A new hydro-climate model for urban water management including nature based solutions : a preliminary application on Paris metropolitan area

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KEYWORDS

urban hydro-climatology, multi-watershed calibration, model evaluation, Hydrological Response Units

ABBREVIATIONS

CSO	Combined Sewer Overflows
HRU	Hydrological Response Units
NBS	Nature based solutions
TEB	Town Energy Balance model
TEB-Hydro	urban hydrological module from TEB
UHI	Urban Heat Island

ABSTRACT

Cities are highly sealed resulting in less infiltration in the ground and so on in high quantities of runoff water and less evapotranspiration. A large part of stormwater is then drained by separate or combined sewer systems. In case of heavy rainfalls, stormwater can join directly the river, eventually leading to urban floods, or overflows through the combined sewer, then increasing the risk of river pollution.

Allowing notably the study of water management and thermal comfort in cities, the Town Energy Balance (TEB) hydro-climatic urban model, constitutes a tool to evaluate adaptation strategies to urbanisation effects. Indeed, it makes it possible to study different nature based solutions scenarios (green-roofs, watering, …). Few studies are modelling the combining effects of hydrology and micro-climate in cities while they are jointly involved in urban planning strategies.

This study relies on a reconstructed sewerage network in the Paris metropolitan area adapted to the model resolution. Such a large area requires a specific multi-watershed calibration approach, rarely applied in urban areas. It will be based on the division of watersheds into hydrological response units. In light of an eighteen years simulation, an evaluation of the performances of the model (stormwater or combined flows) is performed using a multi-site objective function.

1. INTRODUCTION

Cities concentrate more than half of the world's population. This number continues to grow and cities are becoming denser. Cities with more than 10 millions inhabitants, or megacities, are estimated to rise from 33 in 2018 to 43 in 2030 (UN, 2020). This is why understanding urban microclimate and hydrological cycles becomes critically important as the well-being of inhabitants of cities continues to decline. Indeed, added to global climate change, the urban heat island (UHI) effect creates additional heating of city centers compared to the surrounding countryside. Since the surfaces are largely impermeable, the cooling effect of evapotranspiration is reduced from the lack of natural surfaces and water storage capability.

Urban models are then improving to compute the combining effects of hydrology and micro-climate in cities (Mitchell et al., 2007). Indeed, urban fluxes need to be better understood to adapt cities to actual and future climate through maintaining thermal comfort in cities. In this pursuit, adaptation strategies are required. They strongly rely on Nature Based Solutions (NBS), impacting both water and energy budgets strongly dependent on each other.

As a consequence, in order to improve heat flux computation linked to soil water content, urban climate models are on one hand improving vegetation representation in cities (Building Energy Parametrization, BEP, Martilli et al., 2002) and on the other hand integrate more specifically urban subsoil (Surface Urban Energy and Water Balance Scheme, SUEWS, Järvi et al., 2011) but rarely sewer networks like in the urban canopy model Town Energy Balance (TEB-Hydro, Stavropulos-Laffaille et al., 2018). On the other hand, urban hydrological models are improving energy balance through evapotranspiration explicit computation in their models for developing Sustainable Urban Drainage Systems such as the Storm Water Management Model (SWMM) model through the Low Impact Development Controls module (Rossman et al., 2015).

When hydrological processes are taken into account, a calibration is necessary to adjust the model to the soil and subsoil local constraints as for example by determining the values of the parameters that allow it to obtain the best performance (Gupta, 1998). Urban models are applied to rather small areas ranging from plots to a watershed (Yazdi et al., 2019, Saadatpour et al., 2020). Comparative modelling studies of several different but generally unconnected urban watersheds have already been conducted (Bae et al., 2019). Rarely, studies with urban connected watersheds can be made (Haghighatafshar et al, 2019).

Instead, studies of several watersheds and sub-watersheds are observed in the natural environment. To address the problem of setting up a large urban area with multiple catchments and sub-catchments, the methods used in natural environments could be a clue. Multi-watershed calibration towards regionalization approaches are starting to expand as Management Category classification for Dong et al. (2020) or Hydrological Response Units (HRU) for Fang et al. (2020). This allows for multiple watersheds to be calibrated at the same time rather than a uniform calibration on the whole area.

Several studies have shown calibration differences obtained using multiple spatialization methods: single-site calibration at the watershed outlet, sequential calibration from upstream to downstream and simultaneous multi-site calibration (Leta et al., 2016) but also temporally with multi-event method (Awol et al., 2018). They also highlighted the need of an objective function adapted to multi-watershed studies to evaluate model calibration (Alamdari et al., 2017, Dong et al., 2019).

The aim of this study is then to adapt multi-watershed calibration usually used on natural watersheds to a large urban domain with sewer network. It is based on the regionalization method in HRU classification. In this document, a first part will describe the model used and the characteristics of the study site. Then, the calibration method selected for this domain will be detailed. Finally, the first results concerning the application of the method on the Paris metropolitan area will be presented.

2. TOOLS AND STUDY SITE

2.1 TEB MODEL

For this study, the physically-based, distributed urban hydro-climate model, TEB-Hydro is used (Stavropulos-Laffaille et al., 2018). It constitutes the implementation of urban hydrological processes in the TEB model (Masson, 2000).

This model integrates an urban subsoil containing a sewer network (**Figure 1**) in an urban canyon regularly gridded. This town is characterized by 3 different compartments: buildings, road and garden, making it possible to calculate the specific characteristics of each compartment and then aggregate them to the whole mesh. It permits to fully take into account interactions between the energy and water balance through the explicit computation of evapotranspiration (*E* and *ET*). Water interception and retention capacity of roofs and roads through surface water reservoirs is taken into account leading to surface runoff (*R*) if thresholds are exceeded. Infiltration (*I*) of water to the ground is modeled then water is transferred vertically in subsoil layers. This subsoil description is also improved with evolution of soil water content (W^{gr}) through horizontal water transfer (*T*) under the different tiles (garden, buildings and roads). Soil water can be drained by the sewer network (I_{sew}) and *D* represents drainage in the deepest layer of subsoil.

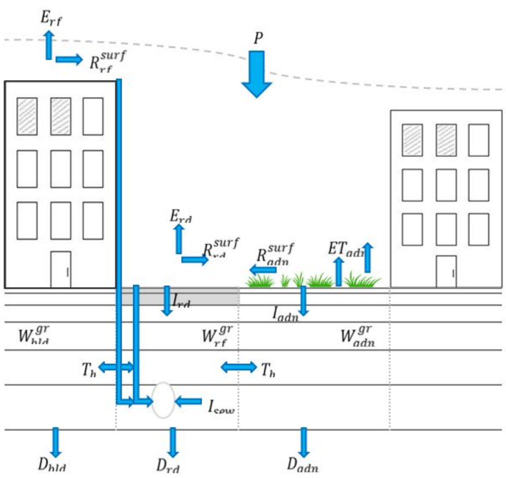

Figure 1 : Diagram of the hydrological processes modelled in the TEB-Hydro model; subscripts *rf* and *bld* stand for building compartment, *rd* for road compartment and *gdn* for garden compartment. (Stavropoulos-Laffaille et al., 2018)

Vegetation is explicitly parameterized with TEB-Veg module that takes into account the effects of low vegetation (Lemonsu et al., 2013) and high vegetation with TEB-Tree module (Redon et al, 2018; Redon et al, 2020) in cities. Currently, it is also possible to introduce NBS such as extensive green roofs thanks to the Greenroof module (de Munck et al., 2013) implemented within TEB.

This study constitutes the first coupled simulations with urban vegetation and hydrology modules in TEB.

2.2 CLIMATOLOGICAL CHARACTERISTICS

The Paris metropolitan area (**Figure 2**), with a size of 5184 km², is characterized by an altered oceanic climate. It is specified by four seasons and high differences in temperature between winter and summer. The mean annual temperature is between 8.9°C (average minimal annual temperature) and 16°C (average maximal annual temperature, Paris Montsouris weather station, **Figure 2a**, 1981-2010). Rainfalls are frequent in all seasons but with low precipitations per year (637 mm). Lowest precipitations are in February with an average of 41.2 mm while May has the strongest precipitations with an average of 63.2 mm.

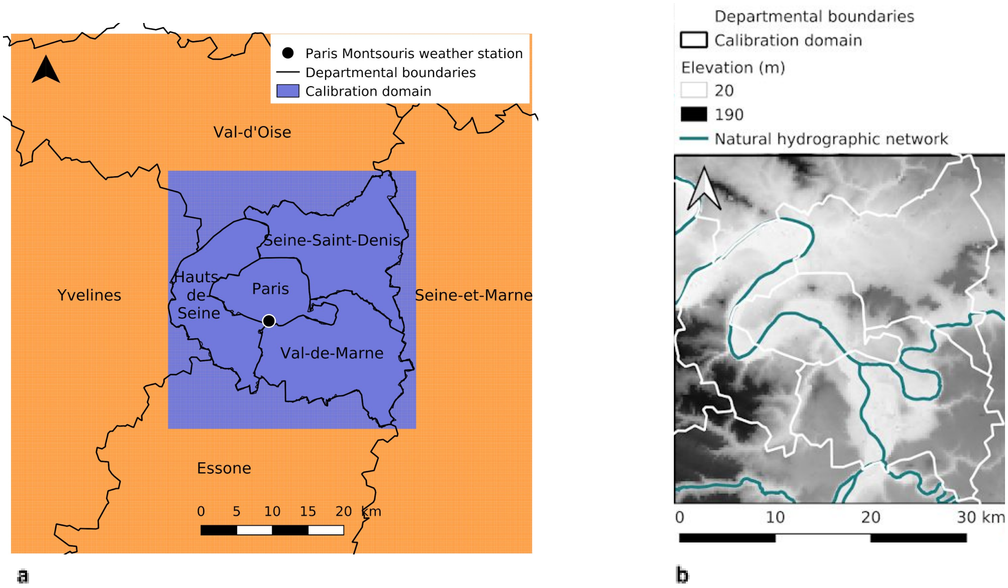

Figure 2 : Study site and topography of the calibration domain

2.3 Land use

The entiere urbanized area is represented by a total imperviousness rate of 25.2%. However, it is very variable, even at the Paris arrondissements scale where it is ranging from 24% to 76%. A sensitivity study of the model to soil texture is underway to determine the most suitable database for our study between Harmonised World Soil Database (HWSD, FAO et al., 2012), Topsoil (Ballabio et al., 2016) and SoilGrids (Hengl et al., 2017) available at a resolution of 1 km to 250 m throughout Europe.

2.4 Sewer network data

This area is an urban watershed included in the wide Seine-Normandie watershed. The catchment is quite flat with a maximum altitude variation of 165 m and an elevation of between 20 and 190 meters above sea level (**Figure 1b**).

Through a collaboration with the sewerage system management teams, the sewer network was obtained on the whole domain comprising the four departments in the Paris metropolitan area : Paris (75), Hauts-de-Seine (92), Seine-Saint-Denis (93) and Val-de-Marne (94). It led to the reconstruction of the sewer network (Chancibault et al., 2020) and the obtention of a substantial amount of flow measurements on transfer points and sewer overflow.

Table 1: Inventory of the various flow measurement points in the sewerage network of Paris metropolitan area

Departments	Number of stations	Availability period
Hauts-de-Seine (92)	33 transfer points on combined sewer 73 CSO	2012-2018

Seine-Saint-Denis (93)	3 transfer points on stormwater sewer 4 CSO	2000-2018
Val-de-Marne (94)	31 transfer points 11 CSO	2002-2007 2002-2008
Paris (75)	30 transfer points on combined sewer 1 CSO	2014

These data constitute a total of 89 sewer overflow and 97 transfer point flow measurements (Table 1) at hourly intervals over periods ranging from 2000 to 2018. Such a large amount of data would be a consequent workload for this specific study. This is why a method was developed to reduce the number of observations data while conserving the ones with the best quality only.

The realism of the reconstruction of the sewerage network upstream of each measuring station is therefore analysed. This makes it possible to eliminate some of the stations. The flow measurements at the retained transfer points are therefore qualified. This also makes it possible to remove certain points that did not have data of a sufficiently good quality. Thus, it permits to save only a few sub-watersheds over the entire area.

Then, on the retained watersheds, the Combined Sewer Overflows (CSO) were qualified in the same way. For each watershed where data from all CSO are of good quality, an equivalent CSO was selected or added at the outlet of the watershed. In this manner, only one maximum CSO is kept for each watershed. The simulated flows at the location of an equivalent CSO will therefore correspond to the sum of the observed upstream overflows of the watershed.

As a result of this process, eighteen transfer points (four for stormwater catchments, three for waste water catchments and 11 in combined catchments) and five equivalent sewer overflows remain. They are distributed fairly evenly throughout the Paris metropolitan area departments, although a few areas remain poorly represented.

These transfer points are mainly located on the combined sewerage network. A method of extracting the wastewater signal and the parasitic clear water is applied to keep only the stormwater signal, which is represented by the model.

3. METHODS

3.1 HRU DETERMINATION

On such a large domain, with heterogeneity, it is not relevant to calibrate the whole area uniformly. This is why we have chosen to rely on a regionalisation method and more specifically on a Hydrological Response Units classification. It allows one to calibrate identically areas that possess the same flow routing properties e.g. imperviousness, soil texture, slope (Flügel, 1995). As it optimizes the calibration, it offers the possibility to reduce computational time compared to a calibration of each sub-watershed independently (Dong et al., 2020).

This method is mainly applied on natural catchment areas, in natural or sub-urban environments but has never been applied on big urban catchment areas, even less which include sewerage networks. Indeed, urban catchment areas are generally set in a uniform way or with a multi-catchment setting. However, this method is well adapted for urban catchments where streets designs and sewer highly influence runoff and flow direction (Gironás et al., 2009, Sanzana et al., 2013).

Specifically adapted for our case study, we choose to distinguish the behaviour of watersheds on three criteria. The first criteria is the type of sewer network encountered in the urban watershed : stormwater or combined sewer. Indeed, they won't have the same hydrological response. The second criteria is the imperviousness rate of each watershed. This parameter has an important impact on flow regimes, changing the stormwater runoff, lag time and intensity of stormflow (Jacobson, 2011). The third criteria is mean slope between adjacent meshes, also influencing the intensity and the lag time of the peak flow.

3.2 Objective function

Numerous studies are demonstrating the necessity of simultaneous multi-site objective function for calibration evaluation (Leta et al., 2017, Alamdari et al, 2017, Awol et al., 2018, Nkiaka et al., 2018). Indeed, objective functions are equations allowing to evaluate the goodness of fit of the model to the observations, adapted to the objectives of the study. To compare the results with all outlets at the same time, Awol et al. (2018) chose the multi-site average objective function as the best adapted. In a case of comparing each indicator separately, more weight is given to a very high score between outlet flow modelling flow and observation, even if another outlet has a lower score.

A multitude of indicators have been developed but our choice is to turn towards the Nash Sutcliffe Efficiency (NSE, Nash and Sutcliffe, 1970) and Pbias (Gupta et al., 1999). Thus these indicators are calculated for each watershed, then the mean of the ensemble is evaluated.

4. RESULTS

4.1 Range of calibration parameters

The parameters to be calibrated for TEB-Hydro are : the rate of soil water infiltration into the sewerage network, the rate of connection of urbanised surfaces to the network, infiltration through the roadway and a drainage limitation term at the base of the soil column, which could possibly represent the effect of a perched water table (Stavropulos-Laffaille et al, 2018). In previous studies using the TEB-Hydro module, ranges were determined for those parameters that need to be calibrated (Table 2).

Table 2: Variation range of calibration parameters (Stavropulos-Laffaille et al, 2018)

Parameters	Min	Max
Sewer pipe tightness (I_p)	10^{-3}	1
Road infiltration rate (I_{rd})	10^{-9}	10^{-5}
Deep drainage limitation (D_*)	0.01	0.05
Impervious surface connected to the sewer network (f_{con})	0.5	0.9

The phasing of the hydrological module of the TEB model with the other modules required modifications in the calculation of the different processes, so a sensitivity study will be carried out to refine new ranges of variation of the different calibration parameters to be set based on the work already carried out by Furusho et al. (2013) and Stavropulos-Laffaille et al. (2018).

4.2 Determination of calibration and evaluation periods

After a qualification phase of the obtained flow measurements, two observation availability periods for calibration stand out for four departments each :

First period : 2003 - 2007 for Seine-Saint-Denis (93) and Val-de-Marne (94). On this period, annual precipitations are highly variable, ranging from very dry to very wet years

Second period : 2012 - 2017 for Seine-Saint-Denis (93) and Hauts-de-Seine (92). On the contrary, this period is quite stable in annual mean precipitation.

The available period of data of the Seine-Saint-Denis department will make it possible to see if the same calibration is obtained on the two distincts periods of time. Indeed, the sewerage network has been modified over this long study period. It is therefore a sensitive element to keep in mind.

Based on the different periods of availability of the flow data, 2002 and 2011 are the modeling warming periods of the two simulations. Calibration period will take place from 2003 to 2005 for the first period and 2015-2017 for the second period. Then, the evaluation period will be held from 2006 to 2007 and 2012 to 2014. For the year 2014, data are available for every department of the studied area including Paris. This year will be used for the whole domain evaluation.

This calibration step will allow for the consequent study of the hydro-microclimatic variability of the Paris metropolitan area in present time and with climate change, which requires a study over a long time period. This is why this study requires a specific calibration not depending on the intensity of precipitation events.

4.3 Watershed delineation

Urban watersheds are determined from routing of the flow in the sewer network. **Figure 3a** shows the combined sewer watersheds in shades of purple and stormwater watersheds in shades of green. Here we have 80 watersheds with specific slopes (**Figure 3b**) characteristics and imperviousness rate (**Figure 3c**). It was possible to determine 5 HRU (**Table 3** and **Figure 3d**) relying on the gauged watersheds. They represent few imperviousness with low slope (class 1) and high imperviousness and high slope (class 2) for stormwater sewer network outlets. Then, on the combined sewer network outlets, class 3 represents city centers with low slope and a high imperviousness rate, class 4 groups highly impervious watersheds and with a high slope and class 5 is for more peripheral watersheds less impervious and with a more important slope.

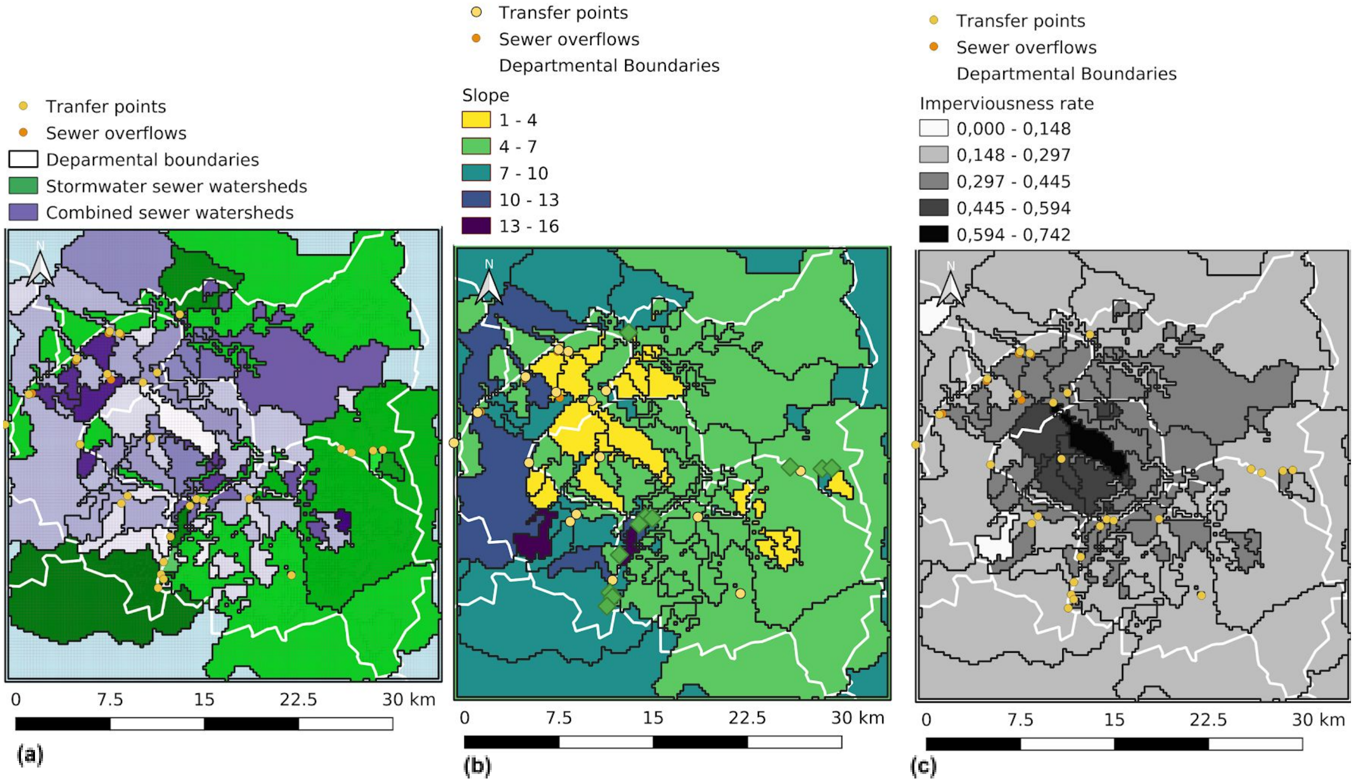

Figure 3 : HRU classification for urban watersheds of the domain (d). It relies on sewer type (a), elevation variation (b) and imperviousness rate (c)

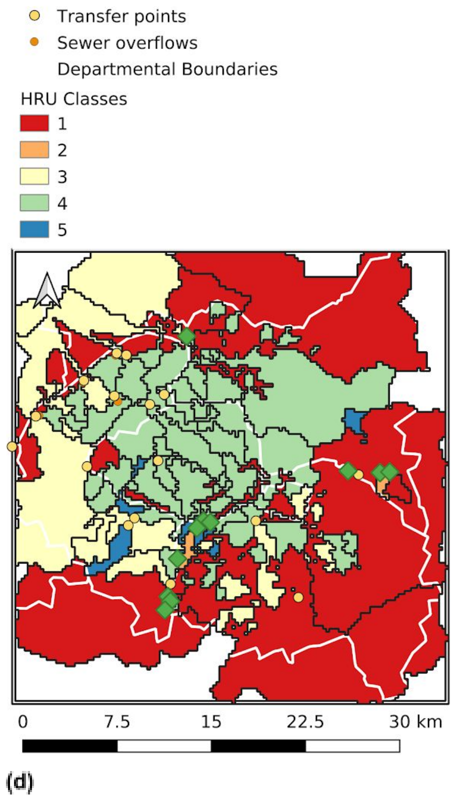

Table 3 : HRU classification along 5 classes described by their sewer type, slope and imperviousness

HRU class	1	2	3	4	5
Sewer type	stormwater	stormwater	combined	combined	combined
Mean slope (%)	<7.5%	>7.5%	<7.5%	<7.5%	>7,5%
Imperviousness rate (%)	<30%	>30%	<30%	>30%	>30%

4.4 Calibration method

A sequential calibration method will be used for this study. The calibration is carried out in a temporally differentiated manner, separating first (**Figure 4a**) and second period (**Figure 4b**). Each of these periods will also be calibrated from upstream to downstream HRU. Thresholds of combined sewer overflow are determined with the same method.

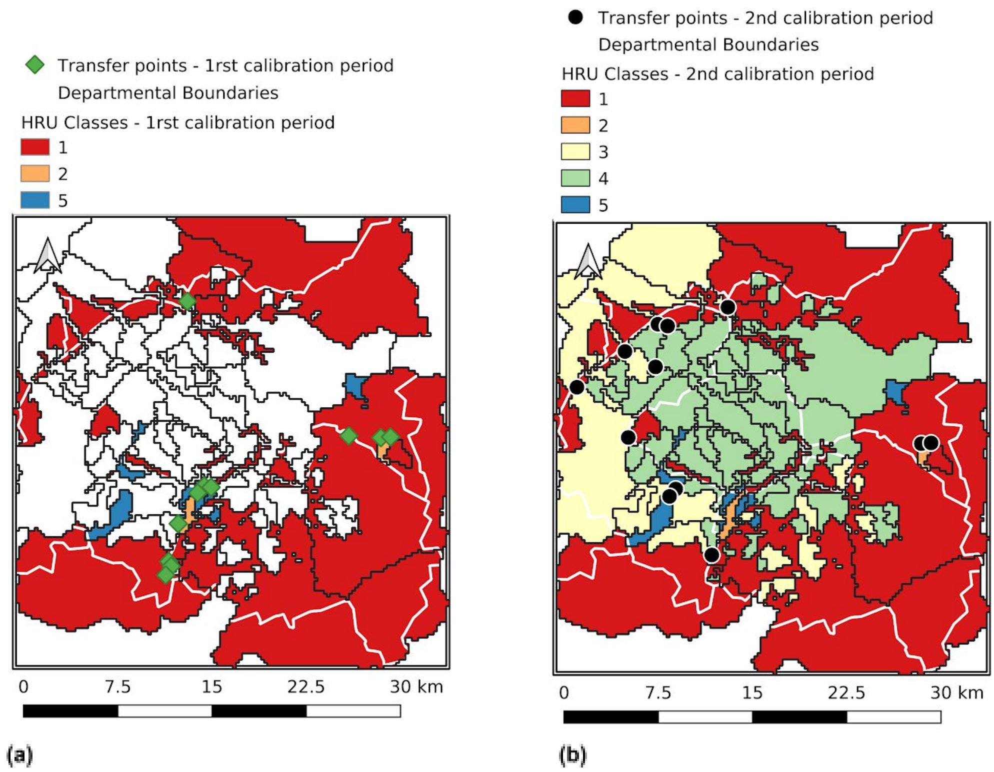

Figure 4 : Subwatersheds that can be calibrated for each calibration period, classified in HRU

Stavropulos-Laffaille et al. (2018) found out the same calibration values applying TEB-Hydro on two watersheds in Nantes (France). They are not connected and composed with different soil and land use characteristics. It could then be possible to find a specific calibration depending on the model particularities. This study would demonstrate this point if the same values of calibration on the whole domain and in the different time periods of calibration are found. It would also be interesting to uniformly calibrate the whole domain and compare scores of the objective function obtained.

Conclusions

This paper highlights the specificities of a large urban watershed modeling and the problems that can be faced in calibrating it. The Paris metropolitan area is the first case study simulation for the coupled version of the TEB hydro-climatic urban canopy model. In addition to the urban intrinsic problem of UHI and sealing of natural surfaces, the effects of climate change could make this area even more vulnerable.

A preliminary work consists in collecting data concerning Paris metropolitan area combined and separate sewer networks description and flow measurements. This led to their reconstruction to adjust it to modeling constraints (Chancibault et al., 2020).

The sorting out and qualification of a large number of flow observations is described. The calibration parameters of TEB-Hydro and their range are detailed. Then a calibration method is developed and presented to adapt to the particularities of this large urban domain comprising several subwatersheds and multi-outlets, based on observations available over multiple long time periods. It relies on hydrological response units classification depending on the sewer network, slope and imperviousness rate of the watershed. The evaluation method leans on multi-site average objective function with Nash Sutcliffe Efficiency, Pbias and correlation coefficient indicators.

This method will be applied and evaluated on the domain of the Paris metropolitan area and the results will be shown in the oral presentation.

As home to 4.5 million inhabitants, the aim of studying this domain is to highlight present and future hydro-climatic responses so that relevant NBS scenarios can be proposed and evaluated to adapt to climate change.

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