Quantifying Benefits of Permeable Pavement on Surface Runoff, An Agent-Based-Model with NetLogo

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Abstract. Permeable pavements benefits are large and well-studied all over the world by the scientific community however they are still not yet frequently used in urban projects. In order to explore permeable pavement benefits an Agent-Based-Model (ABM) was built. The model addresses the impact of the soil occupation of an urban catchment on its hydrological response. Specifically, it aims at quantifying the impacts of permeable pavement on runoff. ABM allows for exploring global phenomena by the integration of local processes. In this model, a simple micro-scale rule (move to the adjacent cell with the lowest piezometric level) performed by all the agents *Drops* gives a very relevant flow simulation at catchment-scale. This conceptual model is GIS-based and does not require important hydraulic data. Results show that turning 2.5% of the impervious cover into permeable pavements can reduce the runoff by 8.3%. Model exploration highlights where and in which proportion permeable pavements should be used to be the most efficient.

Keywords: Agent-based-modeling · Hydrological behavior · GIS
Netlogo · Permeable pavement · Runoff

1 Introduction

The long term process of urbanization, hand in hand with the demographic growth, have resulted in the alteration of the natural hydrological cycle. Indeed, the increase of impervious surfaces in urban catchment leads to the increase of surface runoff through the decreased of infiltration and evaporation capacity (Braud et al. 2013; Haase 2009; Jacobson 2011; Miller et al. 2014). Meanwhile, climate change is likely to lead to an increase of the frequency of extreme rainfall events that will be accompanied by a more frequent occurrence of short duration floods (Yin et al. 2016). Over the past decades, alternative approaches known as Low Impact Development (LID) have been developed to address these issues. Among them, permeable pavements are particularly well adapted for urban planning in dense urban areas. They are well studied all over the world by the scientific community (Brunetti et al. 2016; Illgen et al. 2007). However, permeable pavements are still not yet frequently used in urban projects. The

development of a new pervious concrete formulation at the ESITC laboratory (Nguyen et al. 2014) highlighted the need for tools to help local authority and stakeholder to use these techniques. In this context, modeling permeable pavement benefits on runoff in an urban setting, is increasingly relevant given their high potential benefits. Authors underline also the need for model that integrated the individual component and the urban water cycle at catchment scale (Fletcher et al. 2013; Salvadore et al. 2015). However, building an integrated model at a fine space and temporal resolution is often compromised by the complexities of urban environment and the hydraulic data needed (Chen et al. 2009). One solution is the use of simplified approaches based on cellular automata (Webber et al. 2018). This paper describes the development and test of an Agent-Based-Model (ABM). The model is GIS-based and is applied to an urban catchment in Normandy. This model will help to explore the benefits of permeable pavements on surface runoff with high spatial (1 m^2) and time (1 min) resolution. The final goal of this work is to give recommendations on where and in which proportion permeable pavements should be used to be the most efficient.

2   Materials and Methods

2.1   Catchment Description

Ouistreham is located in the North-West of France, in the region of Normandy (49°17′ N 0°16′ W). The climate is oceanic with rainfalls all year long and a little seasonality variability. The average annual temperature is 11.6 °C and the average annual precipitation is 679 mm. The catchment consists of a district of Ouistreham, named Riva Bella, built by the sea from the year 1960. This 48.3 ha catchment is built on a dune, sandy soil, and has the particularity of not having any storm water sewage network. Indeed rainfalls were historically infiltrated into the dune as all sidewalks and parts of the road were not covered. In the past few years, with the waterproofing of roads and sidewalks, flooding started to occur during heavily rainfall events. To deal with the runoff infiltration wells have been dug at strategic localizations but they require regular maintenance as the sand clogs them quickly.

Topography was obtained from a Lidar database (Litto3D®) with a horizontal resolution of 1 m and a vertical precision of 20 cm. Land use was defined from aerial photography and field observation, Fig. 1.
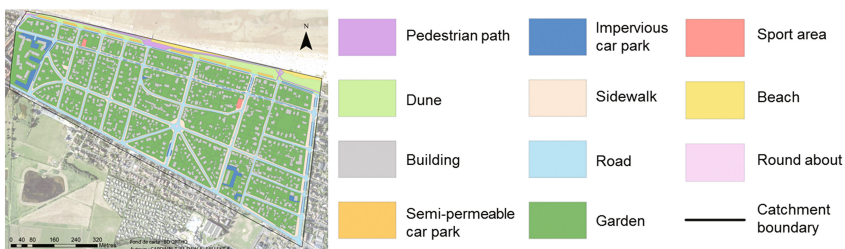

Fig. 1. Land use of the 'Riva Bella' catchment.

2.2   Model Development

Entities, State Variables, and Scales

The model is developed with NetLogo which is a multi-agent programmable modeling environment. ABM consists of two major elements: cellular automata (cells) and agents. First ArcGIS is used to develop land use and topography rasters. Next, NetLogo applies the rasters information to a grid of cells of 1 m^2 dimension. Then, from its land use attribute, each cell gets hydrological attributes in terms of interception (in mm) and infiltration (in mm/min). Two other attributes are used in case the cell is turned into permeable pavement, the flow in (in mm/min) giving the maximum water flow that can enter into the pavement, and the storage (in litres) giving the maximum storage allowed inside the pavement before the drainage. These attributes are obtained from a previous physical-based-modeling of hydrological processes of permeable pavements (Cortier et al. 2017). Two agents are used in the model, *Drops* and *Waters*. They are used respectively to simulate the water flow at the surface and inside the permeable pavement structure. They have one attribute, their size. Four parameters are used for the permeable pavement generation: the ratio of permeable pavement surfaces other impervious surface (in %), their surface area (in m^2), the land use localization (car park, road, sidewalk, etc.) and the elevation localization (top, bottom). Finally the user selects the rainfall profile and return period and the evapotranspiration value.

Process Overview and Scheduling

After a setup process, the model runs the simulation following the same processes at each step (one step corresponds to one minute) and for each cell, Fig. 2. These
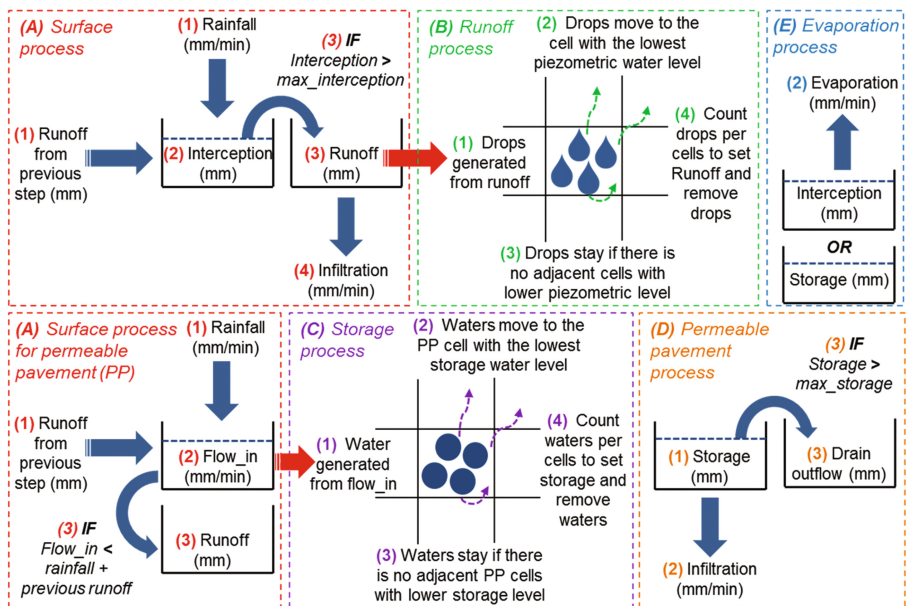

Fig. 2. Schematic of the model processes for one step. Procedures (A), (B), and (E) are run for each cell, procedures (C) and (D) are only run for permeable pavement cells.

processes are repeated until the end of the simulation corresponding to the end of the runoff discharge.

3   Results and Discussion

3.1   Model Sensitivity Analysis

A sensitivity analysis was conducted on each model parameters to both asses the model robustness and identify the key attributes. First, the number of agents *Waters* and *Drops* created at each step was tested from 1 to 9 (per cell). Results show, first that using only 1 agent per cell does not allow for accurate runoff and storage simulation, second that using from 2 to 9 agents only slightly increases the model accuracy. These parameters were set to 4 as a compromise between accuracy and computation time. Second, the hydrological parameters were tested in a range of realistic value for each. A multi-linear regression analysis was run on the results. This analysis shows that soil permeability is the most influent parameter (normalized coefficient of −0.44 and +0.87 on runoff and infiltration respectively). Interception parameters only have a significant impact on interception, and permeable pavement storage parameter only impacts the repartition between storage and drain outflow.

3.2   Main Results on Permeable Pavements Benefits

In order to explore the influence of permeable pavement ratio, size and localization on their benefits 72 simulations were conducted combining the four permeable pavement generation parameters. Results, obtained for a 100 years return period event, reveal that the ratio of permeable surface is the most influential parameter (Table 1). Results also highlighted that; (a) permeable pavement area does not have a significant impact, (b) permeable pavement are slightly more efficient when located at the bottom than at the top of the catchment and (c) they are more efficient when located on car parks than on roads (for this specific catchment).

Table 1. Average values of runoff peak reduction for the main localization parameters (in % of the runoff peak).

Localization parameters	Road	Sidewalk	Car park	Bottom	Top	2.5%	5%	7.5%	10%
Decrease of runoff peak (%)	9.1	13.1	15.1	12.9	12	5.5	10.5	14.6	19.1

4   Conclusions

This study presents an agent-based-model built for the quantification of permeable pavement impacts on urban runoff. Sensitivity analysis revealed that the soil permeability is the most influent parameter on the runoff. An exploration of permeable pavement benefits according to their ratio, size and localization was conducted. Results

reveal that, with the right localization, ratio of 2.5% and 10% of permeable surface can respectively reduce the runoff peak by 8.3% and 24.4% and increase the infiltration by 8.8% and 30.3% (for a 100 years return period event). Further model exploration will allow for better understanding permeable pavement impacts. Such study could help promote a widespread and right use of this LID technique.

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