Chapter 57

Implementation of a Hydrologic Model as an Element of the Litter-TEP Service—Marine Litter Tracking and Stranding Forecast—Or for the Understanding of the Coastal Patterns Change

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Abstract Debris float on the sea-surface and further strand, compelling local authorities to clean the shoreline. Part of these debris are litter which is discharged into the sea by rivers' mouths or flown from seafronts. The main cause of pollution is all the stronger after heavy precipitations when watersheds' soil is washed up and trashe is directed to streams which ultimately end in the ocean. Marine litter is then transported by currents and wind, litter's fate being to sink and/or to be disintegrated into micro marine litter or to finish its course at the coast where it washes ashore. ARGANS launched the development of a platform to track them from their source to the coast. It uses a parametric model of riverine macro litter discharge, to seed drift models of the NE Atlantic Shelf Region, providing to end-users a 5-day running forecast of macro-litter density in the sea, potential beach stranding at the coast. One of the main identified issues for which we currently perform this R&D, is the source's modelling and litter's volume estimation introduced to the sea, with the use of refined hydrologic schemes of watersheds, linked to meteorological events and kind of habitats (rural, urban, industrial, …). The Hydrologic model implementation aims to obtain daily estimation of river flow from near real time rainfall (from satellite images) and temperature data. The model used not only provides flows but can manage the sedimental information allowing its reuse for the understanding of the coastal patterns change obtained from EO analysis.

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57.1 Introduction

If floating marine macro-litter have a strong impact or are dangerous for ecosystems, species, and wildlife in general (ingestion, entanglement, transport of non-native and invasive species, [1] etc.…), subject not tackled in this article, the beach debris (vegetation material or anthropogenic waste) have, they as well, a strong impact both on the economy and on the environment. All types of debris[1] have direct impact on tourism and beach visits [2], but anthropogenic waste (also called marine-litter) have, in addition, an environmental impact (pollution, health risks or injuries, etc.…). In fact, beached litter is considered by beach users to be one of the five most important aspects regarding beach quality [3–5]. The dirty beaches suffer a diminution of the number of visitor, leading to a loss of income [2, 3] and force the local collectivities to find solutions to offer a high level quality standard of touristic service [6].

The litter collection is mainly the solution, it is very expensive [4] and is paid by local authorities and inhabitants [6]. If a large proportion of the stranded debris comes directly from beach users and touristic activities on beaches, during the summer season [7], linked to behavior, for example 42% in UK [8] or 39% in Brazil of the beach litter [9], other sources must be also considered.

Marine litter originates from numerous different sources, and around 80% is from land-based sources with regional variation for this proportion [10]. Land-based sources are rivers, beaches, piers, harbours, marinas, docks, coastal cities, due to public littering, poor waste management practices, industrial activities, sewage related debris, storm water discharges, etc.… and according to OSPAR, 70% of marine litter sinks, 15% floats in the water column and 15% washes up on shore. For the 15% of washed up litter, a high proportion comes from nearby rivers, consisting of both human waste and natural waste [6, 11]. If litter from rivers is stranded nearby to the river estuary during non-flood periods, it can beach far from its source during a flooding period and after storm events [2]. For instance, rivers around the world transport between 1.2 and 2.4 million tons of plastic into the oceans every year [12].

As we have been approached by regional and local authorities to trace back the trash to its original source or estimate the potential volume of stranded litter on their coast in the future to plan beach cleaning campaigns and improve of river water quality, ARGANS Ltd designed a service called Litter-TEP, a platform for data collection, information production and dissemination. It uses a parametric model of riverine macro litter discharge, to seed drift models of the NE Atlantic Shelf

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[1] UNEP: Marine litter consists of items that have been made or used by people and deliberately discarded into the sea or rivers or on beaches; brought indirectly to the sea with rivers, sewage, storm water or winds; or accidentally lost, including material lost at sea in bad weather [1].

By Debris, here, we define Marine litter plus natural litter like driftwood, algae, seagrass, sargassum, drift seeds, etc.

Region (OSPAR II/III), providing to end-users a 5-day running forecast of macro-litter density in the sea, potential beach stranding at the coast and, inversely, where a beach litter event is identified to provide the likelihood of where the litter entered the sea. In order to determine drift trajectories, we use ocean current, wave and wind forecasts from Copernicus Marine Service high quality analysis and forecast products for the European North West Shelf seas. The main issues which have been identified, and for which we perform additional R&D, are the following: (1) source's modelling and estimation of the volume of litter introduced to the sea, (2) The type of litter for which the drift model should be adapted, and c) the spatial resolution of models in the littoral area (nearshore) versus offshore. In fact, for the beaching and refloating models, we need a bathymetry at the scale of 1/3000 and a coastal cartography at 1/1000 to obtain the beach profile, then calculate the runoff on the beach, the rip currents, etc. This paper approaches the on-going R&D, namely, the discharge models, using refined hydrologic schemes for the watersheds.

The first step of our developments is the configuration of the model fed with physical information (land cover, hydrographic network, evapotranspiration, geological structure, etc.…). Then, a phase of calibration linked with information from gauges to obtain coefficients, with explanation of the constraints and limitations of the model. The results are introduced in the Litter-index model to generate daily estimates of litter for the Litter-TEP service. We will attempt to reuse it for the understanding of the coastal patterns change obtained from EO analysis, more precisely in Dublin Bay in the framework of an ESA granted project as the first region analyzed to understand the model and its function was Liffey river and Dublin Bay.

57.2 Hype Model

We decided to use the HYPE model for the implementation of the discharge model. The HYPE model was developed by the SMHI (Swedish Meteorological and Hydrological Institute) between 2005 and 2007. Its code is written in FORTRAN and the software is open source. It is a semi-distributed rainfall-flow model, i.e. the basin is divided into several entities, in this case, sub-catchments. It has been designed for small-scale and large-scale assessments of water resources and water quality and has been implemented for rivers, such as the Niger River in 2012, countries (Sweden in 2009, India in 2013), continents (Europe in 2009, the Arctic in 2014) and worldwide (2016) [13, 14]. In the model, the landscape is divided into classes based on soil type, land use and topography. Model parameters are global or linked to land use or soil type. HYPE is based on the HBV model and its main use is flow prediction for ungauged catchments as well as water quality modelling. HYPE can be calibrated to take into account snowmelt, evapotranspiration, lake and groundwater levels, and to obtain better estimates of flows, nutrients and sediments as well as to more accurately describe the spatial variability of the catchment, in comparison with other models currently used for large scale hydrological modelling with flexible time and space step (i.e. Enki, HBV and WEAP). The HYPE model offers a very advanced description possibility, more than 300 parameters can be filled in and calibrated to describe the studied catchment area in the most accurate way.

The parameters used for the modelling of Dublin Bay flows are limited to those having a direct and noticeable impact on the flows, therefore the sediment and nutrient calculation modules were not used. The main drawbacks of the model are the tedious formatting of the classes and the necessity to have an advanced expertise in hydrological modelling in order to obtain relevant results.

The algorithm chosen for the calibration is the DEMC algorithm whose main advantages compared to the other algorithms proposed by HYPE are the possibility to obtain an optimal value for each parameter and a better convergence towards them at each iteration [15]. The DEMC algorithm requires several parameters to be set and the choice of these parameters has been based on a compromise between the speed of convergence and the accuracy of the set of calibrated parameters. The Kling-Gupta criterion is used as assessment criteria during calibration for a total of 8 hydrometrics stations:

$$KGE = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{sim}}{\sigma_{obs}} - 1\right)^2 + \left(\frac{\mu_{sim}}{\mu_{obs}} - 1\right)^2} \tag{57.1}$$

where KGE is the Kling-Gupta efficiency, r is the linear correlation, σ_{sim} the standard deviation of simulation, σ_{obs} the standard deviation of observation, μ_{sim} the mean of simulation, μ_{obs} the mean of observation.

In the literature, it is often claimed that a positive KGE means a good performance of the model, and a KGE higher than -0.41 means that the model is more accurate than a constant flow equal to the average of the observed values [16]. However, it is still necessary to compare the shape of the simulated curves with the observed ones in order to understand the differences, and to be able to understand the dynamics of the model in order to adjust it if necessary.

57.3 Model Implementation

57.3.1 The Liffey Watershed

The Liffey River and Dublin Bay watershed (Fig. 57.1) covers a total area of 1616 km^2. The largest urban center in the watershed is the city of Dublin. The total population of the watershed is approximately 1,255,000 inhabitants. The watershed hosts the largest population of any other watershed in Ireland and is characterized by a sparsely populated mountainous southeast and a flat, low-density area covering the rest of the watershed. The Liffey River, the longest river in the waterbasin, originates on the western slopes of Tonduff in the Wicklow Mountains, from where it flows

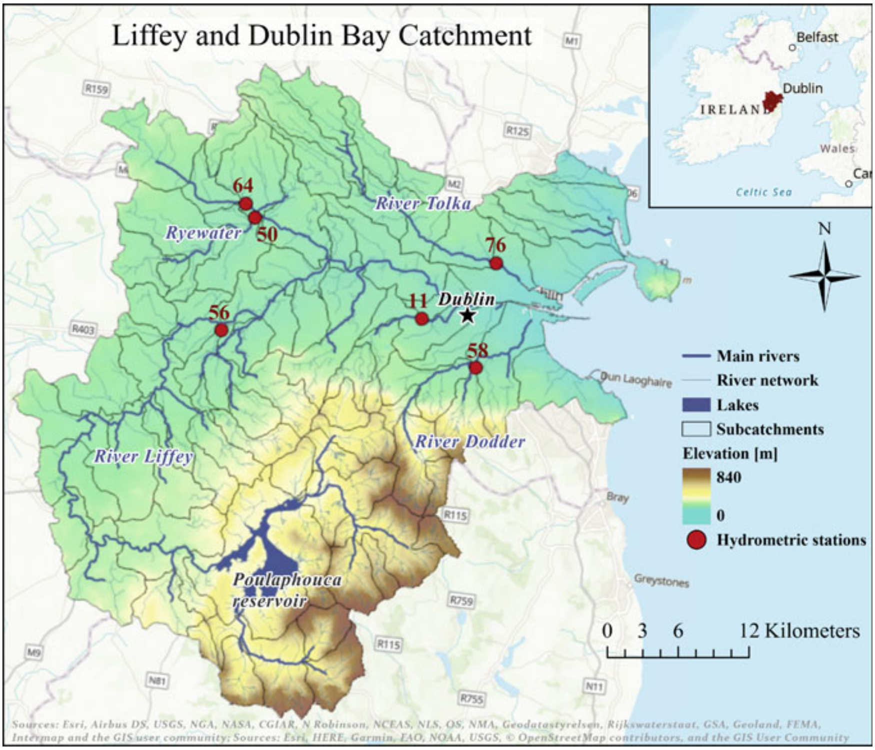

Fig. 57.1 The Liffey and Dublin Bay watershed and its topography

westward, before flowing into the northern end of the Poulaphouca Reservoir (dam lake), created in the 1930s.

The Liffey comes out of the reservoir through the Poulaphouca power station and continues into the lower reservoir and the Golden Falls power station, upstream of the Ballymore Eustace. The Liffey then flows westward before flowing towards Dublin where the river becomes subject to tides, and through the center of Dublin city where it is severely constrained by wharf walls. The Liffey River is then joined by the flow of the Royal Canal and Grand Canal, the Dodder River to the south and the Tolka River to the north. The Liffey passes through the port of Dublin and through the Bull Walls north and south which throw themselves into the sea in Dublin Bay. The eastern portion of the watershed is drained by several small coastal streams (Environmental Protection Agency 2018).

57.3.2 Model Options

Several simulation processes are available in the HYPE model concerning groundwater, soil erosion, consideration of floods, snow, water and soil freezing, calculation of infiltration, evapotranspiration, surface runoff, soil leaking, etc. Aquifers, frost, snow, and floods have not been taken into account in the implementation of the model. Evapotranspiration was calculated before being implemented into the model and the surface runoff is taken by default, i.e. using runoff coefficients and soil water threshold.

57.3.3 Input Data

57.3.3.1 Temperatures and Evapotranspiration

The temperature data comes from the Irish Meteorological Service MET Éireann, where temperatures from 22 weather stations were interpolated with an inverse distance squared weighted interpolation, then averaged for each subcatchment. Temperature data previously interpolated allows to generate evapotranspiration data from the formula (57.2) of Oudin et al. [16] using airGR package [17].

$$PE = \begin{cases} \dfrac{R_e}{\lambda.\rho}\dfrac{T_a+5}{100} & if\; T_a+5>0 \\ 0 & else \end{cases} \tag{57.2}$$

where PE is the potential evapotranspiration, R_e is the extraterrestrial radiation, i.e. the solar irradiance at the top of the Earth's atmosphere, T_a is the air temperature, λ is the latent heat flux, i.e. the flux of energy from the Earth's surface to the atmosphere and ρ is the water density.

57.3.3.2 Rainfall

Precipitation data is retrieved from the NASA server (one image for each timestep). Data are processed to intersect them with each subcatchment. Several precipitation values cover each sub-basin and, as the HYPE model requires a precipitation value per sub-basin, each precipitation value is weighted by the fraction of subcatchment it covers, a scale factor of 10 shall be applied to precipitation data [17], the formula used is:

$$P_{obs_{sub}} = \sum_{px} 10 \times P_{GPM} \times \frac{area_{px}}{area_{sub}} \tag{57.3}$$

where $P_{obs_{sub}}$ is the mean observed precipitation of the sub-basin, px represents the pixel of the raster of precipitation, P_{GPM} the precipitation value stored in the raster, $area_{px}$ the area of the pixel (the resolution) and $area_{sub}$ the area of the sub-basin.

57.3.3.3 Geology and Land Use

Geology (from Geological Survey Ireland) and land uses (from Copernicus Land Monitoring Service) are used to define soil and land use classes (SLCs) which are the hydrological response units of the HYPE model. For this purpose, the geological and land use layers are intersected with the sub-basins to obtain the SLC fractions of each sub-basin, only the first geological layer has been implemented in the model.

In addition, the land use information has been regrouped into five classes, in accordance with the Corine Land Cover categories:

- artificial surfaces (urban fabric, industrial, commercial and transport units, mine, dump and construction sites, artificial, non-agricultural vegetated areas);
- agricultural areas (arable land, permanent crops, pastures, heterogeneous agricultural areas);
- forest and seminatural areas (forest, shrub and/or herbaceous vegetation associations, open spaces with little or no vegetation);
- wetlands (inland wetlands, coastal wetlands);
- water bodies (inland waters, marine waters).

57.3.3.4 Discharge

The flow data are from Environmental Protection Agency. The model requires that only flows at the outflow of the subcatchment be filled in, therefore stations were selected based on this criterion, and a dummy station is created when one or more stations are available for the sub-basin under consideration. Therefore, a fictitious station can have the sum of the flows of several stations as a value (similar to Kirchhoff's circuit laws), or the value of an upstream station when no tributary affects the flow between the real and fictitious station (Fig. 57.2).

57.3.3.5 Lake Data

The only lake implemented in the model is the Poulaphouca Reservoir, which is by far the largest lake in the region with a surface area of 22 square kilometers. Its geometric characteristics are inputted into the model. The outflow from the lake is imposed by the Ballymore Eustace water treatment plant, where a constant flow of 1.5 cubic meters per second is required to maintain the flow of the River Liffey. During power generation, i.e. during flood periods, a flow of 30 cubic meters per second is injected into the River Liffey. For the years 2006, 2007 and 2008, the treatment plant released 1.5 cubic meters per second for 91.54, 86.53 and 79.32%

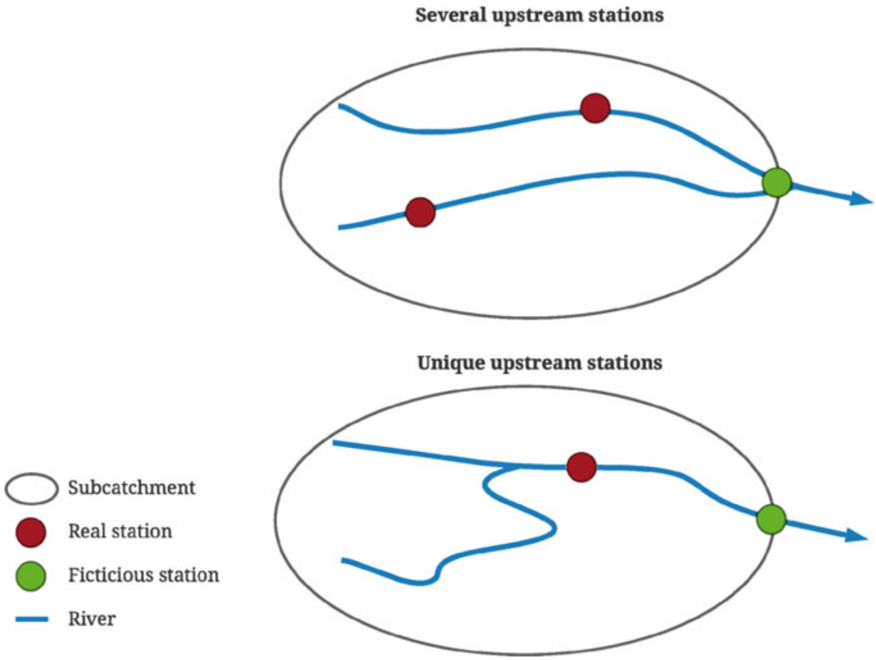

Fig. 57.2 Creation of downstream subcatchment's stations

of the year. 2007 and 2008 were years with extremely high rainfall [18]. So, a base rate of 1.5 cubic meters per second and a variation of 28.5 cubic meters per second are filled in the model.

However, the periods of injection of flow into the river are unknown as they are highly dependent on rainfall and snowmelt upstream. The disparity of these periods does not allow for an accurate implementation of the outflow from the Ballymore Eustace hydrometric station. This is why the characteristics of the rating curve of the lake is calibrated.

57.3.4 Calibration Processes

Firstly, a calibration of the model will be carried out over the period 2010–2017 where the relevant selected parameters will be calibrated. The validation of the calibration will thus be carried out with the parameters found over the year 2018 (Fig. 57.3).

The algorithm chosen for the calibration is the DEMC algorithm whose main advantages over the other algorithms proposed by HYPE are both the possibility of obtaining an optimal value for each parameter, and a better convergence towards them at each iteration [15, 19]

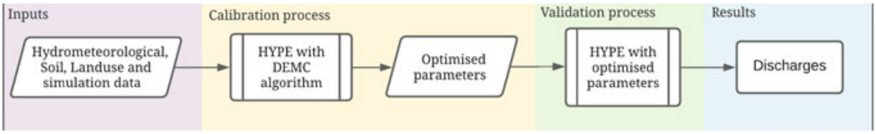

Fig. 57.3 Processes description

The DEMC algorithm requires the fixation of several parameters, and the choice of these parameters was based on a compromise between convergence velocity and accuracy of the resulting parameter set. The required parameters of the DEMC algorithm are:

- the mutation scale *DEMC_npop*, corresponding to the number of set of parameters that is simulated;
- the generation number *DEMC_ngen*, corresponding to the number of simulations effected for each set of parameters in the population;
- the mutation scale *DEMC_gammascale*, corresponding to the probability of creating a new member from two set of parameters;
- the mutation probability *DEMC_crossover*, which corresponds to the probability that the new created set will be kept;
- the standard deviation of the error added to the mutation *DEMC_sigma*;
- the scaling factor *DEMC_accprob* for the acceptance of the parameters proposed by the algorithm (positive integer, 0 to accept only in case of performance improvement).

The calibrated variables used for the calibration of the model are:

- the effective porosity of each soil type *wcep*, it corresponds to the ratio of water volume the soil can hold in a saturated state to its total volume;
- the recession coefficient for surface runoff *srrcs* for each type of land use;
- the uppermost soil layer recession coefficient *rrcs1*, it indicates the tendency of water present in the first geological layer to penetrate the lower geological layer;
- the fraction of surface runoff *srrate*, used to represent the part of the water that runs off the surface;
- the maximum water velocity *rivvel*, used in the calculation of the delay time of the different subcatchments;
- a factor for calculating the soil water limit for potential evapotranspiration *lp*;
- the maximum percolation capacity from the first to the second soil layer *mperc1*;
- the fraction of soil available for evapotranspiration but not for runoff *wcfc*;
- the parameters of the rating curve *gratk* and *gratp.*

The DEMC algorithm has enabled the calibration of the most relevant parameters for obtaining flow data from 50,000 simulations. Performance was assessed using the average KGE for all subbasins with measurements.

Table 57.1 Performance assessment of the calibration part

Subcatchment of the hydrometric station	KGE for the period 2010-01-01 to 2017-12-31
11	0.16
50	0.41
56	0.19
58	0.10
64	0.24
76	0.46

57.3.5 Results

The results of the calibration are reported in Table 57.1 and Figs. 57.4 and 57.5.

Those simulations showed an over-estimation of the base flow and an under-estimation of peak flows for most stations. Underwater resurgence and catching groundwater may explain the over-estimation of baseline flows and the under-estimation of flood peaks. In addition, the Poulaphouca Reservoir data provided do not inform on its buffer role in case of heavy rain or when water demands increase. The KGE of each station is greater than 0, so we can validate the model as a first step.

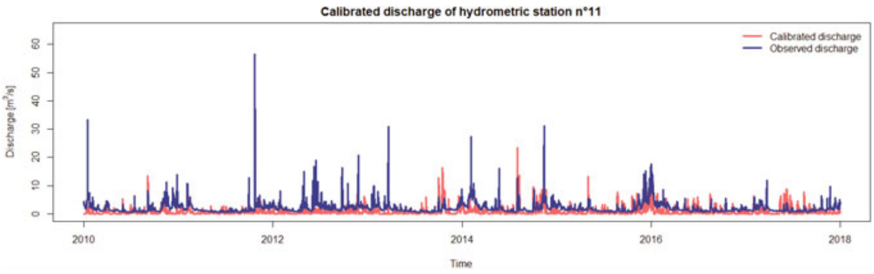

Fig. 57.4 Calibrated discharge of the hydrometric station n°11 (KGE = 0.16)

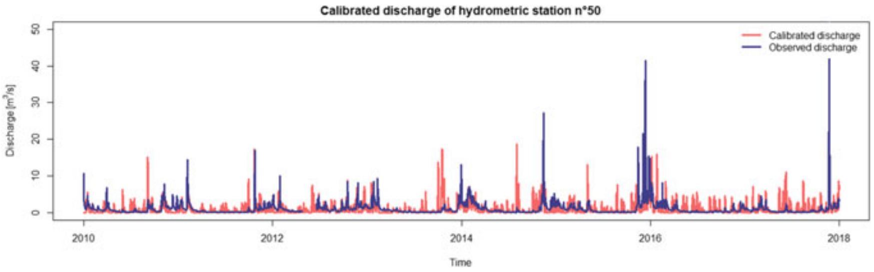

Fig. 57.5 Calibrated discharge of the hydrometric station n°50 (KGE = 0.41)

57.4 Validation

The results of the calibration are reported in Table 57.2 and Figs. 57.6 and 57.7.

Those simulations highlight an underestimation of the flow in a flood period and an overestimation in a low water period can be observed. The KGE are for 5 stations out of 6 higher than 0 and all are higher than the average of the flow over the period considered (Figs. 57.8, 57.9, 57.10, 57.11, 57.12, 57.13, 57.14 and 57.15).

Table 57.2 Results of the validation part

Subcathment of the hydrometric station	KGE of the calibration period 2010-01-01 to 2017-12-31	KGE of the validation period 2018-01-01 to 2018-12-31
11	0.16	0.10
50	0.41	0.31
56	0.19	0.37
58	0.10	−0.12
64	0.24	0.15
76	0.46	0.45

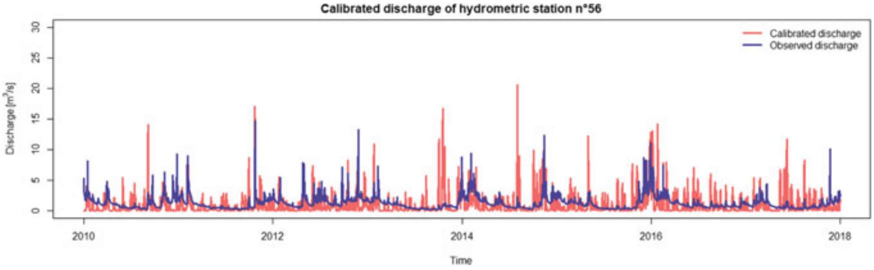

Fig. 57.6 Calibrated discharge of the hydrometric station n°56 (KGE = 0.19)

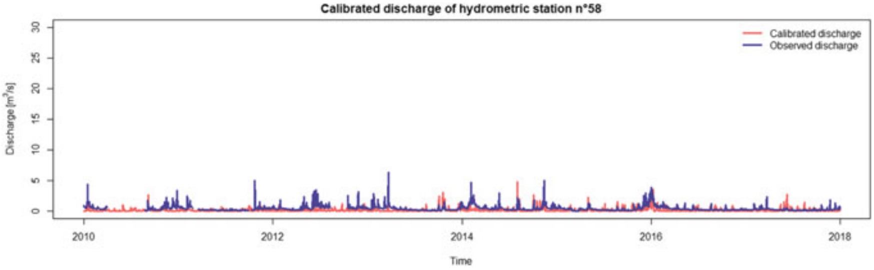

Fig. 57.7 Calibrated discharge of the hydrometric station n°58 (KGE = 0.16)

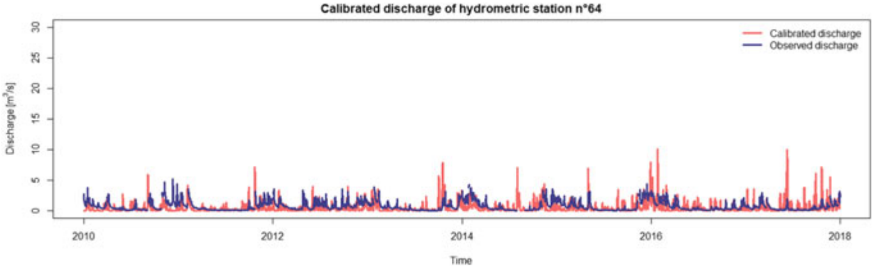

Fig. 57.8 Calibrated discharge of the hydrometric station n°64 (KGE = 0.24)

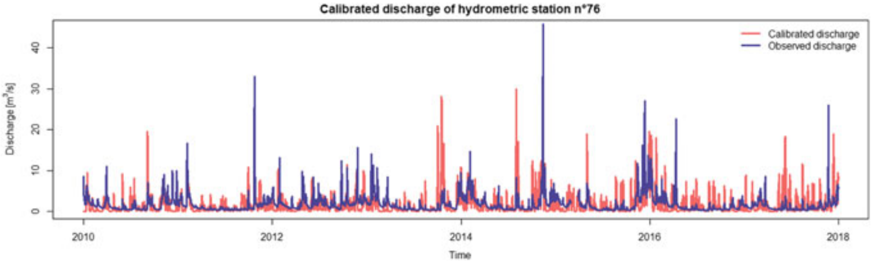

Fig. 57.9 Calibrated discharge of the hydrometric station n°76 (KGE = 0.46)

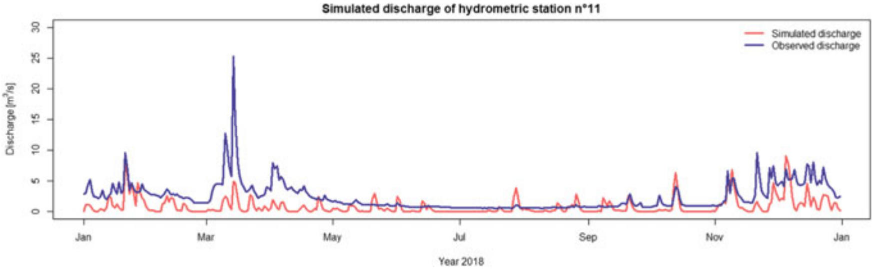

Fig. 57.10 Calibrated discharge of the hydrometric station n°11 (KGE = 0.10)

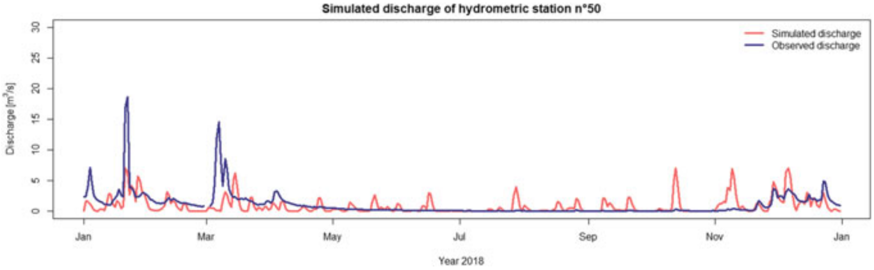

Fig. 57.11 Calibrated discharge of the hydrometric station n°50 (KGE = 0.31)

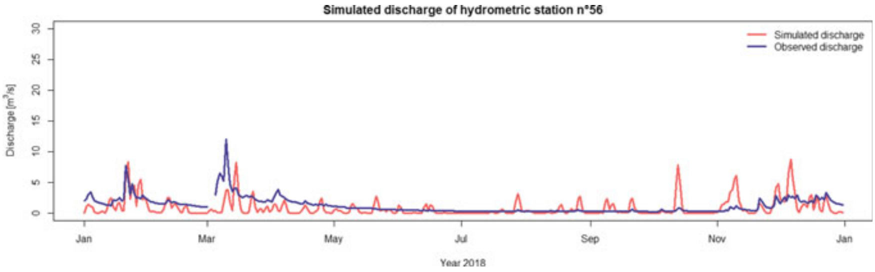

Fig. 57.12 Calibrated discharge of the hydrometric station n°56 (KGE = 0.37)

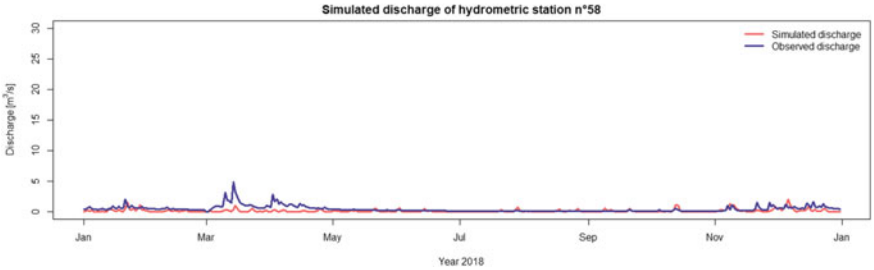

Fig. 57.13 Calibrated discharge of the hydrometric station n°58 (KGE = −0.12)

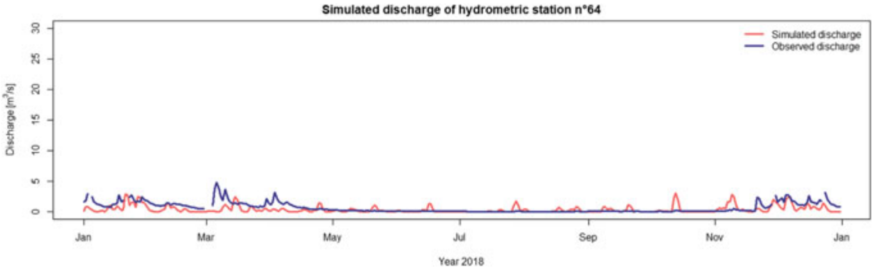

Fig. 57.14 Calibrated discharge of the hydrometric station n°76 (KGE = 0.15)

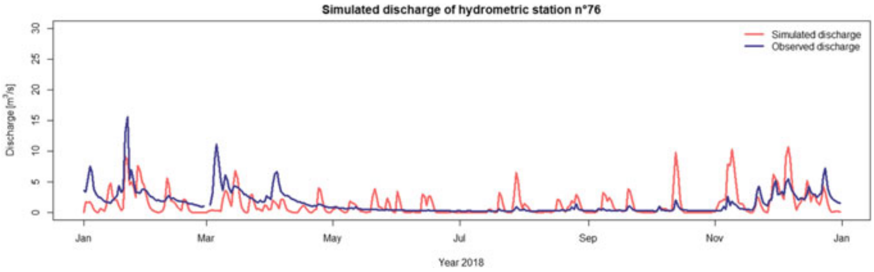

Fig. 57.15 Calibrated discharge of the hydrometric station n°76 (KGE = 0.45)

57.5 Areas of Improvements

In order to obtain more representative and accurate results, the following non-exhaustive list of improvements has been established:

- Represent the dynamics of the Poulaphouca Reservoir with an outflow time series;
- Use correction parameters for input data such as evaporation or precipitation;
- Knowing the real depth of the rivers of each sub-basin could certainly improve the performance, for this purpose measurements are needed at several points along the rivers in order to interpolate an average depth;
- Tables 57.1 and 57.2 underline the disparity in performance of the various stations. The performance of the model depends strongly on the chosen performance criterion, especially via the calibration algorithm. The HYPE model allows for the creation of its own performance criterion. This could be a good option to get a better calibration;
- In the same way, the stations were chosen according to their location and not according to the importance of their flow, which corresponds to the hydraulic contribution of the basin. Defining the basins according to the positions of the hydrometric stations would make it possible to work with a larger number of gauged basins and potentially obtain better results;
- Starting the calibration period at the beginning of the hydrological year (in opposition with the Gregorian one) would allow the water table to be filled more quickly and obtain better performance;
- Adding parameters could refine the calibration and bring better results. Many parameters were not used in the calibration such as dynamic data correction, extraction and pumping parameters, water percolation through the soil…;
- A step-by-step calibration is also possible with the HYPE model, although much more time-consuming than an automatic calibration, it could allow more robust parameter values to be found [15];
- A post-calibration of the results can be done, based on the low and high flow period in order to calibrate the average flow over these periods.

57.6 Conclusions

The DEMC algorithm was used to calibrate the most relevant parameters for obtaining flow data from 10,000 simulations. The performance was evaluated using the KGE criterion. Those simulations showed an overestimation of the base flow and an underestimation of the flood peaks for most stations. A post-calibration correction could be considered to correct these phenomena and obtain a better performance.

The HYPE model provides a highly detailed description, with more than 300 parameters that can be entered and calibrated to describe the studied catchment in the best possible way, the parameters used in this work were limited to those with a direct and significant impact on the flows. A more consistent use of parameters could lead to better results. It is also possible to fill in and create another performance criterion than those proposed by the model and to calibrate the model according to it.

The results obtained are encouraging given the simplifications made, such as classifying the land use layers into only 5 categories and calibrating the model with only the parameters that have a noticeable impact on the flow rate, etc. In addition, the wide possibility of description of the basin offered by the HYPE model suggests that an improvement in the model's accuracy is achievable.

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