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An end-user-friendly hydrological Web Service for hydrograph prediction in ungauged basins

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ABSTRACT

A consolidated geomorphology-based approach for discharge prediction in ungauged basins (PUB) through deconvolution of discharge signals from gauged donor catchments, their transposition and their convolution towards target outlets, has been made available online to end users through a Web Processing Service (WPS) for the synoptic peninsular region of Brittany, France. In the spirit of hydrological services, the SIMFEN WPS allows anyone to execute the hydrological modelling package transfR online through: (1) Open Geospatial Consortium (OGC®) interoperability standards; (2) collection and use of public hydrometric data; (3) connection to the pre-existing MNTSurf WPS for geomorphometric analysis; (4) visualization using a collaboratively developed Mviewer; and (5) innovative WPS workflows. The ability to model discharge series at any ungauged outlet of the synoptic region is offered to specialists of other disciplines, non-modeller water practitioners and interested citizens to support interdisciplinarity, water monitoring and management, and related science-society-policy debates and actions.

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Introduction

According to the World Meteorological Organization (WMO 2015),

hydrological services consist of the provision of information and advice on the past, present and future state of rivers, lakes and other inland waters including streamflow, river and lake levels and water quality. These services focus mainly on the surface component of the hydrological cycle [...]. They also include information on subsurface (underground) water resources.

To do so, they use, produce and add value to data, statistical products, projections, scenarios, models, model outputs, forecasts, warnings, analyses and maps, and provide the information in a user-friendly and meaningful format. Their added value resides at the science-society-policy/operation interface, as they provide hydrological information in a way that assists monitoring and decision-making by individuals and organizations (WMO 2018a, 2018b), consistent with the wider Global Framework for Climate Services (GFCS; WMO 2010, 2014).

The information and decision-making refer to a wide range of the following:

- hydrological processes;
- related and interconnected processes, such as dynamics and co-evolutions of socio-hydrology and the water-energy-food nexus (Liu *et al.* 2017, Cudennec *et al.* 2018, Di Baldassarre *et al.* 2019, Connor *et al.* 2020);

- related time scales, from real-time crisis mitigation (itself spanning orders of magnitude depending on the characteristic times of the events and systems considered) to long-term management of trends and changes (Montanari *et al.* 2013, Ceola *et al.* 2016, McMillan *et al.* 2016, Fovet *et al.* 2018); and
- related spatial scales and organization levels (Blöschl and Sivapalan 1995, Brondizio *et al.* 2016).

These considerations relate to major challenges in hydrology (see unsolved problems in hydrology (UPH); Blöschl *et al.* 2019) along the value chain from monitoring and data management (Pecora and Lins 2020; Dixon *et al.* 2020), conceptualizing and modelling, to delivering to end users with communication of uncertainties (see UPH #21). Besides specialists and professionals, this also strongly relates to increasing societal awareness of hydrological status and citizen involvement in related efforts – from citizen science to enlightened contributions to controversies, foresight options and strategic choices (Wehn *et al.* 2015, Bai *et al.* 2016, Nardi *et al.* accepted).

Streamflow discharge series are essential hydrological information that underlies all hydrological signatures and is relevant for decision-making; however, it is often not available for the exact location(s) for which decisions need to be made. Major methodological progress has been achieved over the past several years in prediction in ungauged basins (PUB) (Blöschl *et al.* 2013, Hrachowitz *et al.* 2013, Pomeroy *et al.* 2013). Dissemination and

operationalization of some of these methods are advancing in specialized institutions due to dedicated education and training programmes. Nevertheless, developing PUB-related hydrological services remains a challenge that would increase the availability of outputs of such methods relevant to end users, at their targeted location(s) of interest, capitalizing on the available raw data and curating the methodological (often modelling) aspects – and thus the associated uncertainties – for non-specialists.

This article presents the development of the interoperable and open-access Web Service SIMFEN (*Service Interopérable de Modélisation des Flux d'Eau Non-influencés* in French, i.e. Interoperable service for modelling non-influenced water flows), which provides a consolidated, robust and flexible PUB modelling method to end users. The method allows users to simulate series of streamflow discharge (i.e. hydrograph) at the outlet of a given ungauged target basin based on series of discharge observed at the outlet(s) of one or more information-donor basins using a geomorphology-based deconvolution-transposition-reconvolution approach. The SIMFEN Web Processing Service (WPS) and associated interface allow end users to simulate discharge series online at any location of the river network draining at least approx. 10 km² of the synoptic region of Brittany (*Bretagne* in French), France, which has a coherent hydrographic area of 29,640 km² and faces serious hydrological (including hydrochemical) issues (Cudennec *et al.* 2015, Fovet *et al.* 2018, de Lavenne *et al.* 2019). The hydrometric data required by the WPS are automatically downloaded from public databases to simplify use by end users. Advanced options are offered for exploring modelling variations and thus the principles, characteristics, accuracy and uncertainties of the approach. The simulated streamflow discharge series is displayed graphically in the web interface and made available via optional download or a WPS workflow to assure full compatibility and ease of use. This article presents the hydrological modelling approach and the rationale of WPSs before describing the combination of both in the SIMFEN Web Service and the latter's hydroinformatic and ergonomic characteristics.

Methods and synoptic data

Geomorphology-based hydrological modelling by transposing discharge series

In line with the geomorphology-based unit hydrograph approach (initiated by Dooge 1959, Surkan 1969 – see Rigon *et al.* 2016 for perspectives), and more specifically the family based on geomorphometric functions of a basin's river network – rather than that based on the Strahler branching topological cascade (Rodríguez-Iturbe and Valdés 1979, Cudennec *et al.* 2004, Cudennec 2007), our approach considers a basin-level hydrological transfer function (TF) deduced from the geomorphometry-based observable probability density function of hydraulic lengths across the relief and river network (Cudennec *et al.* 2004, 2005, Cudennec and Fouad 2006, Aouissi *et al.* 2013) and an assumed average streamflow velocity. The latter linear assumption is a common way to simplify variability and dispersion (Rinaldo *et al.* 1991) to make predictions of little-known or ungauged basins more robust (Snell and Sivapalan 1994, Robinson *et al.* 1995, Moussa 1997).

In line with the unit hydrograph approach, for a given basin, convoluting its TF with an estimate of its basin-averaged net rainfall series (R_n) allows streamflow discharge (Q) at its outlet to be simulated. Consistent with the definition of the geomorphology-based TF, by accounting for transfer across the river network, R_n is the basin-averaged water flow signal that is produced by hillslopes and that enters the river network (Cudennec 2000, Boudhraâ *et al.* 2009). Although the geomorphology-based approach is generic, estimating R_n depends on highly heterogeneous and contingent hillslope hydrology (Fan *et al.* 2019), which limits simulation in ungauged basins. The following alternative approach was thus developed.

For a given gauged basin j , characterized by its linear geomorphology-based transfer function (TF ^{j}), inverting TF ^{j} allows R_n^j to be estimated by deconvoluting the series of observed discharge at the outlet (Q_{obs}^j) (Cudennec 2000, Boudhraâ *et al.* 2018) (Fig. 1). Transposing R_n^j from the gauged basin j (i.e. donor basin j) to the target basin and then convoluting with the transfer function of the target basin (TF) allows the discharge series at the target outlet (Q_{sim}) to be simulated. The TF can be estimated for an ungauged target basin through geomorphometric observation of its relief and river network, as mentioned, and a robust estimate of its streamflow velocity. In addition to this paired approach with a single donor basin, a weighted combination of several donor basins can be considered in a kind of multi-basin ensemble modelling (McIntyre *et al.* 2005, Randrianasolo *et al.* 2011), with weights λ based on the inverse of the Ghosh distances between basins (de Lavenne *et al.* 2016) (Fig. 1). Identifying candidate donor basin(s) depends on hydrological similarity (Blöschl *et al.* 2013, Hrachowitz *et al.* 2013) and was considered in our approach by using nesting and neighbouring basin configurations as a robust framework for operationalization.

This approach has been applied to three contexts: small basins of the Dorsale mountain ridge in semi-arid Tunisia (Nasri *et al.* 2004, Boudhraâ *et al.* 2006, 2009, 2018), the neighbouring Brittany peninsula and Loire River basin in temperate oceanic France (de Lavenne *et al.* 2015, 2016) and a large region north of the Saint Lawrence River in pluvio-nival Québec, Canada (Ecrepont *et al.* 2019). Regional estimates of basin-averaged streamflow velocity were developed by de Lavenne (2013), de Lavenne *et al.* (2016) and Ecrepont *et al.* (2019) for the synoptic domains of the Brittany peninsula, the Loire River basin and the Québec region, respectively. When compared to top-kriging (Skoien and Blöschl, 2007), the approach showed results of similar quality (de Lavenne *et al.* 2016). The robustness of the approach to hydrometric configurations has been shown through sensitivity analysis and leave-one-out pseudo-ungauged tests (de Lavenne *et al.* 2015, 2016, Boudhraâ *et al.* 2018, Ecrepont *et al.* 2019). Robustness to the resolution of the digital elevation model (DEM) used to characterize the geomorphometry has also been shown for Brittany (Ecrepont and Cudennec 2020). In addition, in the spirit of PUB, truly ungauged basins have been simulated between paired donor–target basins (de Lavenne and Cudennec 2014) and via ensemble modelling of multiple donor basins (de Lavenne and Cudennec 2019). In terms of hydroinformatics, scripts for this approach have been

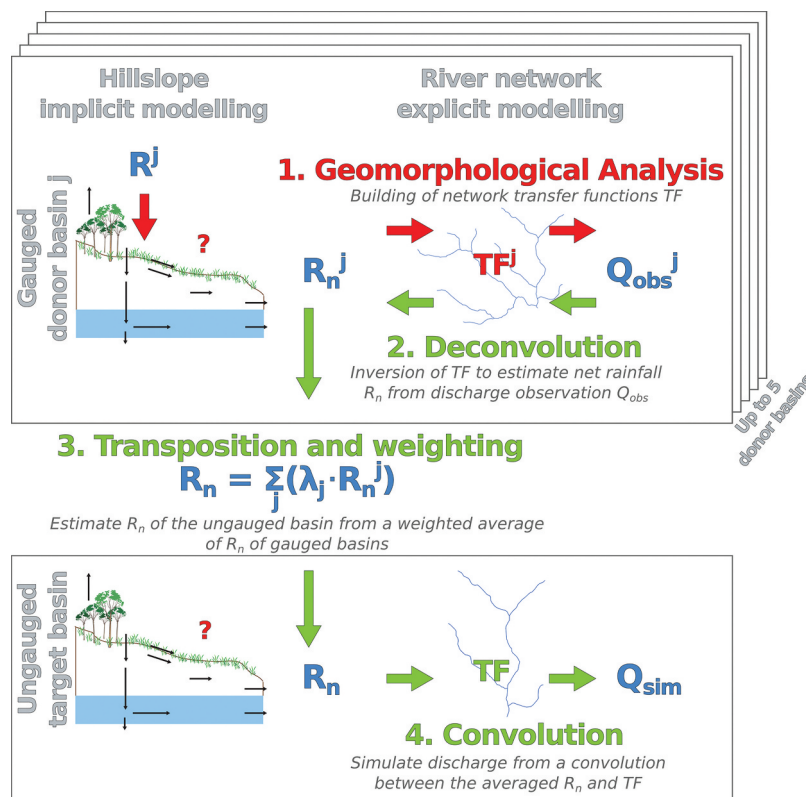


Figure 1. Principles of geomorphology-based hydrological modelling.

developed in a dedicated package (transfR) for R software (R Core Team 2017).

Principles of a Web Service

A Web Service is a set of applications located on servers that can be accessed through the internet via standard protocols for machine-to-machine interaction. These standard protocols have been established by the Open Geospatial Consortium (OGC) and approved by the World Wide Web Consortium (W3 C). They are composed of the Web Services Description Language (WSDL), the Simple Object Access Protocol (SOAP) for information exchange, and Universal Description, Discovery and Integration (UDDI) for registration (Curbera *et al.* 2002, Chinnici *et al.* 2007, Mitra and Lafon 2007). Requests to Web Services are conveyed over the internet by HTTP protocol.

A Web Service facilitates data access (Goodall *et al.* 2008, Kadlec and Ames 2011) by using standard protocols for inputs and outputs, such as WaterML for temporal data (Taylor 2011) and Geography Markup Language (GML) for spatial data (Portele 2007). A Web Service can be used as a stand-alone application or integrated into a workflow (Granell *et al.* 2010, Castronova *et al.* 2013, Goodall *et al.* 2013, Turuncoglu *et al.* 2013) because of its interoperability (Kadlec and Ames 2011). Moreover, using a Web Service to collect data improves the use of the data and limits duplication and redundant maintenance (Goodall *et al.* 2008, Béra *et al.* 2015).

Connecting a Web Service to a web interface and Spatial Data Infrastructure also allows for the development of data

processing, analysis, modelling and visualization functions (Granell *et al.* 2010, Béra *et al.* 2015, Rosatti *et al.* 2018) and, thus, for development of Web Processing Services (WPS), in addition to Web Feature Services (WFS) of the data flux type. The WPS approach can facilitate the performance of hardware architecture (operating system), use of programming languages, and execution of models. The underlying OGC® WPS standard (Whiteside 2007) was initially developed for geospatial processing, but its specifications for data encapsulation and communication between client and server allow it to be used for modelling, linking scripts and automatic updates.

Hydrogeomorphological and hydrometric data of Brittany

The regional reference DEM and associated river network embedded in the SIMFEN WPS was obtained by correcting the 50-m resolution DEM provided by the French Geographical Institute (IGN) of its drainage anomalies with MNTSurf software, itself provided as a WPS (Aurousseau and Squidant 1996, Squidant *et al.* 2015).

River gauging stations are managed by DREAL (Direction Régionale de l'Environnement, de l'Aménagement et du Logement), the regional division of the French Ministry in charge of the Environment. There are 125 stations available in the region, the oldest one dating back to 1938. Hydrometric data and some signatures are contained in the national Banque Hydro website¹ but are currently difficult for end users to access and download. However, DREAL has an OGC-compliant data flux WFS of daily

¹www.hydro.eaufrance.fr

discharges,² which to date has remained for confidential use by a regional consortium for inter-agency coordination (GéoBretagne³) to monitor the regional hydrological status and display it in summaries (e.g. <https://bretagne-environnement.fr>). The SIMFEN WPS uses the DREAL database and data flux WFS to update inputs and – consistent with the principles of Web Service interoperability and reusability, and the INSPIRE directive (EC 2018) – will be easily switched to the complete public hydro-metric data flux Web Service once it is made available at the national level.

Development of the SIMFEN hydrological Web Service

System and architecture

The system is organized into four parts: client, calculation, data and web servers (Fig. 2); and development followed the

INSPIRE-directive architecture, which is organized into three layers: service, data and application (Fig. 3). The service layer is the core of the SIMFEN WPS service-oriented architecture, which has two types of service functions. First, classical and well-known functions, which are used in many other Spatial Data Infrastructures, are discovery, spatial view and spatial download functions, to find, view and download geographical data, respectively. Second, more specific functions are (i) a temporal download function, to share hydrological series; (ii) connection to the pre-existing MNTSurf WPS, which includes geomorphometric functions; and (iii) the SIMFEN WPS itself, which executes the hydrological modelling functions using the transfR package. The data layer describes persistent data storage associated with each service, using different types. For example, the temporal function is associated with a PostgreSQL database, MNTSurf WPS with a simple “directories and files” data organization and the spatial download function with both a PostGIS database and raster GeoTIFF files or vector shapefiles. The application layer

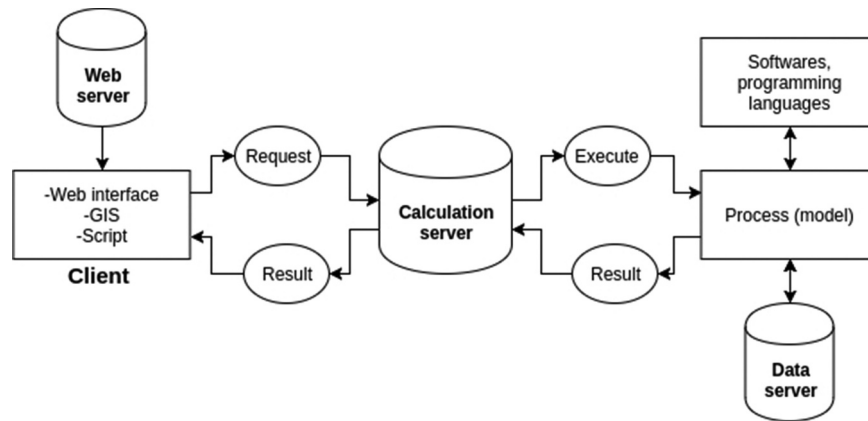


Figure 2. Informatics system supporting the SIMFEN Web Service.

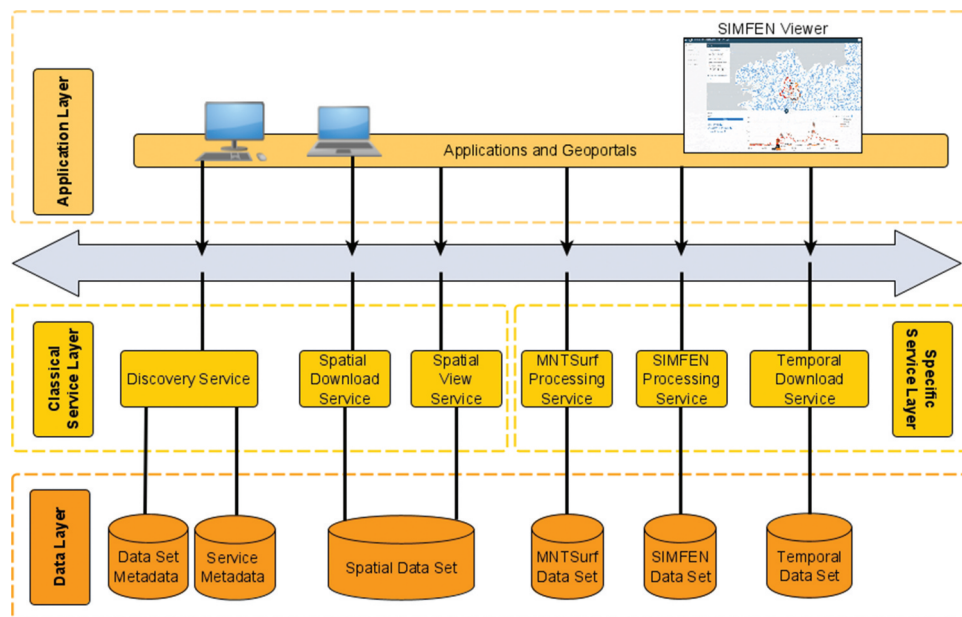


Figure 3. INSPIRE-type architecture of the SIMFEN Web Service.

²https://geobretagne.fr/geoserver/dreal_b/wfs

³<https://geobretagne.fr>

connects end users to the functions and services of the service layer. All of the latter developments can be reused by any OGC-compliant application.

The SIMFEN WPS can be accessed directly using a GIS software, a script or URL request at <http://wps.geosass.fr/simfen>. For ease of use by non-specialist end users, however, we developed a public web interface (<http://bit.do/simfen>).

Description of the SIMFEN WPS

To make it easy to use, the SIMFEN WPS allows users to execute the transfR package, with a minimum of input data (Fig. 4). It is operationalized through a process developed with PyWPS

(version 4.3.dev0), which is an implementation of the OGC® WPS standard written in Python (Čepický and De Sousa 2016) that supports WPS version 1.0.0. Modelling results follow the OGC® WaterML standard (Kadlec and Ames 2011) and, for those using the web interface, are provided in.csv format.

Web application and interface

The web application and bilingual interface (Fig. 5) on the web server are based on the cartographic viewer “MViewer” collaboratively developed by the GéoBretagne consortium,⁴ to which we have contributed for several years as a research unit committed to providing open results and products to

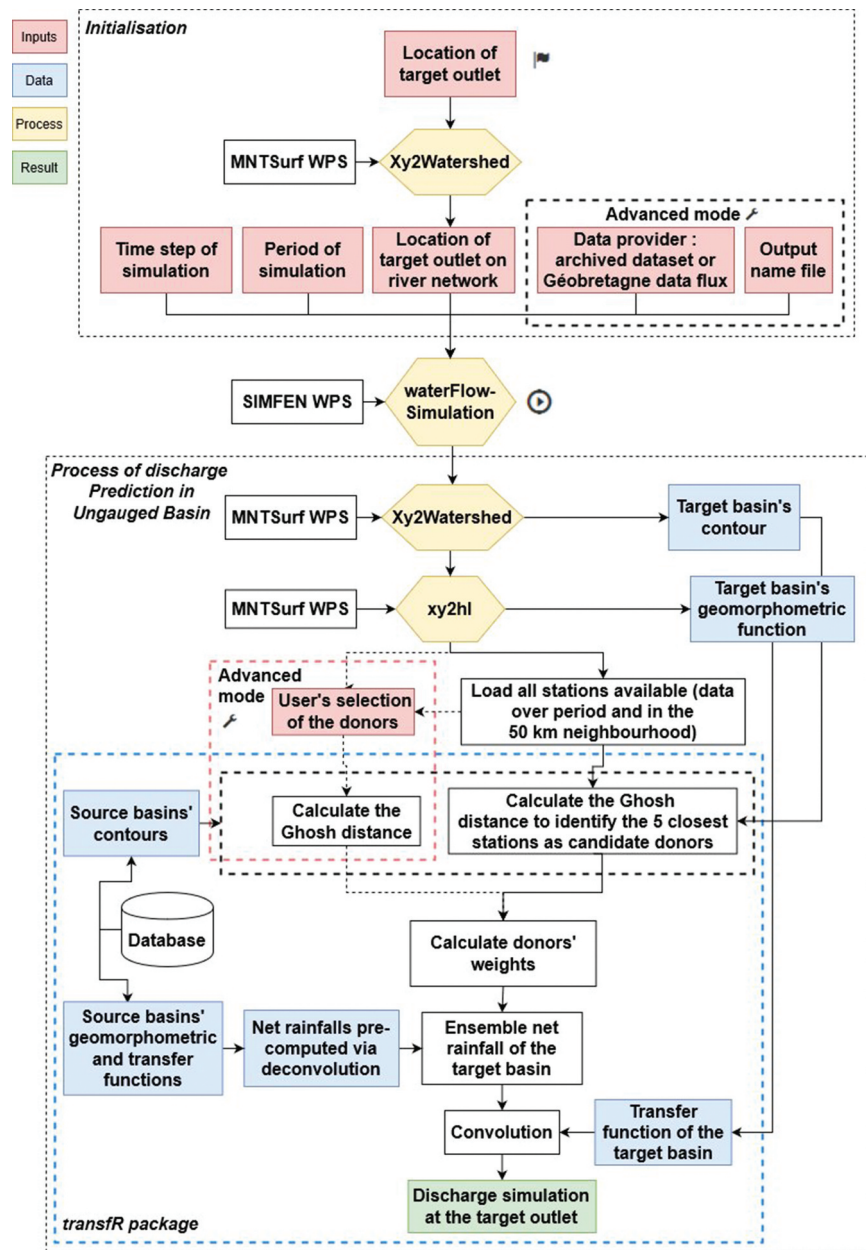


Figure 4. Hydroinformatics flowchart of the SIMFEN Web Service.

⁴<https://mviewerdoc.readthedocs.io/fr/latest/>

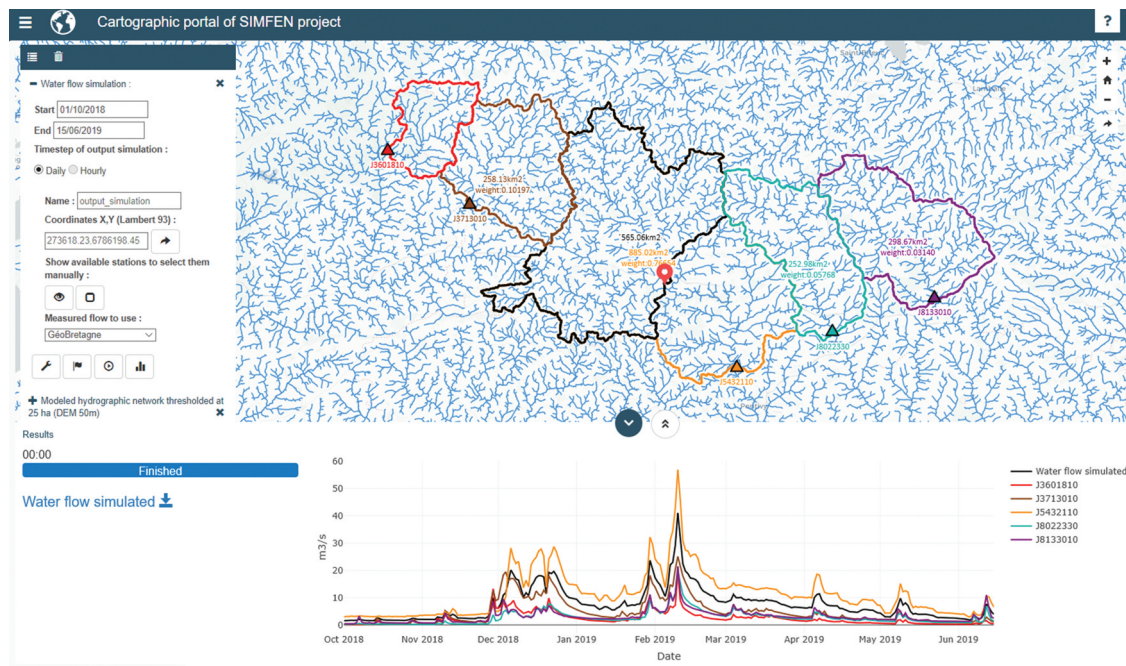


Figure 5. Web interface of the SIMFEN Web Service illustrated with a discharge simulation for an ungauged target outlet based on five donor basins.

the public. It was developed using HTML5, CSS3, JavaScript, JQuery, OpenLayers and Bootstrap. An add-on has been developed to send a form to the SIMFEN WPS with user inputs, to track progression and to collect modelling results.

Pre-treatments and processing time

The hydrological modelling is composed of three steps: deconvolution of observed discharge series of the donor basin(s), transposition using ensemble weighting towards the target basin and simulation of discharge at the target outlet via convolution (Fig. 1). The last two steps depend upon user choices at execution, but the deconvolution step is pre-computed (Fig. 4). It estimates the R_n of a gauged basin as a function of the latter's contour, geomorphometric function and the entire history of streamflow discharge series at the outlet. These characteristics are calculated in advance for every gauged basin (i.e. potential donor basin) in the domain and stored in the PostgreSQL database on the data server. Thus, deconvolution, which requires the most time because of its underlying inverse modelling, does not need to be performed at the time of simulation, increasing the speed of service delivery. The R_n is updated automatically every week by a script that determines whether new discharge measurements are available from the data flux WFS.

In addition, processing time has been optimized by using the OGC® WPS, which allows processes to be executed asynchronously. During the execution of the modelling functions, the WPS returns an iterative XML document with a tag status. The web interface controls this tag to know when the process has finished, allowing users to view and optionally download the results.

Operational use sequence and options

The web interface displays a default configuration to allow anyone to run the SIMFEN WPS, with standard options. The advanced mode, which allows users to customize certain options, is useful for those who wish to use their hydrological expertise in the modelling exercise or to explore alternate options and assess the sensitivity and quality of simulations. This feature, visualization options, accompanying documentation and metadata aim to help end users understand the modelling principles, epistemology, data-dependence and uncertainties. Online documentation includes the rationale, scientific references, credits and disclaimers. A tutorial video is also available.⁵ The entire interface has been tested and finely tuned with a focus group of end users.

To proceed, the user indicates the location of the target outlet and the period over which to simulate streamflow discharge series (i.e. the hydrograph) (Figs. 4 and 5). Consistency of these inputs with the temporal and spatial data available is verified. In the web interface, the user indicates the target outlet by placing a flag symbol on the map of the reference river network in a map window (default mode) or by entering geographic coordinates (RGF93-Lambert 93 coordinate system, EPSG:2154) in a numeric window (advanced mode). Related cartographic data are provided in the web interface to help users locate points of interest and target outlets, and to provide information for interpreting the modelling results. These data, not used by the model, are visualized in the MViewer. The data currently provided are locations of public hydrometric and quality monitoring stations; administrative boundaries of hydrographic regions, reporting sectors and water management plans; and boundaries of hydrogeological entities and potential wetlands. These data are available using WFSs, essentially of the

⁵<https://doi.10.6084/m9.figshare.8982695.v1>

national public service SANDRE,⁶ and they are displayed in the SIMFEN web interface (Fig. 5 provides an illustration) using an on-demand workflow, with no data storage in the SIMFEN database and thus no updating or maintenance issues.

The “xy2watershed” function of MNTSurf WPS (Squidant *et al.* 2015) is used to precisely locate the target outlet on the river network and delineate the contour of the target basin. Then, the “xy2hl” function of MNTSurf WPS analyses the river network within the target basin to extract the geomorphometric function, which then yields the TF when the regional streamflow velocity is applied (Fig. 4).

Next, the process builds a WFS request to identify all gauging stations available in the DREAL database in the geographic neighbourhood of the target basin over the given period. Up to five of the closest gauged basins in terms of Ghosh distance with the target basin are identified within a radius of 50 km and proposed for ensemble modelling in the default mode. In the advanced mode, users can adjust the set of donor basins based on their knowledge of hydrological similarity with the target basin by selecting basins on the map of all available gauging stations (Fig. 4).

Then, users execute the transfR modelling package, using a dedicated button, which simulates streamflow discharge series, at the ungauged target outlet. Using the button is a cognitive engagement for the end user in the modelling exercise. The simulated hydrograph is displayed in the interface and downloadable in .csv format or via a WPS request. Users can also display observed hydrographs of the source basins on top of the simulated hydrograph, which provides a visual comparison of the simulated hydrograph to the envelope of the observed data series used as a source of hydrometric information in the paired or ensemble modelling approach (Fig. 5 displays the example of an enveloped simulation for a target basin based on five donor basins). The combined display of the hydrographs and mapping of the basin contours and networks help users understand the basins’ hydrological behaviour, hydrological similarity, as well as the modelling epistemology, data-dependence and uncertainties. They also allow advanced users to explore options and gain expertise.

The simulated hydrographs are accompanied by the processing metadata, which include the location of the target outlet, the period simulated and the basin(s) used as a source of information. The metadata allow users of the SIMFEN WPS and those with whom simulations are subsequently shared to replicate the simulations and understand the data. In addition, following the WPS standard, a function (GetCapabilities request) allows users to access the Web Service metadata themselves.

Conclusion

Web Service technology and interoperability standards were used to develop a hydrological service that provides a consolidated geomorphology-based modelling approach

online to simulate streamflow discharge series (hydrographs) at ungauged target outlets of societal or technical interest. The SIMFEN Web Service allows anyone to execute the hydrological modelling package transfR online using a dedicated WPS⁷ with the following rationale: (1) respect of OGC interoperability standards; (2) collection and use of public hydrometric and hydrogeomorphological data; (3) connection to the pre-existing MNTSurf WPS for geomorphometric analysis; (4) visualization through a web interface using a collaborative MViewer⁸; and (5) facilitation of future innovative WPS workflows.

The SIMFEN WPS is currently available for the synoptic peninsular region of Brittany, France. It benefits from the combination of a consolidated geomorphology-based hydrological modelling approach and a proactive collaborative strategy for open access to research data and products of the research unit SAS. Its ergonomics and options have been designed in cooperation with a focus group of end users. The Web Service is tuned to current data flux WFSs offered by the regional public hydrometric authorities and is switchable to upcoming national WFS data fluxes, which will allow expanding the geographic domain and may open up new opportunities, especially as the data will have hydrometric time steps shorter than one day. The SIMFEN Web Service provides modelling abilities to end users, such as specialists of other disciplines interfacing with hydrology, non-modeller water practitioners and interested citizens. It supports interdisciplinarity, water monitoring and management, as well as related science-society-policy debates and actions (Cudennec *et al.*, 2020). Along with the modelling results, the ergonomic standards and advanced options of the web interface provide information and visualizations that can further support the cognitive progress and capacity building of individuals and institutions. This support can increase awareness of, understanding of and expertise in hydrological behaviour and similarity, as well as of modelling methodology, data-dependency, and uncertainties. In the spirit of hydrological services, the facilitated modelling can also be used to support targeted analyses, debates and decisions, and to make responsibilities explicit when using data and simulations. The service has been developed in the French region of Brittany and is ready to be switched to the whole of France when the announced complete national public hydrometric data flux Web Service is made available by the Ministry in charge. It can further be considered as a proof of concept to be generalized in many regions of the world.

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Disclosure statement

No potential conflict of interest was reported by the authors.

⁶<http://services.sandre.eaufrance.fr/geo/zonage>

⁷<http://wps.geosas.fr/simfen>

⁸<http://bit.do/simfen>

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