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Integrating atmospheric deposition, soil erosion and sewer transport models to assess the transfer of traffic-related pollutants in urban areas

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ABSTRACT

For the first time, this paper develops an integrated and spatially-distributed modelling approach, linking atmospheric deposition, soil erosion and sewer transport models, to assess the transfer of traffic-related pollutants in urban areas. The modelling system is applied to a small urban catchment near Paris. Two modelling scenarios are tested by using experimentally estimated and simulated atmospheric dry deposits. Simulation results are compared with continuous measurements of water flow and total suspended solids (TSS) at the catchment outlet. The performance of water flow and TSS simulations are satisfying with the calibrated parameters; however, no significant difference can be noticed at the catchment outlet between the two scenarios due to the "first flush" effects. Considering the Cu, BaP and BbF contents of different particle size classes, simulated event mean concentration of each pollutant is compared with local in-situ measurements. Finally, perspectives to improve model performance and experimental techniques are discussed.

1. Introduction

Urban traffic emission is a major cause of nonpoint source pollution in cities and near high-ways (Fletcher et al., 2013; Petrucci et al., 2014; Shorshani et al., 2015). Key pollutants such as total suspended solids (TSS), heavy metals and polycyclic aromatic hydrocarbons (PAHs) are largely accumulated in the atmosphere with traffic activities, causing severe sanitation problems (Sabin et al., 2006; Wesely and Hicks, 2000). With time, these atmospheric phase pollutants can be transported and settled to urban surfaces forming dry or wet depositions (Huston et al., 2009). Finally, these nonpoint source pollutants are entrained by urban stormwater runoffs from separated sewer systems to water bodies, causing the degradation of aquatic environments and ecosystems (Shirley Clark, 2007). In the context of the European Water Framework Directive (2000), the mitigation of diffuse urban pollutions such as heavy metals and PAHs is one of the main objectives. Therefore, it is essential to understand the transport of such pollutants in urban air-surface-sewer systems during rainfall events.

According to the chemical nature and the source of pollutants, heavy metals and PAHs in urban stormwater runoff can be partitioned into solid and liquid phases (particulate and dissolved pollutants, respectively). Several investigations of the chemical and physical properties of these pollutants have been reviewed by (Aryal et al., 2010; Cho et al., 2016; Pant and Harrison, 2013). Generally, the authors conclude that most of the PAHs, Cu, Pb, Fe, and Ni are associated with fine particles. Based on these research results, we supposed that such pollutants are in particulate phase and distributed in different sizes of suspended solids (SS). Consequently, the spatial and temporal variations of the urban nonpoint source pollutants can be simulated by using physically-based and spatially-distributed soil erosion models.

Up to now, a large amount of integrated systems linking traffic flow, pollutant emission and atmospheric dispersion models have been developed (e.g. Elsawah et al., 2017; Hamilton et al., 2015; Lim et al., 2005; Oxley et al., 2013). However, very limited attention has been paid to couple atmospheric deposition and stormwater

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quality models. Shorshani et al. (2015, 2013) firstly proposed the concept of integrated traffic, air and stormwater modelling for urban areas. Nevertheless, the stormwater model in their modelling chain still relies on exponential, catchment scale washoff functions (Sartor et al., 1974). Moreover, the resolution of their model is restricted by the size of subcatchments. Since the Sartor et al. (1974) functions consider that the rate of pollutant loss on a subcatchment is directly proportional to the water flow at the outlet and to the averaged dry deposits, such equations are not capable of accurately describing the urban washoff processes, linked to the high variability of urban surfaces at very small scale (Bonhomme and Petrucci, 2017; Sage et al., 2015). An alternative way to improve the performance of the urban stormwater quality modelling might be to test the physically-based and spatially-distributed erosion models, which were initially developed for rural/agricultural catchments, to simulate the particle transport in urban areas. This novel modelling approach could lend itself to new ways of thinking in the field of urban stormwater quality modelling, and could potentially advance our modelling techniques.

In this paper, we linked for the first time a physically-based 2D erosion model (openLISEM, De Roo et al., 1996; Jetten and Roo, 2001) to an air quality model (SIRANE, Soulhac et al., 2011) and a sewer network model (SWMM, Rossman, 2010), in order to simulate the transport of particles of multiple size ranges and their associated pollutants in urban areas. The integrated modelling approach separately simulates the transfer of different sizes of particles, allowing the distribution of pollutants among various particle classes possible. Moreover, this integrated model independently calculates the detachment process caused by rain splash impacts and by shear stress effects, which is confirmed to be a crucial factor for accurate modelling of urban washoff process (Hong et al., 2016b). Finally, the coupling of spatially-distributed atmospheric depositions and the 2D surface models, emphasizes a promising potential for the improvement of the urban nonpoint source pollution management.

2. Materials and methods

2.1. Overview of pollutants pathways in urban areas

Generally, the particles deposited on urban surface preceding a rainfall event originate from two different sources, including the atmospheric depositions and the direct depositions from urban traffic and other anthropogenic activities (Fig. 1). During a rainfall event, the deposited particles can be detached and transported from surface runoffs to sewer networks. However, it is difficult to separate the traffic related pollutants from other sources by experimental measurements. Since it has been argued that the traffic-related pollutants which are emitted into the atmosphere contains large amounts of PAHs and metals, causing serious sanitary risks (Fletcher et al., 2013; Shorshani et al., 2013), thus this paper attempts to investigate the transfer of traffic-related pollutants from the atmosphere to the sewer outlet by an integrated modelling approach. Moreover, according to the studies of (Hong et al., 2016c; Shorshani et al., 2015), the particle size distribution (PSD) of suspended solids in stormwater runoff are quite different from that of surface dry deposits and atmospheric particles (Fig. 1), appropriate classification of particle size groups should hence be considered for adequate simulations.

2.2. Development of the integrated modelling system

The integrated modelling system consists of three separated components: the air quality component, the 2D surface component, and the roof and sewer network component. Due to the traffic activities, particles and their associated pollutants such as heavy metals and PAHs are firstly emitted and dispersed in the atmosphere, and then deposited on the urban surface. These processes are simulated by the air quality component. During the rainfall events, the surface dry depositions can be detached and transported by the urban washoff processes, the 2D surface component is used to simulate the urban washoff mechanisms. Finally, the roof and sewer network component is used to simulate the water routing and pollutants routing in sewer networks, from the sewer inlets and directly connected building roofs, to the catchment outlet. The scheme of the integrated model is presented in Fig. 2:

2.2.1. Air quality component

The air quality component of the integrated modelling system uses the SIRANE model (Soulhac et al., 2011) to simulate the dispersion and deposition of urban atmospheric pollutants. In the framework of the ANR (French National Agency for Research) Trafipollu project, the collection of the input data and the simulations were performed by AirParif (a non-profit organization accredited by the Ministry of Environment to monitor the air quality in Paris and in the Ile de France region). The outputs of the air quality component are adapted and connected to the 2D surface component in this study.

Within the SIRANE model, the streets are modelled as a network of connected road segments. Traffic emissions are firstly assumed to be uniformly mixed within each segment of street, the model then simulates the transport of pollutants in and out of the street segments by three main mechanisms: (i) advection along the street due to the mean wind along their axis, (ii) diffusion across the interface between the street and the overlying atmospheric boundary layer, and (iii) exchange with other streets at street intersections. The simulation at street level is then complemented by a standard Gaussian plume model for atmospheric transport and dispersion above roof level. Assuming that the deposition velocity is 0.1 cm/s, the deposition rates for different types of pollutants are calculated for the bottom layer of the atmospheric columns, forming spatially-distributed dry and wet deposits at the urban surface.

The input data for the air quality component is the traffic emissions, the meteorological situations (wind, precipitation, temperature), and the urban geometries. In the framework of the Trafipollu project, the hourly counting traffic data and the characteristics of vehicles were collected for the studied urban catchment over several weeks, in order to simulate realistic average daily traffic intensities. The emission of the traffic-related pollutants is then calculated by considering the vehicle types, traffic speeds, road characteristics (slope, composite materials, etc.), engine power and temperature (performed by AirParif). The weather data is offered by Meteo-France (The French national meteorological service), and the urban geometry data is provided by the National Institute of Geography of France (IGN).

According the European Water Framework Directive (DCE 2000/60/CEE), several substances should be investigated in priority for the protection of human health. Among these substances, the PM10 (<10 μm particles), Cu, Zn, Cd, benzo (a) pyrene (BaP) and benzo (b) fluoranthene (BbF) can be found either on air, surface and stormwater runoffs. Therefore, the air quality component simulate the dispersion and deposition process of such pollutants. The hourly deposition rates for such pollutants are calculated at regular points with 10 m distance. The total mass of the atmospheric deposition at each point between two rainfall events can be calculated by accumulating the hourly dry deposits during the dry period, indicating the dry hours between the end of the last rainfall event and the beginning of each selected rainfall event. Since this study focuses on the modelling of non-soluble pollutants, and PAHs are mainly

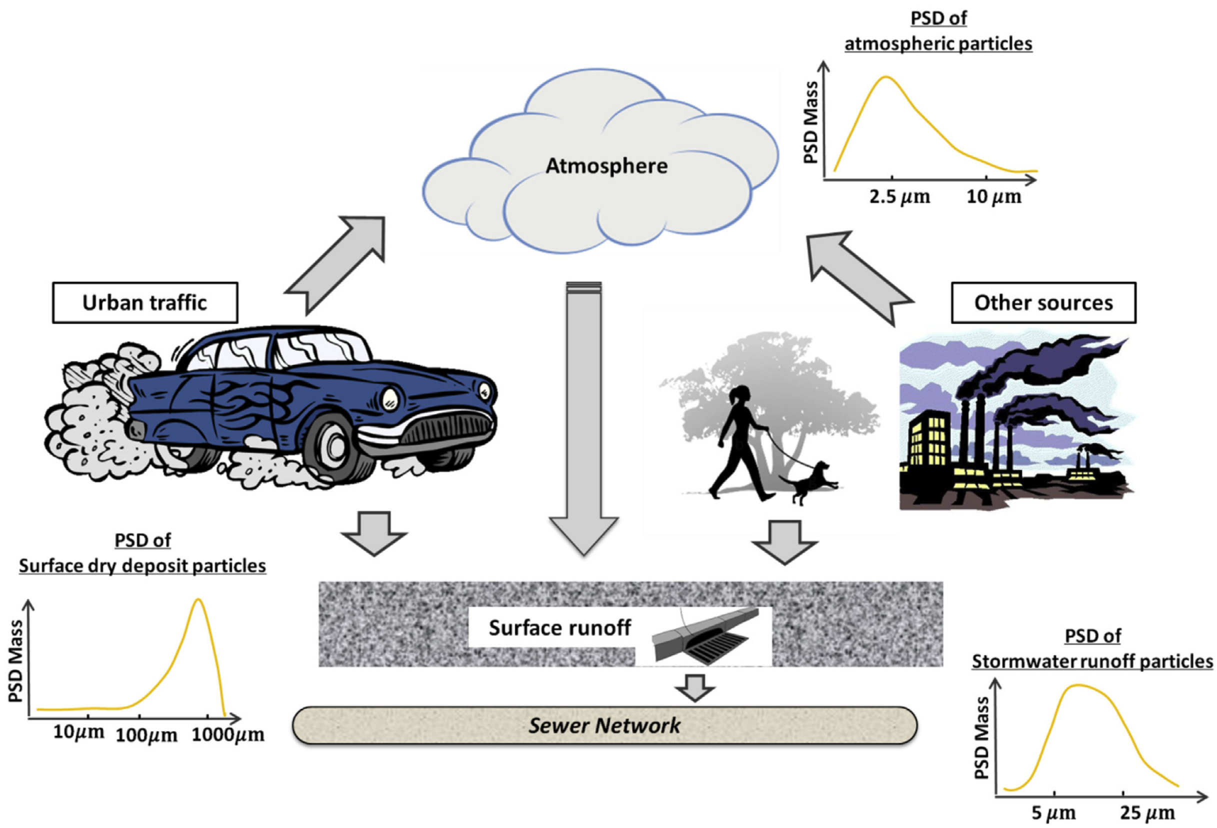

Fig. 1. Overview of the pollutants pathways in urban areas, accompanying with an outline of particle size distribution (PSD) calculated based on mass, for atmospheric particles, surface dry deposits and suspended solids in stormwater runoffs, respectively.

related to a certain sizes of particles which are not sensitive to the rain scavenging process, named as "Greenfield Gap" (Duhanyan and Roustan, 2011; Loosmore and Cederwall, 2004; Slinn, 1977), the modelling of wet deposition loads are hence neglected in this research.

In order to link the air quality component with the 2D surface component, the accumulated atmospheric dry deposits at regular points (10 m) are then transformed into 5 m-resolution dry deposit maps by using the triangle interpolation method. Since the deposition of Cd is not significant in the studied urban catchment, the Zn is more soluble than most other heavy metals and hence cannot be physically simulated only considering suspended solids a (Herngren et al., 2005; Huston et al., 2009). The present modelling approach focuses on the simulations of PM10, Cu, BaP and BbF.

2.2.2. 2D surface component

The physically-based, two-dimensional model openLISEM (stand for Limburg Soil Erosion, De Roo et al., 1996; Jetten and Roo, 2001) is used for simulating water flow and pollutant transport in the 2D surface component. OpenLISEM is a raster-based model that simulates the surface water and sediment balance for every grid-cell. Each grid-cell can be attributed by a certain type of landuse and a specific altitude, it is event based and has great spatial and temporal resolution.

The process within openLISEM can be separated into two categories: the hydrological part and the sediment transport part. In the hydrological part, openLISEM uses the kinematic wave 2D approximation of shallow-water equations for the surface runoff modelling, the Green and Ampt (1911) method for infiltration calculations and the canopy storage for interception estimations at the grid-cell scale. A finite volume scheme is applied for numerical solution. In order to adapt the Green and Ampt (1911) model, which is developed for permeable surface infiltration calculations, to the simulations on urban areas, specific parameter values can be set for simulating very limited infiltrations (Ramier et al., 2011). In this paper, an extremely low saturated hydraulic conductivity (Ksat = 0.1 mm/h) is applied for the grid-cells of impervious surfaces (road, parking, etc.).

As for the sediment transport part, the detachment and deposition processes are simulated at steady state. For each grid-cell, the urban surface dry depositions are considered as the initially deposited particles on the surface top layer. Within each time-step, these particles can be detached, transported and deposited according to the rainfall splash and water flow mechanisms. Otherwise, the original layer of the impervious urban surfaces is not erodible by fixing specific parameter values, that the original surface layer contains no available particles and has extremely high cohesion coefficient. In order to calculate the erosion processes of the deposited layer, available particles are firstly detached by the rainfall splash effects ($det_{splash,i}(t)$); the splash detachment can be directly added to the concentration of suspended solids of the previous time-step ($C_i(t\text{-}1)$); the updated concentration ($C_i(t)$) is then compared with the transport capacity of the water flow ($T_i(t)$). The flow-driven detachment ($det_{flow,i}(t)$) takes place when the updated concentration falls below $T_i(t)$, while the deposition ($dep_i(t)$) occurs when the $T_i(t)$ is exceeded.

The $det_{splash,i}(t)$ is simulated as a function of the sediment aggregate stability (A_s), rainfall kinetic energy ($Ke(t)$) and the water depth ($h(t)$) (Eqs. (1) and (2), derived from unpublished test data). Eqs. (3) and (4) represents the calculations of the concentration of the *i-th* class of particles in a grid-cell from the previous time-step ($C_i(t-1)$) to the end of the current time-step ($C_i^*(t)$). For each class

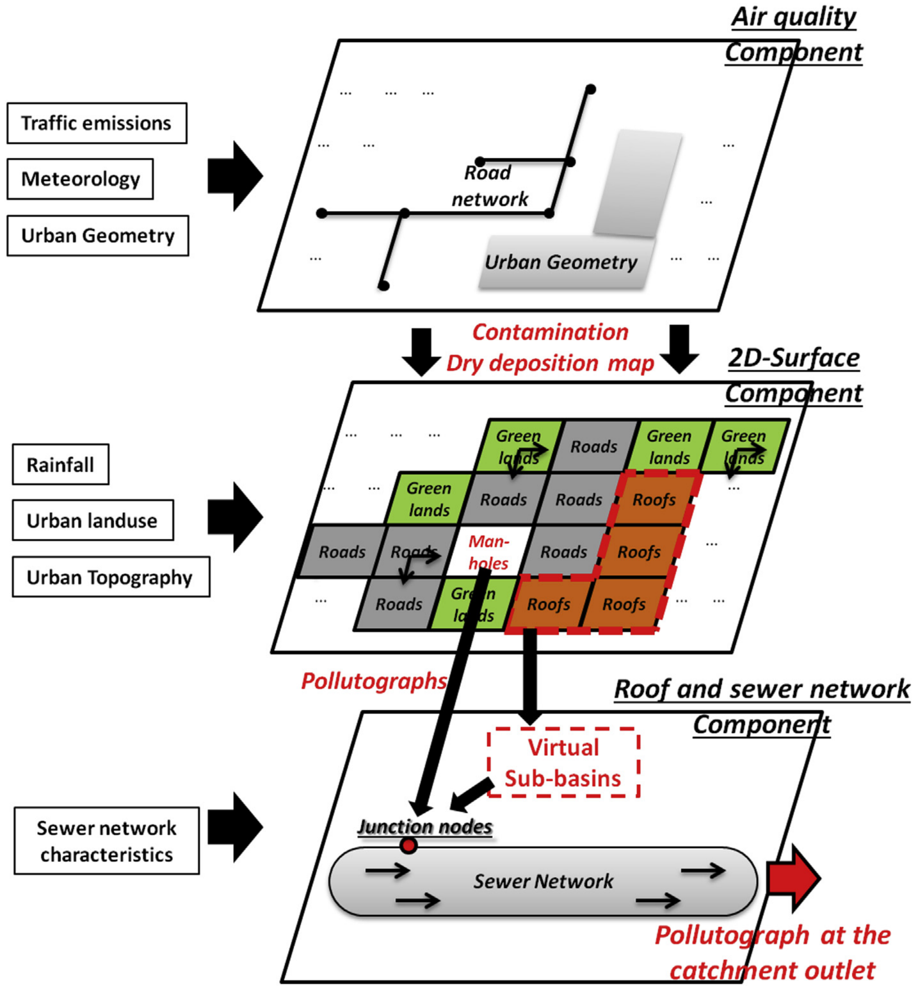

Fig. 2. Conceptual scheme of the integrated modelling framework for the simulation of the transfer of traffic-related pollutant on air-surface-sewer networks.

of particles, the Hairsine and Rose (1992) model (H-R) is used to calculate the $T_i(t)$ (Eq. (5)). The $det_{flow,i}(t)$ is calculated by assuming that the $T_i(t)$ deficit becomes detachment (Eq. (6)), where the Rauws and Govers (1988) erosion efficiency factor (γ) is used to limit the detachment by the cohesion of the sediment material (Eq. (7)). Finally, the $dep_i(t)$ is calculated by assuming that the $T_i(t)$ surplus becomes depositions (Eq. (8)), and the settling velocity ($v_{s,i}$), is calculated by the Stoke's equations (Eq. (9)).

$$\begin{cases} if \quad C_i(t) < T_i(t), \quad C_i^*(t) = C_i(t) + \dfrac{dt}{A\,h(t)}\left(det_{splash,i}(t) + det_{flow,i}(t)\right) \\ if \quad C_i(t) > T_i(t), \quad C_i^*(t) = C_i(t) + \dfrac{dt}{A\,h(t)}\left(det_{splash,i}(t) - dep_i(t)\right) \end{cases} \tag{4}$$

$$\begin{cases} if \quad m_i(t) > 0, \quad det_{splash,i}(t) = P_i\left(\dfrac{2.82}{A_s}\, K_e(t)\, e^{(-1.48\, h(t))} + 2.96\right) \dfrac{A\,h(t)}{dt} P_h(t) \\ if \quad m_i(t) = 0, \quad det_{splash,i}(t) = 0 \end{cases} \tag{1}$$

$$K_e(t) = 8.95 + 8.44\, Log(I(t)) \tag{2}$$

$$C_i(t) = C_i(t-1) + + \frac{dt}{A\,h(t)}\, det_{splash,i}(t) \tag{3}$$

$$T_i(t) = F_r\left(\frac{\rho_{s,i}}{\rho_{s,i} - \rho_w}\right)\left(\frac{\omega(t) - \omega_{cr}}{\omega(t)}\right) S_f(t)\, \rho_w \tag{5}$$

$$det_{flow,i}(t) = \gamma\,(T_i(t) - C_i(t))\, v_{s,i}\, A \tag{6}$$

$$\gamma = \min\left(1, \frac{1}{0.89 + 0.56\,coh}\right) \quad (7)$$

$$dep_i(\mathrm{t}) = (C_i(\mathrm{t}) - T_i(\mathrm{t}))\left(1 - \exp\left(dt\frac{v_{s,i}}{h(t)}\right)\right) v_{s,i}\, A \quad (8)$$

$$v_{s,i} = \frac{2}{9}\frac{\left(\rho_{s,i} - \rho_w\right)}{\mu}\, g\, R^2 \quad (9)$$

Where:

- $m_i(t)$ is the available *i-th* class of particles in the deposited layer at the current time-step (kg/m^2);
- $det_{splash,i}$(t) is the rainfall splash detachment rate of the *i-th* class of particles of the current time-step (*kg/s*);
- P_i is the fraction of available sediment that lies within the *i-th* class of particles;
- A_s is the aggregate stability (median number of raindrops to decrease the aggregate by 50%);
- $K_e(t)$ is the kenetic energy of the rainfall of the current time-step ($J/m^2\ mm$);
- A is the surface area of a grid-cell (m^2);
- $h(t)$ is the water depth at the current time-step (m);
- dt is the time step (s);
- $P_h(t)$ is the rainfall depth in the current time-step (m);
- $I(t)$ is the rainfall intensity at the current time-step (*mm/hr*);
- $C_i(t-1),\ C_i(t),\ and\ C_i^*(t) are$ the concentration of the *i-th* class of particles at each grid-cell for the previous, the current and the end of the current time-steps, respectively (kg/m^3);
- $det_{flow,i}(t)$ is the flow detachment rate of the *i-th* class of particles of the current time-step (*kg/s*);
- $dep_i(t)$ is the deposition rate of the *i-th* class of particles of the current time-step (*kg/s*);
- T_i (t) is the transport capacity for the *i-th* class of particles of the current time-step (kg/m^3);
- F_r is the re-entrainment parameter of the H-R equations;
- $\rho_{s,i},\ \rho_w$ are the mass densities of the *i-th* class of particles and water, respectively (kg/m^3);
- $\omega(t),\ \omega_{cr}$ are the flow velocity for the current time-step, and the critical flow velocity for sediment erosion, respectively (*m/s*);
- S_f (t) is the friction slope for the current time-step;
- γ is erosion efficiency coefficient;
- *coh* is the surface cohesion coefficient *(k Pa).*
- $v_{s,i}$ is the settling velocity of the *i-th* class of particles *(m/s).*
- g is gravitational acceleration, $= 9.8\ m/s^2$;
- μ is the dynamic viscosity (http://en.wikepedia.org/wiki/Dynamic_viscosity), ($= 0.001\ kg/m^*s$);
- R is the radius of the particle (m);

As shown in the above equations, the transport capacity (Eq. (5)) is calculated for each class of particles, allowing the simulation of size-selective erosion possible. Besides, since the characteristics of the sediment material are different from one rainfall event to another, the cohesion coefficient (*coh*) may need calibrations for different rainfall events. The values of other parameters can be fixed according to published literature.

Generally, the inputs for the 2D surface component consist of rainfall data, urban landuse information and urban topographic data. Details of these input data will be presented in the sections below. Otherwise, the outputs of this modelling component are hydrographs and pollutographs for the cells representing manholes, which will be linked to the roof and sewer network component.

2.2.3. Roof and sewer network component

Roof rain gutters are directly connected to the sewer networks in the studied urban catchment. As the roof slopes are not provided, water quantity and quality processes for the areas of building roofs cannot be physically described in the 2D surface component. Instead, the grid-cells of roofs are assembled as different virtual sub-basins connecting to their nearest sewer nodes. The area of each virtual sub-basin is equal to the total area of all the connected roof cells. These sub-basins are treated as the non-linear reservoirs, surface runoff occurs when the depth of water in the "reservoir" exceeds the loss of initial wetting for roofs. The outflow of each sub-basin is given by the Manning's equation. The washoff process is simulated by using exponential equations, where the eroded mass is proportional to the water flow and the remaining particles on roofs.

The sewer network part of the integrated modelling approach is based on SWMM model (Rossman, 2010). Interactions between the 2D surface component and the roof and sewer network component is modelled through flow exchange at identified linking points, named "junction nodes". These "junction nodes" can receive water and pollutant flows from the virtual sub-basins and the manholes. The water flow in sewer networks is computed by the 1D kinematic wave approximation of the Shallow Water equations and solved by the finite-difference scheme. Otherwise, water quality routing within conduits assumes that the conduit behaves as a continuously stirred tank reactor (CSTR). Using the CSTR method, the concentration of a constituent exiting the conduit at the end of a time step is calculated by integrating the conservation of mass equation. The sewer network module only requires the characteristics (connections, slope, length, etc.) of the urban drainage network as the input information, while the outputs are hydrographs and pollutographs at the sewerage outlet, which could be further compared with the in-situ observations.

2.3. Study site

The modelling system is applied to a small urban catchment near Paris (Le Perreux sur Marne, Val de Marne, France). This study area is a typical residential zone in the Paris region, characterized by a highly trafficked main street in the Eastern Paris (more than 30,000 vehicles per day). The total area of this catchment is 12 ha, about 70% of the surface is impervious, and the building roofs represent approximately 35% of the entire catchment. The western section has a higher altitude than the eastern side, with an average slope of less than 2% (Fig. 3).

The stormwater drainage system consists of 1156 m major pipes (vertical ellipse, 2.3 m height and 1.3 m large) along the main street, and nearly 1000 m minor pipes (circle, 0.3 m diameter) for connecting manholes to the major pipes. In total, there are 35 manholes in the studied catchment. The sewerage outlet is located at the North-Eastern edge of the presented drainage network, where the flow is continuously monitored by a Nivus Flowmeter with 2 min time interval, and the turbidity is consistently measured by a multi-parameter probe (mini-probe OTT). The total suspended solids (TSS) - turbidity relationship is therefore established based on samplings during 16 studied rainfall events. That follows a linear regression TSS = 0.8533 × Turbidity, with the R^2 equal to 0.97.

2.4. Input data and model configurations

2.4.1. Rainfall events

A tipping-bucket rain gauge is installed on the roof of a building close to the urban catchment (see Fig. 2). The pluviometer has a resolution of 0.1 mm. As the study area is quite small, homogeneous rainfall is considered for the entire urban catchment. The

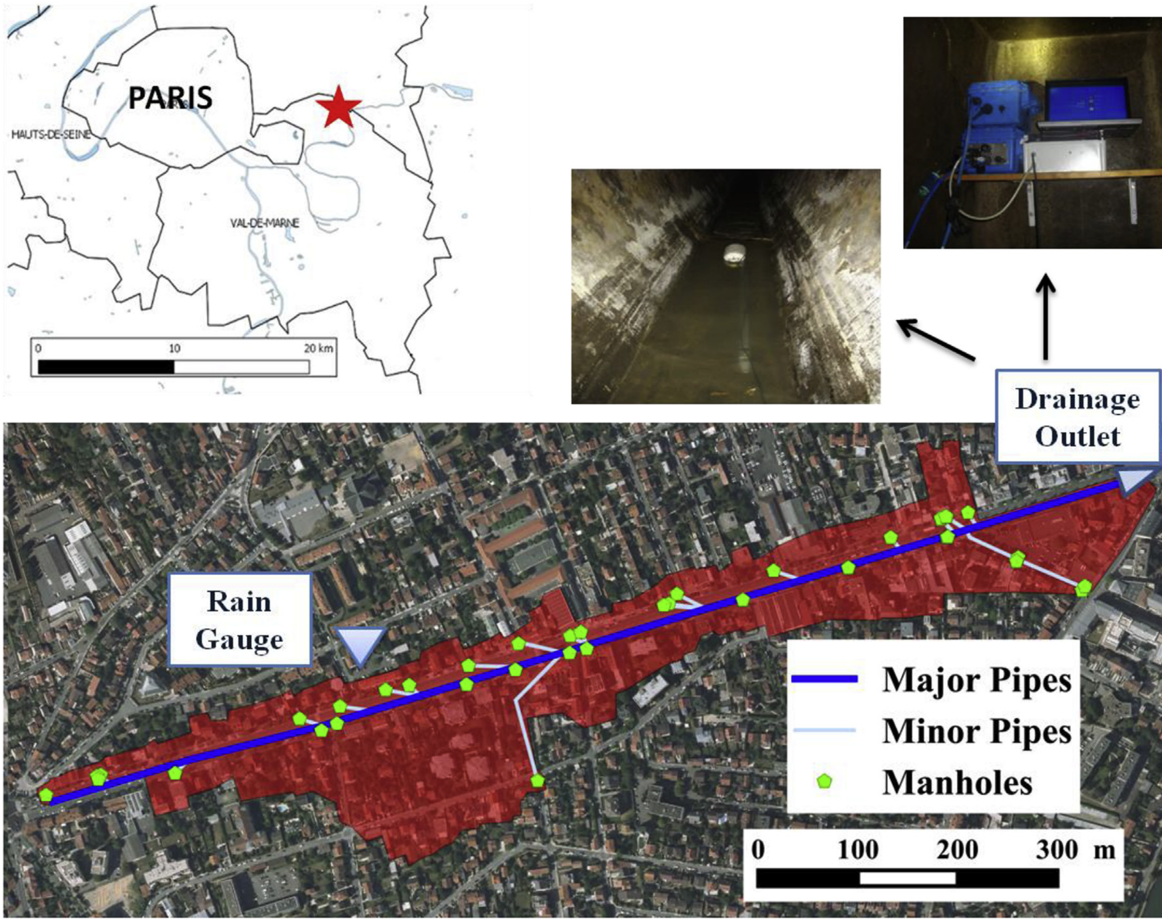

Fig. 3. Study area at Eastern Paris (Le Perreux sur Marne). Instrumental settings for measuring water flow and turbidity at the drainage outlet, as well as rainfall intensities.

monitoring was performed between the 20th of September 2014 and the 27th of April 2015.56 rainfall events were identified during this study period, more than 88% of the studied events had a rain depth less than 8 mm, nearly 89% of the events had a mean intensity smaller than 3 mm/h, and 87% of the events had a duration shorter than 7 h. Since the simulations are quite time-consuming, we have to select several rainfall events which contain different characteristics in order to characterize the overall performance of the modelling approach within an urban context. Among the observed rainfall events, we selected 4 typical events for model application and performance evaluation, with the rainfall depths varying from 2.9 to 9.3 mm, and the mean intensities differing from 1.3 to 2.8 mm/h. The characteristics of selected rainfall events and the summary of the entire 56 rainfall events are listed in Table S1.

2.4.2. Topography and landuse

High-resolution topographic data is essential for the accurate simulations of physically-based models. In Europe, thanks to the Inspire Directive (2007/2/EC) of the European Parliament and of the Council, Digital Terrain Model (DTM) databases are accessible for public research centres. In France, the large scale reference database (RGE®, http://professionnels.ign.fr/rge) containing DTM data of 25 m resolution is available for the whole country. In addition to this DTM data, a Mobile Mapping System (MMS) called Stereopolis (Hervieu and Soheilian, 2013; Paparoditis et al., 2012) has been applied around the study area in order to produce a 20 cm resolution topographic data (LiDAR) of the roads and sidewalks. Following Gallegos et al. (2009) and Fewtrell et al. (2011), the proper spatial resolution for 2D modelling of the urban surface can be set by considering the minimum distance between buildings, which is approximately 5 m for the studied urban catchment. Therefore, we firstly resample the LiDAR data (20 cm) and the DTM data (25 m) to 5 m resolution using the cubic resampling method, then merge the two types of data by overlaying the LiDAR-derived raster onto the DTM-derived raster. With this final topographic data (Fig. S1a), the urban catchment is represented by 224 × 85 rectangular grids.

One of the most significant benefits of using such a spatially-distributed model is to be able to accurately simulate the impacts of urban landuses. In collaboration with the IGN France, detailed landuse data is applied in this study, with manholes added as a specific type (Fig. S1b). The locations of manholes are identified from the GIS and AutoCAD sewer network data. Afterward, the vectorial landuse data are transformed into 5 m resolution grid-cells following a specific hierarchy of different landuse types. The priority order of landuses is defined by considering the connectivity of urban surface runoff pathways. In the current study, the prior landuse is the "manhole", followed by road, sidewalk, parking, various types of roofs and green lands. Since the raster data are derived from the aerial photography, the shade of several urban objects, such as plant canopies, can lead to overestimation of urban greenland surfaces, causing unrealistic discontinuities of flow pathways in the modelling system. Using the hierarchic order could hence ensure that the high order landuses (for example, roads) can be represented in the model, by which the pathways of urban surface runoffs are not surprisingly blocked by buildings or trees.

2.4.3. Atmospheric dry depositions of PM10, Cu, BaP and BbF

As presented in the above sections, the atmospheric dry deposition maps can be simulated for each studied rainfall event. Taking the event of 26th of November 2014 as an example, the deposition maps for PM10, Cu, BaP and BbF are presented in Fig. 4.

As can be seen in Fig. 4, the atmospheric pollutants in the studied urban catchment are generally accumulated and deposited on the main streets, which are located nearby their sources (traffic emissions). As the studied catchment is highly urbanized, the atmospheric dispersion of traffic-related pollutants can be constrained by obstacles such as buildings or vegetation close to the road.

2.4.4. Characteristics of detachable particles in surface runoffs

Water flow samples have been collected at a manhole in the studied urban catchment using a peristaltic pump (Watson Marlow), which pumped 250 mL of water at regular volume intervals entering the manhole. For each rainfall event, the measured TSS concentration in the stormwater sample can be considered the same as the mean TSS concentration in the total surface runoff. By assuming that the surface dry stocks at the beginning of a rainfall event (initial dry deposits) is equal to the amount of detachable particles which can be afterward found in stormwater runoffs, the surface dry deposits can be estimated by Eq. (10):

$$Deposit_{dry} = \frac{Conc_{TSS} * Volume_{manhole}}{Area_{manhole}} \tag{10}$$

Where $Deposit_{dry}$ is the experimentally estimated initial dry deposits for the urban catchment (g/m^2); $Conc_{TSS}$ is the mean TSS concentration of the stormwater runoff sample (g/L); $Volume_{manhole}$ is the total volume of stormwater runoffs collected in the sampling manhole (L); and $Area_{manhole}$ is the drainage area of the urban surface contributing to the sampling manhole (m^2).

The experimentally estimated urban dry deposits for the sampled rainfall events are presented in Fig. 5a, the average value is 1 g/m^2. Granulometric analysis was performed in the laboratory (Bechet et al., 2015) to evaluate the Particle Size Distribution (PSD) of the suspended particles for each stormwater samples. The averaged percentages of particles in the different particle size ranges in the assessing the PSD for the overall rainfall events. The overall PSD and the accumulated percentage of suspended solids are presented in Fig. 5b. Since the air quality component only simulates the dispersion and depositions of PM10 (<10 μm particles), particles are separated into two different classes. The first represents the PM10 (noted fine particles), with the median size (D50) equals to 5 μm, indicating the particles emitted from urban traffic to the air. The second stands for the >10 μm particles (noted coarse particles), which D50 is equal to 25 μm, implying the directly deposited particles caused by traffic activities.

Of course, the pollutant loads in the stormwater samples only represent a fraction of the total surface dry deposits. Significant part of pollutants may remain on the urban surface after a rainfall event. However, our previous research has demonstrated that for most rainfalls in the Paris region, only a small part of urban surface dry stocks can be removed to the sewer networks (Hong et al., 2016c). Therefore, we assumed to consider only the removable particles in this paper. Moreover, since the H-R model is used in this modelling approach (Eq. (5)) for the calculation of transport capacity ($T_i(t)$), the "transport capacity" is calculated for each class of particles.

2.4.5. Cu, BaP and BbF contents of different particle classes

Based on the simulated mass of atmospheric dry depositions of Cu, BaP, BbF and PM10 (Fig. 4), the pollutant contents of fine particles (D50 = 5 μm) can be calculated by Eq. (11). Experimental measurements have been performed in order to assess the concentration of different pollutants in urban stormwater samples. Cu was analyzed by an inductively Coupled Plasma – Mass Spectrometry (ICP-MS), while the PAHs were determined by a high performance liquid chromatography (HPLC) coupled with UV fluorescence assay. Using the measured mass of Cu, BaP, BbF and TSS, the pollutant contents of TSS (all particle sizes mixed) can be calculated by Eq. (12). Considering that the fine particles and coarse particles represent 45% and 55% of the TSS, respectively (Fig. 5b), the pollutant content of coarse particles (D50 = 25 μm) is calculated by subtracting the pollutant contents of fine particles from the that of TSS (Eq. (13)). The Cu, BaP and BbF contents of different classes of particles are represented in Table S2.

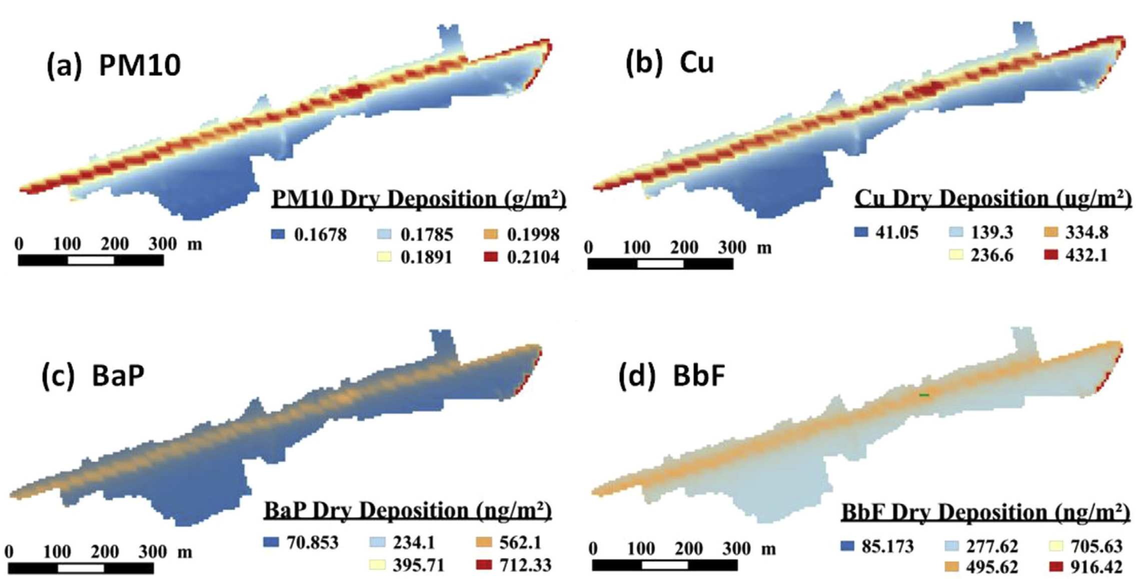

Fig. 4. Simulation of the accumulated atmospheric dry depositions for the event of 26th of November 2014. The dry deposition maps of (a) PM10, (b) Cu, (c) BaP, (d) BbF.

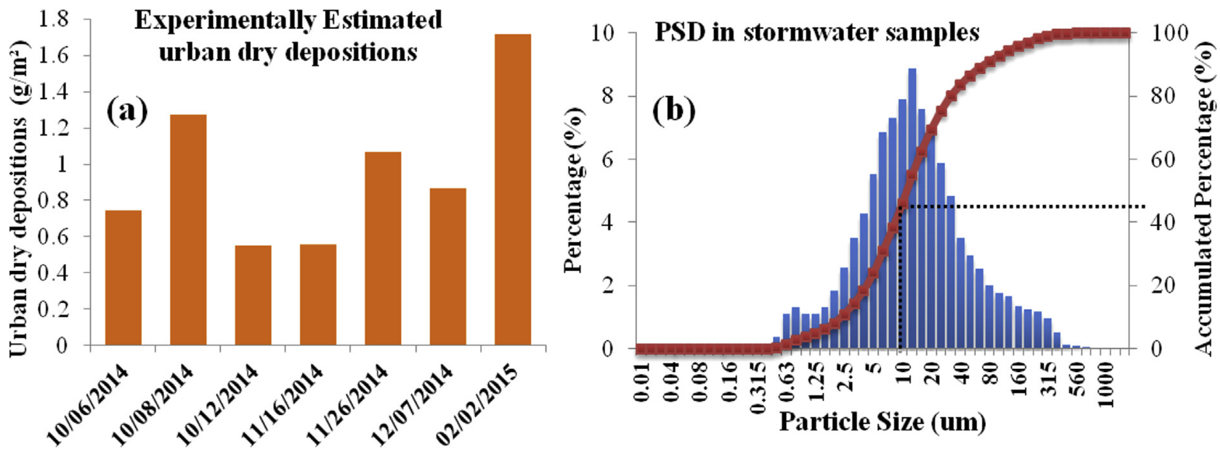

Fig. 5. (a) Experimentally estimated urban dry deposits of detachable particles (for both fine and coarse particles). (b) Particle Size Distribution (PSD) of the suspended particles in urban stormwater runoffs.

$$Content_{fine,\ pollut} = \frac{depot_{pollut}}{depot_{PM10}} \tag{11}$$

$$Content_{TSS,\ pollut} = \frac{conc_{pollut}}{conc_{TSS}} \tag{12}$$

$$Content_{coarse,pollut} = \frac{\left(Content_{TSS,pollut} - 45\% * Content_{fine,pollut}\right)}{55\%} \tag{13}$$

Where $Content_{fine,\ pollut}$, $Content_{coarse,pollut}$, $Content_{TSS,pollut}$ are the pollutant (Cu, BaP, BbF) content of fine particles, coarse particles and TSS (all particle sizes mixed), respectively; $conc_{pollut}$, $conc_{TSS}$ are the measured concentration of pollutants (Cu, BaP, BbF) and TSS in stormwater samples, respectively; $depot_{pollut}$, $depot_{PM10}$ are the atmospheric dry depositions of pollutants (Cu, BaP, BbF) and PM10, respectively.

2.4.6. Configuration of parameters for urban areas

In order to reduce the calibration efforts, several parameter values are determined from bibliographic works. As for water quantity simulations, the rainfall interceptions for different urban landuses are defined by considering the canopy interception values of Xiao et al., (1998); the random roughness values are defined as Zobeck and Onstad (1987); besides, in accordance with Rossman (2010), we fixed three parameters for Green and Ampt (1911) method such as porosity, initial moisture content and average suction at wetting front, as well as three parameters used in the sewer network module, including the initial loss of roof wetting, the Manning's N for conduits and virtual sub-basins. As for the water quality part, the aggregate stability is defined following Jetten and Roo (2001); the re-entrainment parameter of the H-R equations is decided the same as Hairsine and Rose (1992); the critical flow velocity for detachment is explained as Rauws and Govers (1988); and two washoff-coefficients of the virtual sub-basins are determined from Rossman (2010).

Contrarily, calibrations are performed for three parameters using the trial-and-error method. For the water quantity modelling, the Manning's N value for surface runoffs and the saturated conductivities (Ksat) are calibrated for the event of 26th of November 2014, and then validated for the other studied rainfall events. While for the water quality modelling, the cohesion coefficient (*coh*) is calculated for each rainfall event. The parameter values are listed in Table 1:

2.5. Simulation scenarios

Since the dry deposits of coarse particles are usually caused by direct depositions, such as surface abrasion and tyre wear. The air quality component only simulates the atmospheric dry depositions of fine particles (PM10). Therefore, the experimentally estimated dry deposits (Fig. 5a) of coarse particles are used in the model as the input data. Consequently, two modelling scenarios are tested in this study: Scenario 1 uses the experimentally estimated urban dry deposits for both fine and coarse particles; Scenario 2 uses the simulated atmospheric dry depositions for the fine particles, while the dry deposits of coarse particles follow the experimentally estimated values. The initial dry deposits of the two scenarios are presented in Table 2.

3. Results and discussions

3.1. Water flow simulations

Accurate water quantity simulations are required for reliable water quality modelling. The trial and error procedure is performed for calibrating the Manning's N and the saturated conductivities (K_{sat}), in order to precisely reproduce the dynamics of water flow at the catchment outlet. Parameters are calibrated for the event of 26th of November 2014, and then validated for the other studied rainfall events. The Root-Mean-Square-Error (RMSE) coefficient (Eq. (14)) is used to evaluate the model performance. The optimized Manning's N is equal to 0.012 and 0.2 for the impervious and pervious surfaces, respectively. The calibrated K_{sat} is equal to 0.1 and 25 mm/h for the impervious and pervious surfaces, respectively. Comparing with the commonly used parameter values in literature (Rossman, 2010; Tsihrintzis and Hamid, 1997), the calibrated parameter values of this study are in agreement with typical values for such landuses. The simulated water flow is compared with the continuous measurements at the catchment outlet (Fig. 6).

$$RMSD = \sqrt{\frac{\sum_{t=1}^{n}(Sim_t - Obs_t)^2}{n}} \tag{14}$$

where n is the simulation duration, Sim_t and Obs_t are the simulated and observed TSS concentration at the t-th minute.

Table 1
Parameter values for the integrated air-surface-sewer modelling.

Water quantity parameters		
	Impervious surface (road, sidewalk, etc …)	Pervious areas (grass, trees, etc …)
Rainfall interception (Smax, mm)	0	1
Random roughness (cm)	0.3	0.7
Initial moisture content (cm^3/cm^3)	0.1	0.4
Porosity (cm^3/cm^3)	0.1	0.5
Critical stream power for erosion (cm/s)	0.4	0.4
Initial loss of roof wetting (mm)	1	
Manning's N for sewer networks	0.014	
Manning's N for virtual sub-basins	0.012	
Manning's N values for surface runoffs	1 calibrated value for all the rainfall events	Idem
Saturated conductivities (mm/hr)	1 calibrated value for all the rainfall event	Idem
Water quality simulations		
Re-entrainment parameter	0.013	None
Critical flow velocity for detachment (m/s)	0.004	None
Washoff coefficient for virtual sub-basins	0.32	
Washoff exponent for virtual sub-basins	0.43	
Cohesion coefficient	1 calibrated value for every rainfall event	Idem

Table 2
Initial dry deposits at the beginning of a rainfall event for the two scenarios.

	Scenario 1 (experimentally estimated)	Scenario 2 (simulated)
Initial deposits of fine particles on roads (g/m^2)	0.45	Atmospheric simulations
Initial deposits of fine particles on roofs (g/m^2)	0.45	Atmospheric simulations
Initial deposits of coarse particles on roads (g/m^2)	0.55	0.55
Initial deposits of coarse particles on roofs (g/m^2)	0	0

As shown in Fig. 6, the performance of the quantitative simulations is quite satisfying with RMSE varying between 2.70 and 9.07. This result confirms that using such a spatially-distributed, integrated model is accurate for the water flow simulations at the scale of a small urban catchment.

3.2. Simulations of Total Suspended Solids (TSS)

Simulations using different initial dry deposits (Scenario 1 and 2) are performed for the four studied rainfall events. Since the surface conditions (humidity, heat, etc.) of the urban catchment can be different from one event to another, the cohesion coefficient (*coh*) is calibrated for each studied rainfall event using the trial-and-error method. The simulated TSS concentrations are compared with the measurements at the catchment outlet. Simulations of each rainfall event and scenario are shown in Figs. 7–8, respectively. The calibrated values of *coh* are presented in Table 3.

As can be seen in Figs. 7 and 8, simulated concentrations of TSS generally fit well with the continuous measurements, especially for the amplitude and the time to the first peak. The RMSE values vary from 48.9 to 178.6, being of the same order as the uncertainty of the experimental measurements. These results confirm the good performance of using the presented modelling approach to simulate TSS dynamics in the urban context. Comparing with our previous work which used the USLE equations (Kinnell, 2010) to simulate urban sediment erosions (Hong et al., 2016a), this paper is undoubtly an improvement of stormwater quality simulations for urban areas.

In spite of the good performance of the TSS simulations, it should be mentioned that the calibrated *coh* values are not steady between the different scenarios and rainfall events. Generally, the calibrated *coh* for Scenario 2 are lower than that of Scenario 1. This phenomenon is due to the fact that the simulated atmospheric deposits are lower than the experimentally estimated dry depositions. As a consequence, lower *coh* values are calibrated for Scenario 2 simulations. Nevertheless, the calibrated *coh* for the both two scenarios correspond with the typical values of the non-cohesive solids (Geotechdata.info, 2014), the clay particles of 300 mm diameter (Bonala and Reddi, 1999), and the calibrated and validated values of Zi et al. (2016). Considering the uncertainties of the parameter values related to water quality simulations (Dotto et al., 2012; Fletcher et al., 2013), the present study provides encouraging results in the field of urban stormwater quality modelling.

It should be indicated that although the spatial distribution of the atmospheric dry deposits is different from Scenario 1 to Scenario 2, however, quite similar simulations of TSS concentration are obtained at the outlet of the urban catchment. This phenomenon may be explained by the “first flush” effects of the studied rainfall events. For every studied rainfall event, the peak of the TSS concentration can be always observed 20 min after the beginning of the rain, regardless of the variations of rainfall intensities or the water flow dynamics. Of course, this delay is linked to the time concentration of the catchment. Since most pollutants are eroded at the beginning of the rainfall events, the impacts of the spatially-distributed dry deposits are not significant at the scale of the catchment outlet. Nevertheless, the effects of the spatial distribution of atmospheric dry depositions may be further assessed by experimental measurements by sampling manholes at different locations of the urban catchment. That model assessment can lead to develop advanced stormwater management strategies, such as filter systems located at the determined locations of the urban catchement, to reduce the traffic-related pollutants entering the sewer networks. This type of source-control techniques are easy to implement and can be effective and cheap.

Furthermore, in order to assess the dynamics of the two classes of particles for different scenarios, the evolution of the fractions of the fine and coarse particles of TSS for Scenario 1 and 2 are

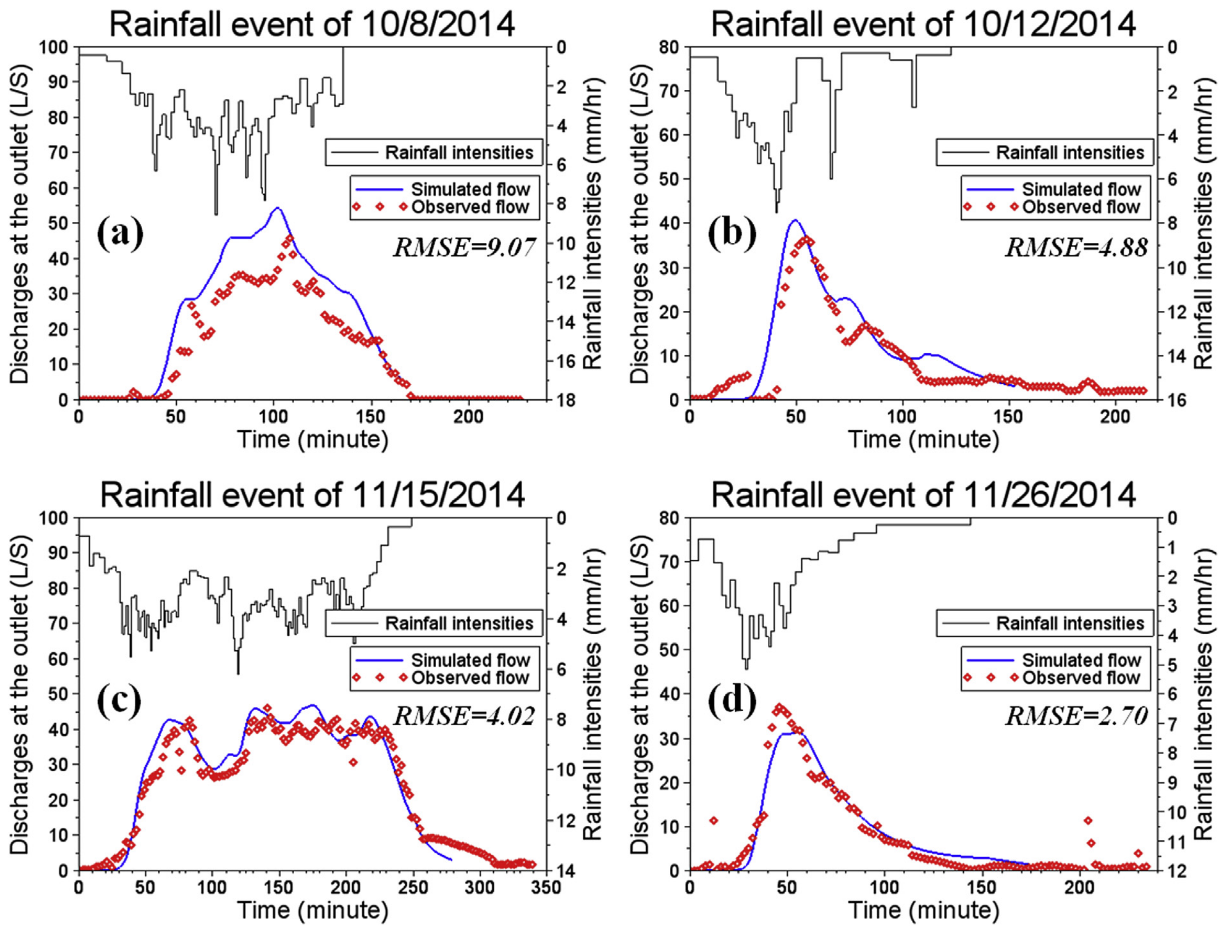

Fig. 6. Water flow simulations using the integrated modelling approach. The simulated discharges at the network outlet (solid blue lines) are compared with the measured data (red circles). Rainfall is plotted on the upper part. For events (a) 8th of October 2014; (b) 12th of October 2014; (c) 15th of November 2014; (d) 26th of November 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

compared in Fig. S2. The fraction of fine particles in TSS in Scenario 1 is higher than in Scenario 2. This result is in agreement with the above findings, that the simulated dry deposits of PM10 are lower than the experimentally estimated values. For both scenarios, the fine particles are firstly eroded at the beginning of the rainfall events, while the fraction of coarse particles in TSS rapidly increases with the rise of rainfall intensities. For the events of 8th of October 2014 and 15th of November 2014 (Fig. S2 a, c), due to the steady rain throughout the rainfall event, the fractions of the different particle classes in TSS remain stable. On the contrary, for the events of 12th of October 2014 and 26th of November 2014 (Fig. S2 b, d), the fraction of coarse particles in TSS significantly decreases with the reduction of rainfall intensities.

It should also be mentioned that in both scenarios, the dry deposits used in the model cannot completely represent the real conditions of the urban surface. On the one hand, it is quite difficult to assess the exact mass of initial dry deposits on urban surfaces. In fact, Bechet et al. (2015) showed that the variation range of the total mass of different road deposit samples is close to a factor 10. Therefore, our first scenario which takes into account the averaged deposit mass, has to be questioned regarding to the spatial variability of the urban catchment. On the other hand, atmospheric model outputs are also affected by large uncertainties. For instance, (i) the present modelling approach considers a null background concentrations, but in reality, the atmospheric background concentrations could have significant effects and are quite variable during different seasons; (ii) the modelling of atmospheric depositions uses simulated inputs such as rainfall intensities, wind speeds and directions, however, these meteorological simulations are related to considerable uncertainties; (iii) the atmospheric dry deposition is calculated by using the settling velocity of particles in air, yet the granulometric distribution of the suspended particles in air is ambiguous and the fluctuant settling velocities of atmospheric particles, cause high uncertainties. For all these reasons, the simulated dry deposits of Scenario 2 should be considered carefully. Nevertheless, this paper challenges for the first time the new field of integrated 2D air-surface-sewer urban stormwater quality modelling with reasonable assumptions. Moreover, the model performance can be further discussed by comparing the simulated concentrations of traffic-related pollutants (Cu, BaP and BbF) for the two studied scenarios as well as the local measurements.

3.3. Simulations of Cu, BaP and BbF

Considering the Cu, BaP and BbF contents of fine and coarse particles (Table S2), the dynamics of pollutant concentrations at the catchment outlet can be evaluated. The simulated pollutant concentrations (Cu, BaP and BbF) of Scenario 1 and Scenario 2 are presented in Figs. S3–S4. Benefitting from the measurements of event mean concentrations of Cu, BaP and BbF in stormwater runoff samples (section 2.4.5), the simulated concentrations of such pollutants can be compared with the observed values (Fig. 9).

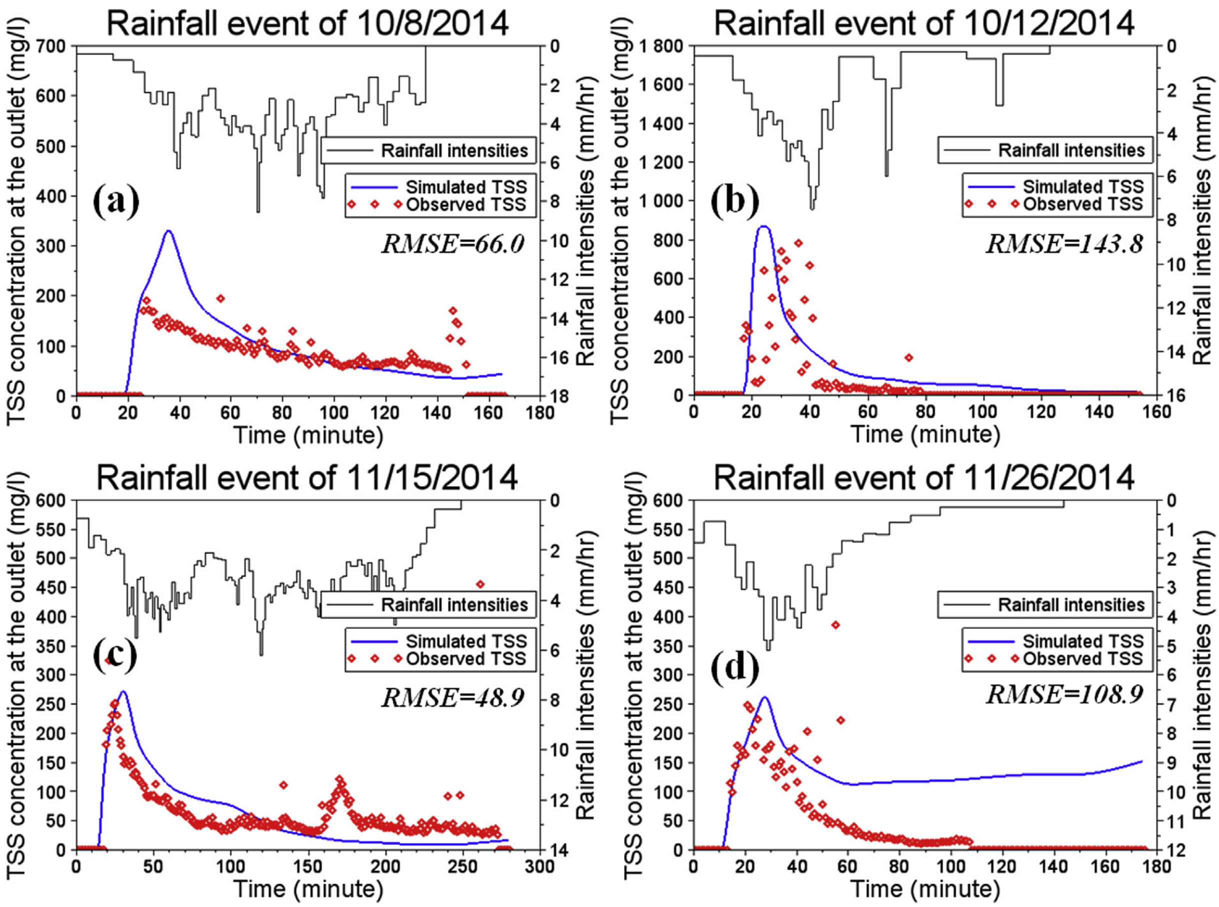

Fig. 7. Total Suspended Solids (TSS) concentration of Scenario 1 simulations (measured initial deposits). The simulated TSS concentrations at the network outlet (solid blue lines) are compared with the measured data (red circles). Rainfall is plotted on the upper part. For events (a) 8th of October 2014; (b) 12th of October 2014; (c) 15th of November 2014; (d) 26th of November 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Considering the large uncertainties in measurements of heavy metals and PAHs (Bechet et al., 2015), the Fig. 9 shows that both scenarios give realistic results comparing with the measurements of pollutants in stormwater runoff samples. These encouraging results confirm the validity of using the presented modelling approach for simulating the transfer of traffic-related pollutants from air to the sewer outlet.

Nevertheless, it should be noted that the simulated concentrations of pollutants in Scenario 2 are always less than that in Scenario 1. This can be explained by the higher fractions of fine particles in TSS for Scenario 1 (Fig. S2). Since the pollutants are preferred to attach to fine particles (Table S2), TSS of Scenario 1 can transport more associated pollutants. Analyzing the outputs of the air quality component (used in Scenario 2) for the four studied rainfall events, the averaged atmospheric dry deposits of PM10 for the entire urban catchment is equal to 0.055 g/m^2. This value is far below the estimated mass of the fine particles from the stormwater runoff samples (used in Scenario 1), which is equal to 0.45 g/m^2. This result can be mainly explained by four reasons: (i) The presented modelling approach simulates also significantly influence the atmospheric pollution and deposition. (ii) Stormwater runoff samples are collected in a manhole along the road. Since there are more deposited particles on roads than on other types of urban landuses, the experimentally estimated dry deposits for the entire urban catchment is hence overestimated for Scenario 1. (iii) The air quality simulations do not take into account the background atmospheric pollution, the PM10 deposits in Scenario 2 are certainly underestimated in this study. (iv) The precipitation inputs used in the air quality component are based on a prediction model of MeteoFrance (AROME model, Bouttier, 2007). With such a meteorological model, insignificant precipitations (<1 mm), which are usually not recorded by the rain gauge, are considered as wet weather periods. These wet weather simulations further decrease the simulated dry deposits in Scenario 2.

Finally, uncertainties for the pollutants content of PM10 should also be mentioned. Due to the uncertainties in rainfall event simulations, deposition velocities, and particle size distributions, the variation range for the simulated atmospheric deposits of pollutants can easily reach a factor 2 to 4 (Shorshani et al., 2015). Therefore, the results in Fig. 9 are quite acceptable for the modelling of heavy metals and PAHs in the urban context.

4. Conclusion and perspective

In this paper, we develop an integrated air-surface-sewer modelling approach, in order to simulate the transfer of traffic-related pollutants in urban areas, and we formulate some necessary modelling assumptions to achieve this goal.

The modelling system consists of three separated components, including the air quality component, the 2D surface component, as well as the roof and sewer network component. For the air quality component, the SIRANE model (Soulhac et al., 2011) is coupled with realistic traffic data to generate spatially-distributed atmospheric dry depositions; in the 2D-surface component, the openLISEM

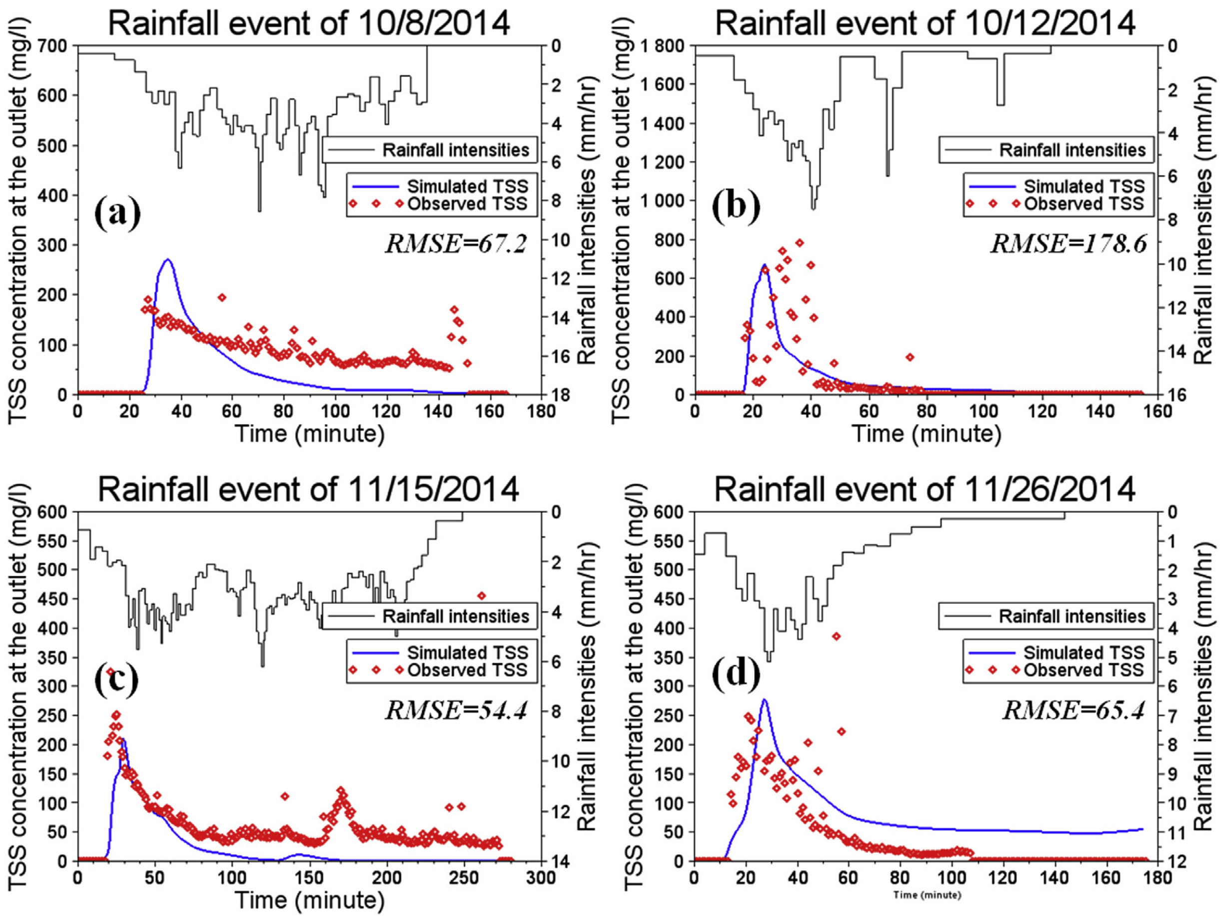

Fig. 8. Total Suspended Solids (TSS) concentration of Scenario 2 simulations (simulated initial deposits). The simulated TSS concentrations at the network outlet (solid blue lines) are compared with the measured data (red circles). Rainfall is plotted on the upper part. For events (a) 8th of October 2014; (b) 12th of October 2014; (c) 15th of November 2014; (d) 26th of November 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Calibrated cohesion coefficient (*coh*) values (*kPa*).

coh (kPa)	Oct. 8 2014	Oct. 12 2014	Nov. 15 2014	Nov. 26 2014
Scenario 1	13	10	13	13
Scenario 2	12	10	10	12

model (De Roo et al., 1996; Jetten and Roo, 2001) is applied to simulate the transfer of water and particulate pollutants on roads and green areas; in the roof and sewer network component, building roofs are considered as virtual sub-basins which are directly connected to the sewer networks, the SWMM model (Rossman, 2010) is used to simulate the transport of water and pollutants from roofs and manholes to the outlet of drainage networks.

The integrated modelling platform is applied to a small urban catchment near Paris (12 ha, Le Perreux sur Marne, Val de Marne, France). Simulation results are compared with continuous measurements of water flow and total suspended solids (TSS) at the catchment outlet. The performance of the quantitative simulation is highly satisfying with calibrated and validated parameter values of Manning's N and saturated conductivity (K_{sat}). As for the water quality modelling, two modelling scenarios are performed: Scenario 1 uses experimentally estimated dry deposits, which are homogenously distributed on the urban catchment; Scenario 2 uses simulated atmospheric dry depositions, which are spatially-distributed. With a simple calibration of the surface cohesion coefficient (*coh*), the TSS concentration simulations fit well with the observations for both scenarios. Nevertheless, no significant difference can be noticed at the catchment outlet between the two scenarios. This phenomenon is mainly due to the “first flush” effects of the urban catchment. For the studied rainfall events, since most pollutants are eroded at the beginning of the rainfall events, the spatially-distributed dry deposits have little effect at the scale of the catchment outlet. Therefore, specific experimental surveys such as sampling manholes, should be considered in order to test the modelling performance at different locations of the urban catchment.

Considering the Cu, BaP and BbF contents of different particle classes, the pollutographs of such pollutants are evaluated for each studied rainfall event. The simulated event mean concentrations of pollutants are compared with local in-situ measurements. For the first time, realistic simulations of traffic-related pollutants are achieved at the catchment outlet. Additionally, the differences between the two scenarios as well as the measurements are due to the modelling assumptions and the uncertainties of the atmospheric dry deposits simulations. As a perspective, sensitivity and uncertainty analysis should be considered for this modelling approach.

For the purpose of improving the model performance, the atmospheric background concentration of pollutants and the direct deposition of traffic activities, such as surface abrasion and tyre wear should be considered. In order to evaluate the model

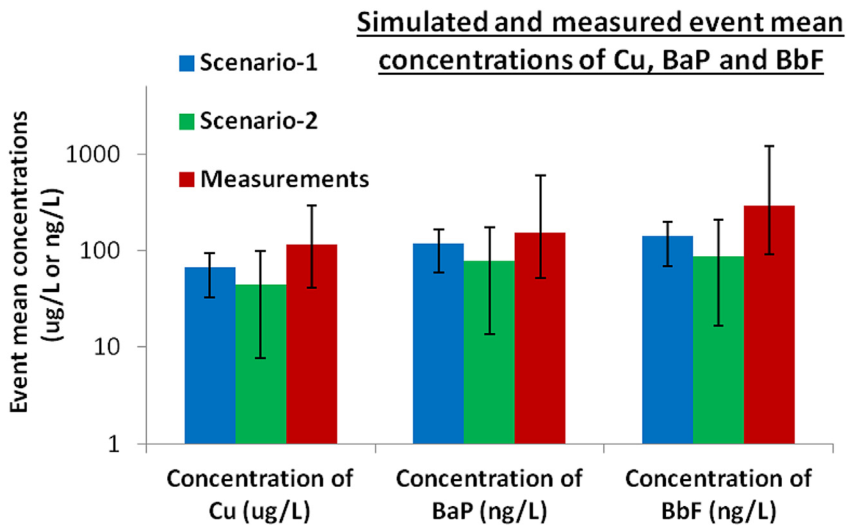

Fig. 9. Simulated and measured event mean concentrations of Cu, BaP and BbF (all particle size mixed).

performance in transporting different particle classes and the associated pollutants to the catchment outlet, the sampling at the sewer outlet with granulometric separation would be an important next step. Moreover, since Zinc (Zn) is not significantly associated with suspended particles, the modelling of soluble pollutants with adsorption/desorption processes can be integrated in the future studies.

The main interest in developing such an integrated modelling approach is undoubtedly to be able to understand and to predict the transfer of traffic-related pollutants in urban areas. This innovative work proves the effectiveness of using erosion models for the modelling of urban stormwater quality. Moreover, the present integrated modelling approach could be further coupled with traffic models and pollutant emission models for a real-time control, in order to assess the impacts of different traffic management strategies on urban separate sewer discharges.

Software availability

Name of the software: LISEM-SWMM integrated modelling platform.

Program Language: C, C++, and Scilab programming languages.

Program Size: Approximately 3 MB.

Availability: The source code of the LISEM-SWMM integrated modelling platform can be obtained for free. Please contact Dr. Yi Hong, LEESU, MA 102, École des Ponts, AgroParisTech, UPEC, UPE, Champs-sur-Marne, France, email: yi.hong@enpc.fr; and Prof. Victor Jetten, ITC-ESA, Department of Earth Systems Analysis, Enschede, Netherlands, email: v.g.jetten@utwente.nl.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2017.06.047.

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