulations were performed at an hourly time step.

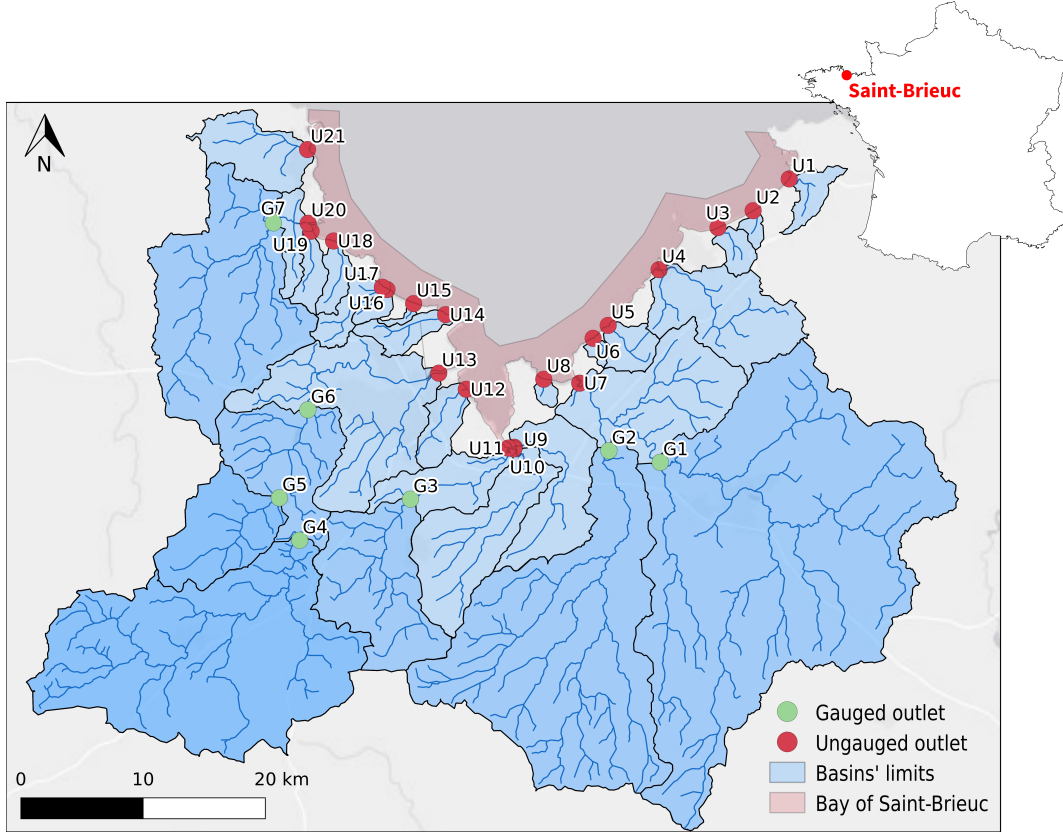


Figure 1: Saint Brieuc Bay with gauged and ungauged basin outlets.

64 2.2. Modelling framework

65 2.2.1. A geomorphology-based hydrological model

66 Some physically-based modellings have been performed for few of the coastal basins in Brittany, especially to
 67 explore options for mitigation of water quality issues through farming transitions (*Moreau et al.*, 2013; *Durand*
 68 *et al.*, 2014; *Gascuel et al.*, 2015). Yet these approaches are much demanding in terms of data and hence cannot be
 69 regionalised to be used in ungauged basins. We here propose the transposition of measured discharge series, thanks
 70 to a geomorphology-based modelling approach, as an alternative approach to the transposition of a rainfall-runoff
 71 model itself and its parameterisation.

Following pioneer intuitions (*Surkan, 1969*), the geomorphology-based unit hydrograph framework has been developed through two major approaches (*Cudennec, 2007; Rigon et al., 2016*): the one based on the hierarchical topology of the branched out river network (e.g. *Rodríguez-Iturbe and Valdés, 1979; Cudennec et al., 2004*) and the other one based on easily observable geomorphometric width and area functions (*Kirkby, 1976; Snell and Sivapalan, 1994; Robinson et al., 1995*). This opens modelling opportunities which exploit an explicit structure, low calibration requirements, and flexibility. The hydrodynamic and geomorphological dispersions along the river network have been assessed and quantified in theory and in well known basins (*Rinaldo et al., 1991*), but the assumption of a simpler transfer function proved to be acceptable when considering only the travel time in the river network in small to meso-scale basins (*Blöschl and Sivapalan, 1995; Robinson et al., 1995; Moussa, 1997*). Moreover, it allows to limit the number of parameters that needs to be estimated when few data are available. When the transfer function TF is limited to describing water dynamics across the river network, the net rainfall is defined as the hillslope response, i.e. the water flowing through the hillslope-river interface (*Wang et al., 1981; Gupta and Mesa, 1988; Robinson and Sivapalan, 1996; Formetta et al., 2011; Boudhraâ et al., 2018*), hence implying that the production function encompasses all the hillslope processes.

This study focused only on the TF through the river network. It was constructed from a geomorphometric description of the flow paths (*Cudennec et al., 2004; Cudennec, 2007*) which values the strong hydrogeomorphological structure-function relationship (*Cudennec and de Lavenne, 2015; Rigon et al., 2016*). For each pixel of the digital elevation model (DEM), the flow path to the outlet is performed and the hydraulic length L corresponds to the length of the channelized part of the path within the river network only. This was estimated using GRASS 6.4 supplemented with the toolkit of *Jasiewicz and Metz (2011)*. The DEM had a 50 m resolution but was resampled at 25 m using bicubic sampling to increase the number of pixels within small basins. The D8 algorithm (e.g., *O'Callaghan and Mark, 1984*) was used to model drainage, and a predefined river network provided by the *Sandre/CARTHAGE* database was burned into the DEM using an algorithm based on the inverse distance to the network (*Nagel et al., 2011*). This procedure calculates the probability density function of the hydraulic length $pdf(L)$ for each gauged and ungauged basin (*Aouissi et al., 2013*).

The pdf of water travel time t through the river network ($pdf(t)$) can then be derived from the $pdf(L)$ by applying a mean channel flow velocity and assuming a linear transfer function through the river network (*Naden, 1992; Beven and Wood, 1993; Blöschl and Sivapalan, 1995; Robinson et al., 1995; Yang et al., 2002; Giannoni et al., 2003*). The mean channel flow velocity was estimated from a sample of runoff events detected from 1990-2010 (*de Lavenne, 2013*). For gauged basins and each runoff event, channel flow velocity was calculated as follows:

$$v_i = \frac{\bar{L}}{t_i} \quad (1)$$

where \bar{L} [m] is the mean hydraulic length of the basin and t_i [s] is the rise time of the runoff event i (time difference between the peak flow and the beginning of the rise). For each basin, the median V [$\text{m}\cdot\text{s}^{-1}$] of these velocities v_i [$\text{m}\cdot\text{s}^{-1}$] was then calculated to provide a unique steady velocity.

Because this estimate of velocity is based on rise time, it relies on runoff measurements and is consequently not compatible with ungauged basins. For this reason, estimating the velocity of ungauged basins took advantage of the relation (Eq. 2) between velocity within the network and hydraulic length defined in Brittany (using 85

catchments) by *de Lavenne* (2013) as:

$$V = 8.6 \cdot 10^{-4} \cdot \bar{L}^{0.61} \quad (2)$$

Figure 2 demonstrates that this regional regression fits relatively well with the studied catchments which represent a sub-region. The mean average error over the gauged catchments is $0.03 \text{ m}\cdot\text{s}^{-1}$, making explicit the expected performance at ungauged locations where the regression is also applied (section 2.2.2).

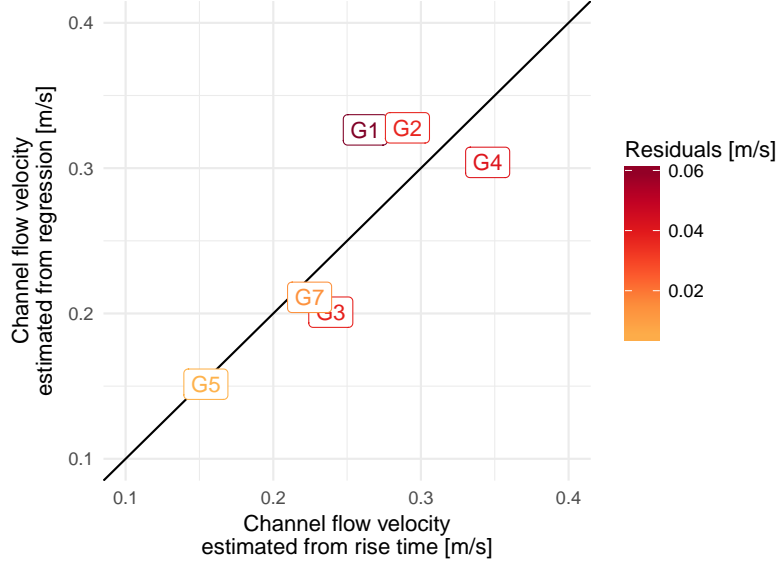


Figure 2: Evaluation of the performance of the regression (Eq. 2) to estimate channel flow velocity for the different gauged catchment (G1 to G7, G6 is excluded because of the influence of the dam limiting rise time estimation).

The unit hydrograph assessed $pdf(t) = TF(t)$ was then used to estimate the discharge at the outlet $Q \text{ [m}^3\cdot\text{s}^{-1}\text{]}$ (Step 1, Fig. 3) with the following convolution:

$$Q(t) = S \cdot R_n(t) * TF(t) \quad (3)$$

where $t \text{ [s]}$ is the time, $S \text{ [m}^2\text{]}$ is the basin's surface area and $R_n \text{ [m]}$ is the net rainfall.

2.2.2. Principle of deconvolution and hydrograph transposition

Streamflow in ungauged basins is estimated by transposing net rainfall R_n from a gauged onto an ungauged basin. In other words, considering pairs of nested and neighbouring basins, the net rainfall of the gauged (donor) basin is used to represent that of the ungauged (target) basin. Net rainfall is defined as the depth of runoff provided by a basin's hillslope into its river network. This time-series thus has the advantage of being independent of the size of the basin. In this way, assessing the net rainfall time-series solves the scaling issue underlying the transposition of hydrographs.

Net rainfall of the gauged basin is estimated by deconvoluting the hydrograph measured at its outlet (*Cudennec*, 2000; *Boudhraâ et al.*, 2018). This deconvolution is performed by inverting the gauged basin's geomorphology-based transfer function (Step 2, Fig. 3), which enables the net rainfall time-series to be estimated from the discharge time-series. Net rainfall is then transposed onto the target basin, valuing hydrological similarity, where it can

126 be reconvoluted with its own transfer function to predict the hydrograph (Step 3, Fig. 3). By using only a
 127 basin's transfer function, production functions do not need to be estimated, thereby avoiding the development of
 128 heterogeneous and highly non-linear functions.

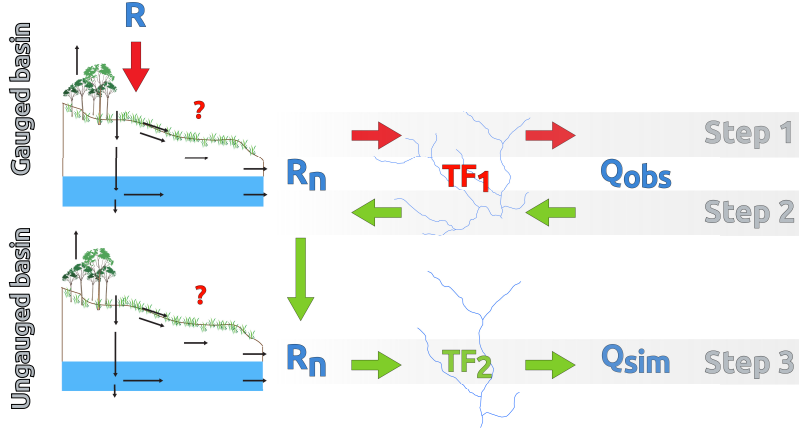


Figure 3: Principle of hydrograph transposition (from *de Lavenne and Cudennec (2015)*).

129 Deconvolution aims to determine the net rainfall time-series R_n which best reconstitutes the observed discharge
 130 time-series Q_{obs} according to the model TF provided by the equation 3. It is an inverse problem (*Tarantola and*
 131 *Valette, 1982; Menke, 1989*) which consists of maximising the joint probability density of errors on input data and
 132 on modelling outcomes, i.e. minimising the following equation 4:

$$(Q - Q_{obs})^T \cdot (C_Q^{obs})^{-1} \cdot (Q - Q_{obs}) + (R_n - R_n^{ap})^T \cdot (C_{Rn}^{ap})^{-1} \cdot (R_n - R_n^{ap}) \quad (4)$$

133 where R_n^{ap} is initialising *a priori* information about R_n ; C_{Rn}^{ap} and C_Q^{obs} are covariance matrices for vectors R_n^{ap}
 134 and Q_{obs} , respectively; and superscript T is the matrix transpose. R_n^{ap} is estimated from specific discharge of Q_{obs}
 135 delayed by its time of rise.

136 Based on previous studies (*Boudhraâ et al., 2006, 2009*) and according to the inverse problems theory (*Tarantola*
 137 *and Valette, 1982; Menke, 1989*), a maximum likelihood solution can be obtained as follows:

$$R_n = R_n^{ap} + C_{Rn}^{ap} \cdot TF^T \cdot (TF \cdot C_{Rn}^{ap} \cdot TF^T + C_Q^{obs})^{-1} \cdot (Q_{obs} - TF \cdot R_n^{ap}) \quad (5)$$

138 Covariance matrices need six parameters to be estimated: Ad , Ap , Bd , Bp , Dd , Tp . These parameters quantify
 139 the errors related to the Q_{obs} and R_n^{ap} , which are assumed to be 0-centred Gauss-distributed (*Cudennec (2000)* and
 140 *Boudhraa et al. 2018*). These parameters were fixed manually (Tab. 1) based on the results of *de Lavenne (2013)*.

Ad	Ap	Bd	Bp	Dd	Tp
0.01	0.9	0.01	0.001	1	20

Table 1: Parameter values used to inverse the transfer function of each basin of Saint Brieuc Bay.

141 2.2.3. Transposition strategy

142 The choice of donor basin for a given ungauged basin is an essential aspect of the approach (*de Lavenne et al.*,
143 2016; *Ecrepont et al.*, 2019). *McIntyre et al.* (2005) used models of the 10 basins most similar to the ungauged
144 basin to perform ensemble prediction. *Randrianasolo et al.* (2011) also used parameter sets obtained from different
145 gauged basins to perform ensemble prediction of ungauged basins and to demonstrate that neighbouring basins
146 are relevant donors. Following this idea, and in contrast to the work of *de Lavenne and Cudennec* (2015) and
147 *Ecrepont et al.* (2019) in which only one donor basin was chosen to estimate net rainfall of an ungauged basin, we
148 combined several donor basins to estimate the net rainfall of one ungauged basin. This approach benefits from net
149 rainfall's independence of scale, which allows the net rainfall time-series of several donor basins to be compared
150 and combined. We estimated the net rainfall time-series of one ungauged basin by averaging the rainfall time-series
151 obtained by inversion from the donor basins. In this way, according to the configuration of monitoring stations
152 around the ungauged basin, the difficulty in choosing one single donor basin is solved by taking advantage of all
153 available stations that are relevant for the transposition.

154 For a given target basin, one or several donor basins (Tab. 2) are chosen with the following rules: i) priority is
155 given to stations upstream of the target basin instead of neighbouring stations; ii) when several upstream stations
156 are available, net rainfall of the target basin is estimated by averaging net rainfall of the donor basins; iii) when
157 no upstream stations are available, the closest stations according to the centroid distance are chosen as the donor
158 basins; and iv) when streamflow is influenced by a dam located upstream and outflow measures are available, the
159 only donor basin is the dam itself.

	Donor basin ID numbers						
	G1	G2	G3	G4	G6	G5	G7
U1	x						
U2	x						
U3	x						
U4	x						
U5	x	x					
U6	x	x					
U7	x	x					
U8	x	x	x				
U9		x	x				
U10		x	x				
U11			x				
U12			x	x		x	
U13					x		
U14						x	x
U15						x	x
U16						x	x
U17						x	x
U18							x
U19							x
U20							x
U21							x

Table 2: Transpositions performed to model the total volume of fresh water flowing into Saint Brieuc Bay.

3. Results and Discussion

3.1. Combining contributions of several basins

As previously explained, several donor basins can be combined to estimate the streamflow at one ungauged point. This allows the relative uncertainty in predictions of the simulations to be estimated by investigating multiple donor basins and checking the degree of agreement between the resulting simulations. In this way, heterogeneity in hydrological responses can be assessed, and low heterogeneity leads to higher confidence in the hydrograph's transpositions.

The addressed uncertainty is not the one of the model itself; but the one related to the underlying simplifying assumption: the similarity of net rainfall production between the donor and the target basins. Through this graphical visualisation it is then possible to appreciate how much this assumption could be accepted and how well the approach is dealing with it (by combining several donors).

For example, streamflow at point U7 is influenced by two distinct tributary flows (Figure 1): the Gouessant (point G1) and Évron Rivers (point G2). The need to consider several donor basins appears clear in this configuration of two contributing basins.

When considering donor basins G1 and G2 separately, simulation results show that transpositions onto basin U7 lead to similar streamflow predictions (Fig. 4). This illustrates the high hydrological similarity of these two basins.

176 The simulation combining both donor basins can thus be given a strong degree of confidence, as the hydrological
 177 behaviour does not appear to vary greatly in space.

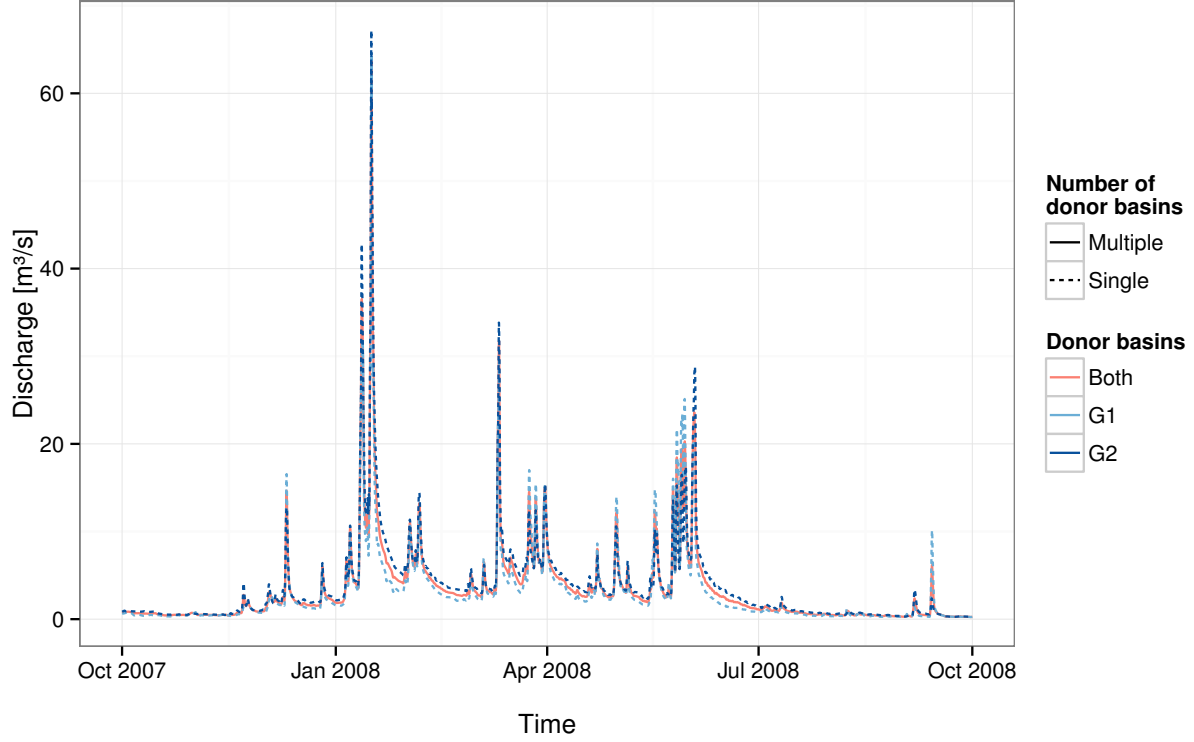


Figure 4: Streamflow simulation at the river confluence (point U7) of basin G1 (Gouessant River) and basin G2 (Évron River) for the hydrological year 2007-2008.

178 3.2. Combining several neighbouring basins

179 In contrast to the previous example which combined two tributary flows, another example (Fig. 5) uses two
 180 neighbouring basins as donors. Streamflow at point U10 is estimated from basin G2 (Évron River) and basin
 181 G3 (Urne River). Both donor basins tended to give similar results when used to simulate the ungauged basin.
 182 However, higher uncertainty is observed during the second half of the hydrologic year (mainly during the spring).
 183 This illustrates that the basins' similarity also varies over time, and spring often displays greater heterogeneity in
 184 hydrological response, as previously demonstrated by several studies (*Patil and Stieglitz*, 2011, 2012; *Loritz et al.*,
 185 2018; *Ecrepont et al.*, 2019).

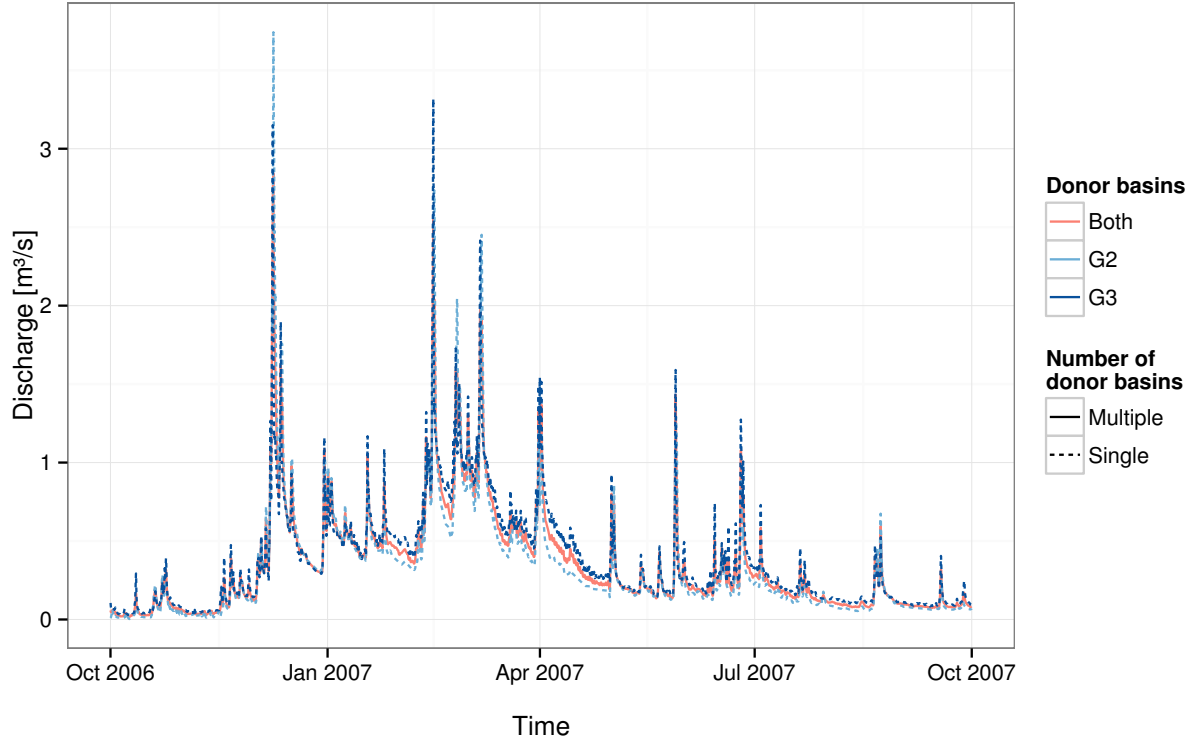


Figure 5: Streamflow simulation at ungauged point U10 using neighbouring donor basins G2 (Évron River) and G3 (Urne River) for the hydrological year 2006-2007.

3.3. Influence of a dam

The method allows to manage the influence of a dam located upstream of the ungauged basin. Because the approach is based on runoff measurements, the dam's outflow can be used directly and transposed onto a downstream portion. Consequently, the influence of the dam is integrated, unlike in most rainfall-runoff modelling approaches.

The dam in Saint Barthélémy, located in the Gouët River (point G6), contains seven million cubic meters of water which produce hydroelectric power and supply drinking water. Hydrograph transposition onto the mouth of the Gouët River (point U13) is performed using outflow of the dam (point G6), but for illustrative purpose, Figure 6 also describes the transposition that is using the two upstream gauged stations (points G4 and G5) not influenced by the dam. Runoff production is slightly higher in basin G4 than in basin G5 during low-flow periods, while high-flow periods have more similar hydrological behaviour (Figure 6).

The averaged simulation, with the added range of uncertainty given by the two donor basins, can then be compared to the dam's (point G6) outflow transposition (Figure 6). This verifies that extreme streamflow variations due to opening the dam's gates can still be observed at the mouth of the Gouët River (point U13). Although the dam reduces daily streamflow variations, dam outflow generally follows the natural discharge of the river at an annual scale. These results demonstrate the importance and benefits of the approach when considering the magnitude of water management in the stream.

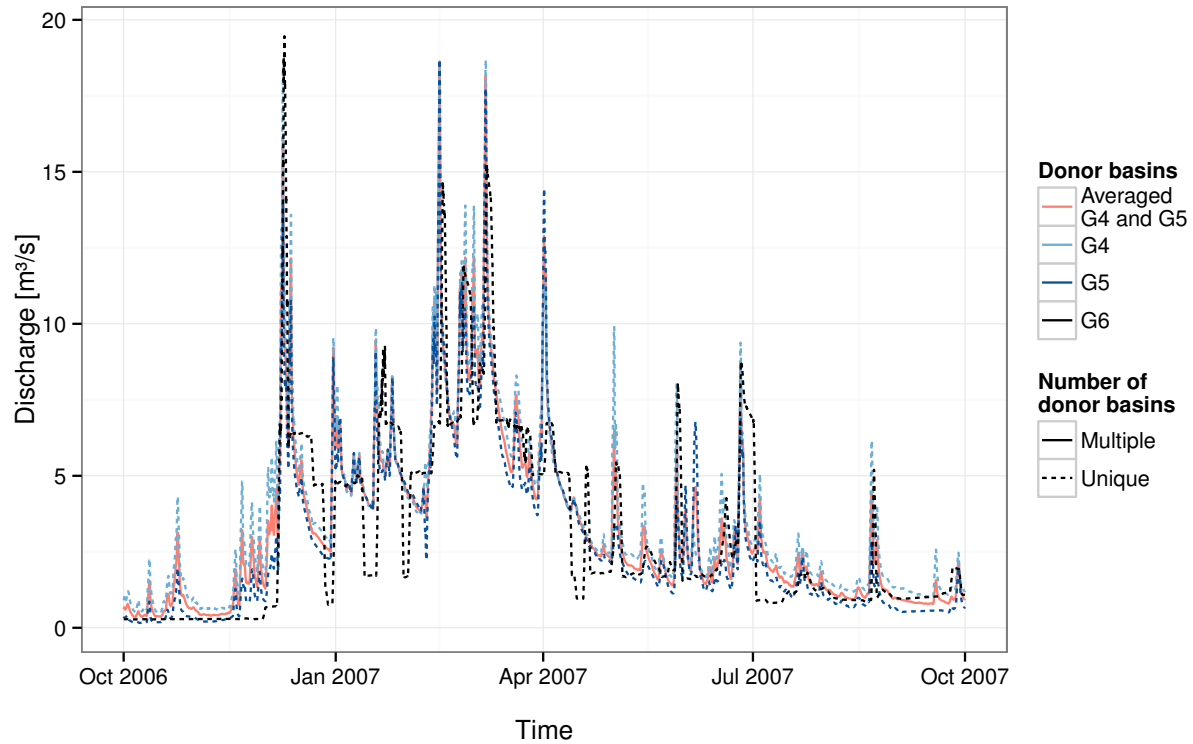


Figure 6: Predicted streamflow at point U13 for the hydrological year 2006-2007. Transposition using outflow of the dam in Saint Barthélémy (Gouët River, point G6) is compared to that using upstream basins G4 (Gouët River) and G5 (Maudouve River), not influenced by the dam.

3.4. Freshwater flowing into the bay

The contribution of 21 ungauged basins to the total fresh water flow into Saint Brieuc Bay was assessed by summing their simulated hydrographs. It allows to estimate a discharge that is actually not measured. As previously illustrated, several donor basins can be used to estimate the hydrograph of one ungauged basin. This allows assessment of the relative uncertainty caused by the variability in hydrological behaviour of donor basins surrounding the ungauged one. At the bay scale, this uncertainty can also be plotted using an envelope of minimum and maximum values of predicted discharge among the simulations that used a single donor (Fig. 7).

The envelope appears relatively narrow, highlighting low variability in hydrological behaviour within the region. This provides a relatively high degree of confidence in the prediction. However, this uncertainty may not be highly robust as it depends on the availability and characteristics of the donor basins. Consequently, if hydrological behaviours and climatic conditions of ungauged basins differ from those of the donors, the flow range may not be accurately estimated.

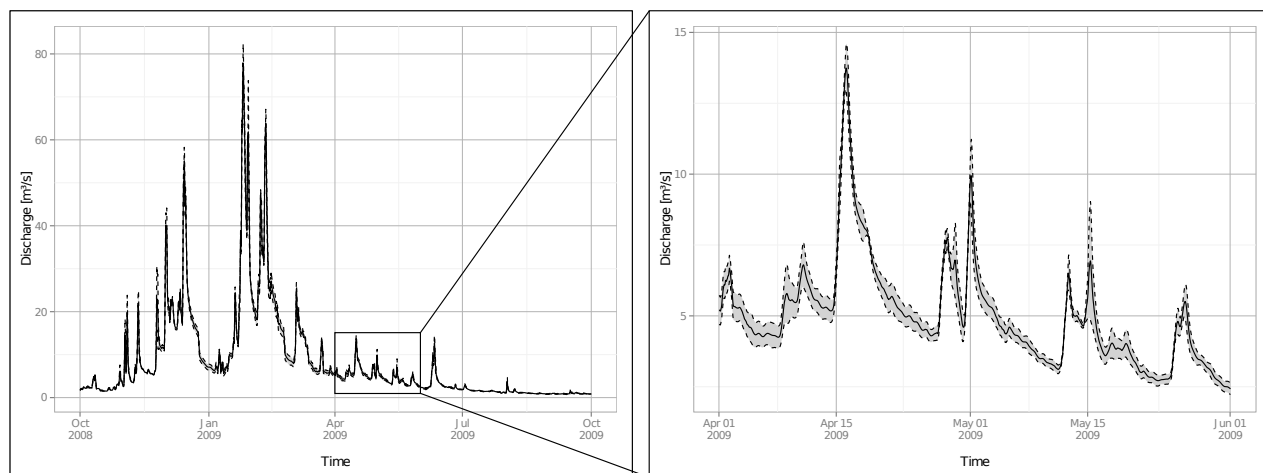


Figure 7: Predicted total fresh water flowing into Saint Briec Bay at an hourly time step for the hydrological year 2008-2009. The solid line is made by averaging the net rainfall of several donor basins, whereas grey envelope is delimited by the single donor transpositions (minimum and maximum) in order to illustrate the variability of the hydrological behaviour of the donor basins.

In addition to total bay outflow, this study explored the absolute and relative contributions of each basin (Fig. 8). The three main streamflow contributions clearly appear to come from basins U7 (Gouessant River), U13 (Gouët River) and U20 (Ic River), which are the three largest basins. Their relative contributions, however, vary throughout the year. For example, at the beginning of the 2008-2009 hydrological year, U13 was the main contributor to low flow in October 2008, while U7 was the main contributor during storm events in November 2008. These results, available at an hourly time step from 1990-2010, could serve as useful information for understanding and solving issues related to the bay.

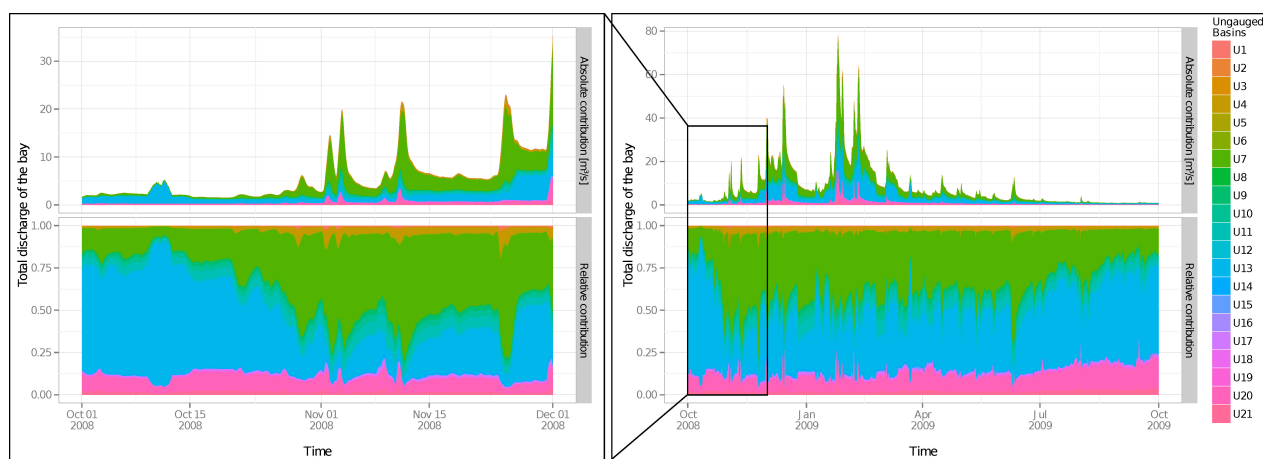


Figure 8: Contributions of ungauged basins to fresh water flowing into Saint Briec Bay at an hourly time step for the hydrological year 2008-2009.

4. Conclusion

This study offers a method that makes it possible to estimate the total amount of freshwater entering a coastal bay. It uses measured hydrographs from upstream monitoring stations and transposes them onto downstream river mouths. The modelling focuses on water transfer through the river network and is based on geomorphometric descriptions that are easily accessible for any basin. In the gauged basin, inversion of this transfer function allows its net rainfall time-series to be estimated from its measured discharge. This net rainfall is finally transposed onto the ungauged basin to estimate the latter's hydrograph.

The method was applied to the real context of the controversial Saint Brieuc Bay, which experiences algal blooms caused by nutrient pollution. Knowledge about the discharge of basins into the bay is essential to understand the issue and find solutions. This method can support assessing the main nutrient load contributors into the bay, but the limitation is then observations and estimations of nutrient concentration.

In opposition to a large part of the literature that addresses prediction in ungauged basin through the regionalisation of rainfall-runoff models, the proposed approach is essentially based on the transposition of discharge measurements. Only one parameter needs to be estimated, the streamflow velocity, in order to describe the transfer dynamic across the river network of every catchment. The rest of the hydrological behaviour is embedded in the discharge measurement which, despite the lack of explicit description (and particularly about the net rainfall production as an outcome of hillslope hydrology), greatly reduces the complexity of the modelling and the associated potential errors.

In this study, the approach benefits from seven monitoring stations that enable the discharge of 21 ungauged basins to be estimated. In this manner, each basin's contribution to the bay's total freshwater inflow, and temporal variability at an hourly time step can be analysed. Because the approach is based on discharge measurements, and one of the monitoring stations is a dam, the approach appears to effectively address the dam's influence, unlike the classic rainfall-runoff modelling approach.

By combining several donor basins, the approach can estimate the uncertainty in these predictions. The donor basins' flow ranges allow estimating the degree to which predictions based on them agree. This is interpreted as the variability in the hydrological behaviour of the basins surrounding the ungauged one. Low variability provides a high degree of confidence that the ungauged basin is similar. Even though uncertainty is not assessed in a fully robust manner, because of the structural lack of data associated to the considered PUB approach, it partially solves the difficult choice of donor basin by taking advantage of all available information. Finally, it enables better graphical evaluation of simulations.

One challenge of the approach remains on combining the time series of different donor basins in order to provide a robust average final simulation. For this study the donors have been combined on a case-by-case basis using simple average of the net rainfall time series of donor basins to estimate the one at the target ungauged location. However, when applied to a larger dataset, the approach could benefit from a quantification of the hydrological similarity between the donor and the target basins (e.g. spatial proximity, physiographic and climatic descriptor). A quantification of the similarity could then be used to vary the weight of each donor time series according to the similarity with the target catchment. The challenge would then be on the quality of this assessment, in order to be

able to improve the simulation performance.

Research data

Discharge data are freely available online through the French Banque HYDRO database (www.hydro.eaufrance.fr). The R code (*R Core Team*, 2017) to perform the inversion is available through requests to the corresponding author.

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