Prediction of streamflow from the set of basins flowing into a coastal bay

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Abstract Many coastal basins of the Brittany peninsula (France) display a high level of nitrate pollution, nine of them highlighted by the European Commission since 2007, as causing algal blooms in several coastal bays. To precisely diagnose and solve this issue the fluxes of every contributing basin have to be considered. However, this faces a strong data-scarce situation as most of the basins are ungauged. In this context, we propose to transpose hydrological information from one gauged basin to neighbouring points of interest. The methodology uses a simple geomorphology-based transfer function on the gauged basin, which allows assessment of the net rainfall time series through the de-convolution of the gauged discharge series. This net rainfall is then transposed and convoluted on the ungauged basin using its own transfer function in order to estimate discharge. This approach enables the quantification of the whole volume of freshwater entering the controversial Saint-Brieuc Bay.

Key words ungauged basin; model; geomorphology-based model; regionalisation; inversion; transposition

INTRODUCTION

French coastal basins of Brittany are hydrological hot spots. A high level of nitrate pollution is responsible for green tide caused by algal blooms in several coastal bays. Nine coastal basins have been pointed out by the European Commission since 2007. The Saint-Brieuc Bay, presented in this paper, is one example. To precisely diagnose and solve this issue, the fluxes of every contributing basin have to be considered. However, most of the concerned basins are either poorly gauged or not gauged at the point of interest, which is, for such study, the river mouth. In this context, the proposed solution is to transpose hydrological measures from gauged basins to ungauged basins. Based on geomorphology-based modelling, this objective is achieved by estimating the net rainfall of the gauged basins. Benefiting from the scale independency of this variable, the latter is transposed to an ungauged basin in order to simulate the hydrograph therein. Taking advantage of the available monitoring stations in the studied area, this work aims at estimating the total fresh water flowing into the bay and the relative contribution of each coastal basin.

MATERIALS AND METHODS

Studied catchments and data

Four main basins flow into the Saint-Brieuc Bay (Fig. 1): Ic (point 1282, 79 km^2), Goët (point 1279, 194 km^2), Gouessant (point 1274, 242 km^2) and Urne (point 1276, 40 km^2) rivers. Many other small basins also contribute to the inflow to the bay. All those basins are located on the Armorican bedrock with a high drainage density, few aquifers and a fast response to rainfall. The west part (Gouët, Ic) is topographically characterised by deeper valleys compared to the east part (Gouessant).

This study focused on streamflow estimation of the freshwater flowing into the bay. The rivers are not gauged at their mouth point but at some upstream sites. For this reason, the study faces the issue of streamflow prediction of ungauged basins (Hrachowitz *et al.* 2013). The methodology is based on hydrograph transposition from one gauged basin to an ungauged basin. Those streamflow estimations aim to serve the quantification of the hydrogeochemistry of the bay, as most of its basins are subject to green tide caused by algal bloom.

In order to estimate the bay's freshwater inflow, every river flowing into the bay is taken into account. Discharge is estimated at the rivers' mouth point, which represents 21 truly ungauged points of interest. Streamflow at those points will be estimated using five monitoring stations of
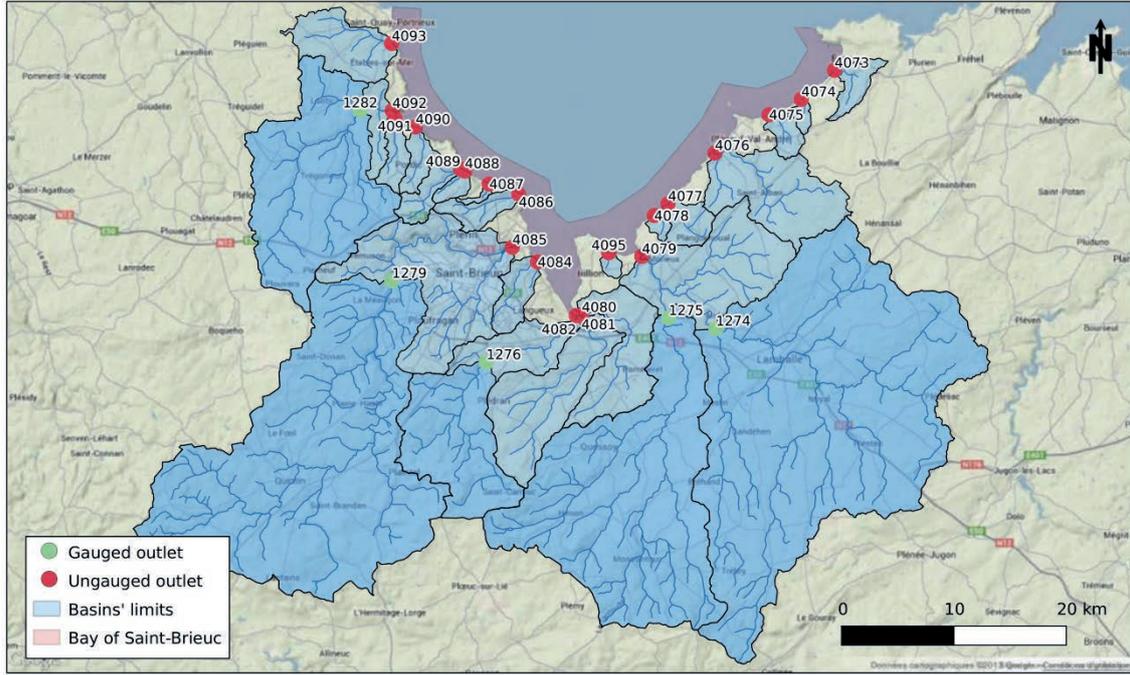
Fig. 1 Saint-Brieuc Bay with gauged and ungauged basins' outlets named by their identifying number (ID). Background map 2013 ©Google.

the French Banque HYDRO database (www.hydro.eaufrance.fr). Runoff measurements are extracted at a variable time step and converted to a one hour time step. Simulations are performed at one hour time step.

Modelling framework

The modelling approach is focused on a geomorphometry-based transfer function across the network, which is distinguished from processes over the hillslopes (Robinson *et al.* 1995). This transfer function *TF* is built from morphometric analysis of the river network. Using GRASS 6.4 completed by the toolkit of Jasiewicz and Metz (2011), the flow path length inside the network *L* (so-called hydraulic length; Cudennec *et al.* 2004, Aouissi *et al.* 2013) is calculated throughout the basin from a digital elevation model (DEM). The DEM is at 50 m resolution, but is resampled at 25 m using bicubic sampling to increase the number of pixels inside small basins. The drainage modelling use the D8 algorithm and is forced toward the predefined river network given by the Sandre/BD CARTHAGE database. This is done using an algorithm based on the inverse distance to the network (Nagel *et al.* 2011). This allows the probability density function of hydraulic length *pdf*(*L*) to be built for every basin (gauged or ungauged).

Assuming a linear transfer function through the river network (Beven and Wood 1993, Blöschl and Sivapalan 1995, Robinson *et al.* 1995, Giannoni *et al.* 2003, Nasri *et al.* 2004, Rodriguez *et al.* 2005, Cudennec 2007), the mean channel flow velocity is then needed to estimate the pdf of the water travel time *t* through the river network (*pdf*(*t*)). Mean channel flow velocity was estimated from a sample of runoff events detected between 1990 and 2010. For gauged basins and each runoff event, channel flow velocity is calculated from the following equation:

$$v_i = \frac{\overline{L}}{t_i} \tag{1}$$

where $\overline{L}$ [m] is the mean hydraulic length of the basin and t_i [s] the rise time of the runoff event *i*. The median of those velocities v_i [m·s^{-1}] for each basin is then calculated to provide a constant velocity over time and space.

This velocity estimation requires runoff measures and is therefore not suitable for ungauged basins. As a consequence velocity estimation of ungauged basins takes advantage of a relation between velocity inside the network and hydraulic length defined by de Lavenne (2013) over the Brittany region:

$$V = 8.5947 \cdot 10^{-4} \cdot \overline{L}^{\,0.6146} \tag{2}$$

The assessed unit hydrograph $pdf(t) = TF(t)$ is then used to estimate the discharge at the outlet Q [m^3·s^{-1}] (step 1, Fig. 2). This calculation is made by the following convolution:

$$Q(t) = S \cdot R_n(t) \times TF(t) \tag{3}$$

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

Streamflow of ungauged basins is estimated by transposing net rainfall R_n from a gauged to an ungauged basin. Net rainfall is defined as the depth of runoff provided by a basin's hillslope to its river network. Considering pairs of nested and neighbouring basins, the estimated net rainfall of one is used to represent the other. The time-series of discharge of the donor basin is de-convoluted by inverting its geomorphology-based transfer function to estimate the time-series of net rainfall (step 2, Fig. 2). The latter is then transposed to the receiver basin, where it can be re-convoluted with its own transfer function to predict the hydrograph therein (step 3, Fig. 2). By using only a basin's transfer function, production functions do not need to be estimated, thereby avoiding development of heterogeneous and highly nonlinear functions.
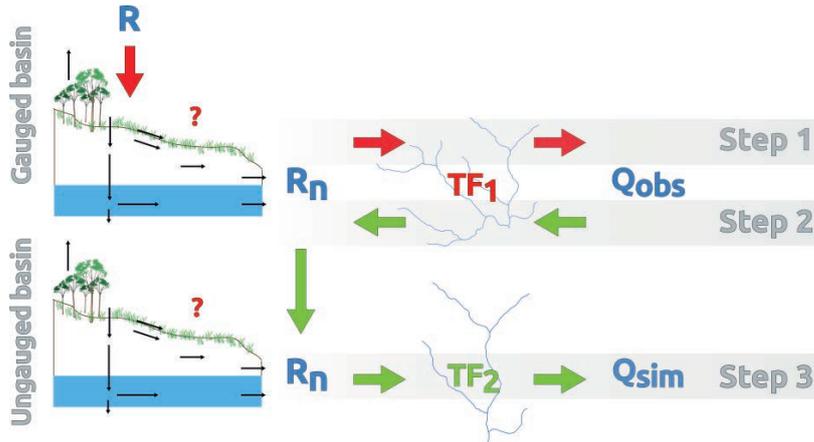

Fig. 2 Principle of hydrograph transposition (derived from de Lavenne *et al.* 2014).

De-convolution aims to determine the net rainfall vector series R_n that best reconstitutes the observed outflow vector series Q_{obs} according to the model given by equation (3). It is an inverse problem (Tarantola and Valette 1982, Menke 1989) that consists of minimizing the following:

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

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

Based on previous studies (Boudhraâ 2007, Boudhraâ *et al.* 2006, 2009), and according to the inverse problems theory (Tarantola and Valette 1982, Menke 1989), a maximum likelihood solution can be obtained as follows:

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

Performing this de-convolution is based on:

(a) assessing errors related to the Q_{obs} and R_n^{ap} data that need to be parameterised, assuming that errors are 0-centred Gauss-distributed, and

(b) initialising via *a priori* assessment of the R_n^{ap} parameters sought.

Covariance matrices need six different parameters to be estimated: Ad, Ap, Bd, Bp, Dd, Tp (see Cudennec (2000) and Boudhraâ (2007) for more details). Those parameters are fixed manually (Table 1) based on the results of de Lavenne (2013).

For a given receiver basin, the choice of a donor basin (Table 2) is made by applying the following rules:

(a) Priority is given to upstream stations draining the largest part of the receiver basin.
(b) When no upstream stations are available, the closest uninfluenced station is chosen to be the donor basin.

Indeed, the Goët River is influenced by the Saint-Barthélémy Dam (point 1279) where output discharge data are available. Because the approach uses runoff data directly as an input of hydrograph transposition, it was also possible to use this influenced discharged to consider the effect of the dam on the downstream part of the river.

Table 1 Parameter values used for inversing transfer function of every basin of Saint-Brieuc's Bay.

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

Table 2 Transpositions performed for modelling the total volume of freshwater flowing into the Saint-Brieuc's Bay.

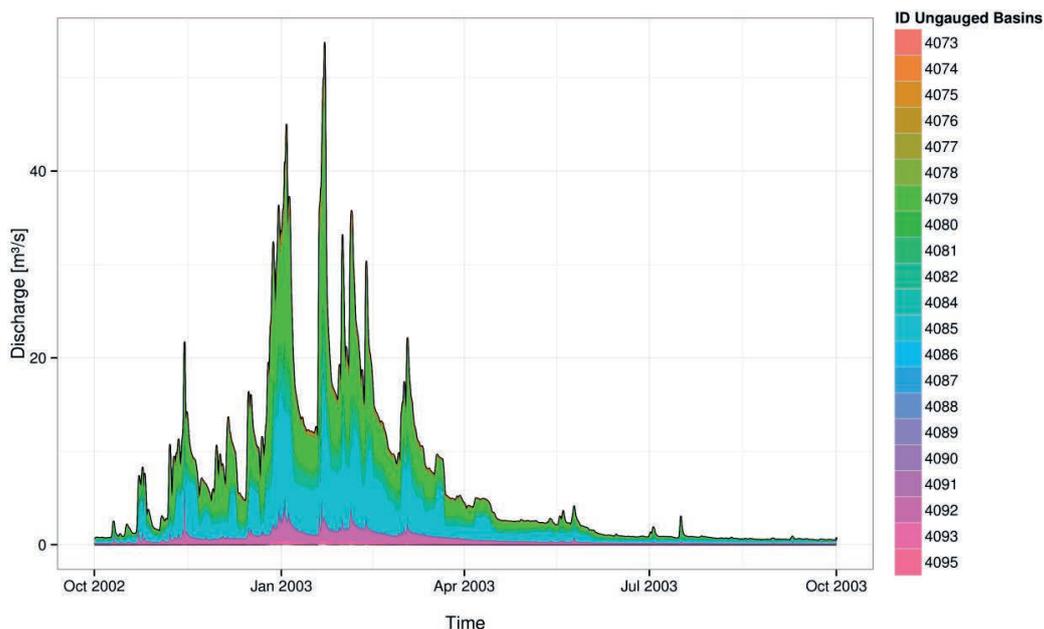| Receiver basins ID	4073	4074	4075	4076	4077	4078	4079	4080	4081	4082	4084	4085	4086	4087	4088	4089	4090	4091	4092	4093	4095
Donor basins ID	1274	1274	1274	1274	1274	1274	1274	1275	1275	1276	1276	1279	1282	1282	1282	1282	1282	1282	1282	1282	1275

Fig. 3 Total freshwater flowing into the bay of Saint-Brieuc at hourly time steps.

RESULTS AND DISCUSSION

Freshwater flowing into the bay

Once streamflow is simulated for each of the 21 ungauged basins, the total streamflow is estimated by summing the hydrograph of the 21 basins flowing into the bay. The resulting outflow is then able to characterise the absolute contribution (Fig. 3) and the relative contribution (Fig. 4) of every basin to the total freshwater entering the bay at an hourly time step.

The three main basins of the bay are highlighted, basins 4079 (Gouessant River), 4085 (Goët River) and 4092 (Ic River). It is seen that at an annual scale the relative contribution of each basin is not always constant throughout the year. For the hydrological year 2002–2003, it is seen that basin 4079 (Gouessant River) contributes more during the winter than during the summer. However, this conclusion was not confirmed for every year. Furthermore, unsteady contributions are observed on a daily scale. For instance, the influence of the Saint-Barthélémy Dam (point 1279) is still observed at the bay's scale through fast variations of the outflow.
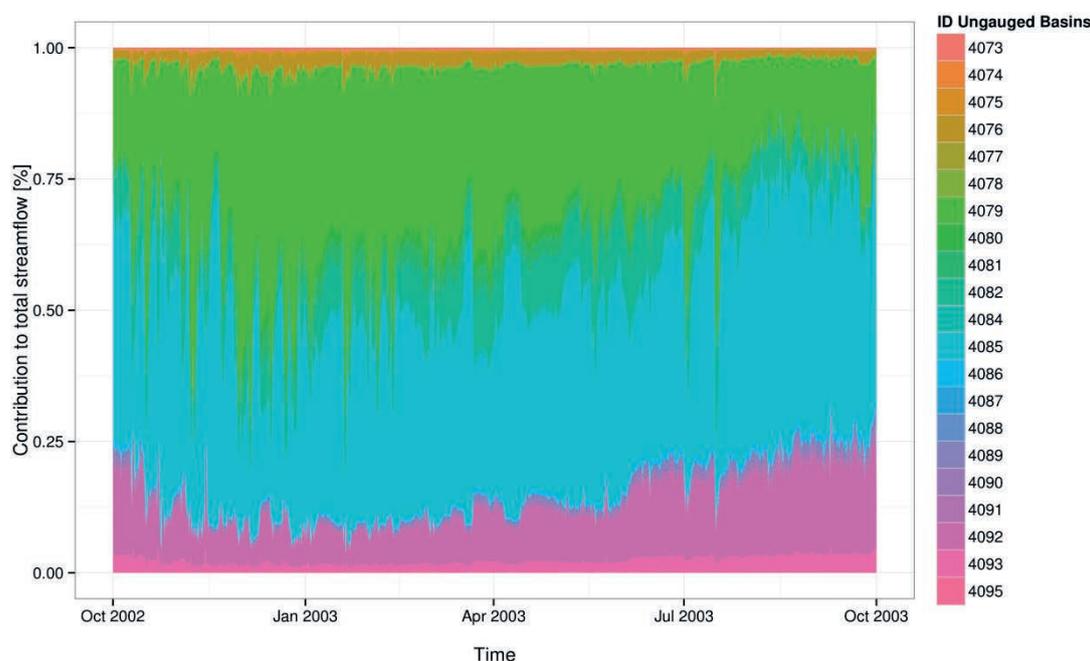

Fig. 4 Relative contributions to freshwater flowing into the bay of Saint-Brieuc at an hourly time step.

CONCLUSION

This study aimed to simulate the total outflow of Saint-Brieuc Bay. The approach consists of hydrograph transposition from a gauged basin to an ungauged one. This transposition was made possible by benefiting from a scale independent variable, which is the net rainfall assessed through inverse modelling. The approach has proved to be practical to simulate streamflow in ungauged basins. Indeed, based on geomorphological observations and parameterization, streamflow from 21 ungauged basins has been assessed from data from five gauged basins. In this way, the approach increases the value of those different monitoring stations. Finally, unlike the classical rainfall–runoff modelling approach, the approach is capable of dealing with the influence of a dam in order to check its effect on the total outflow from the bay.

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