Environmental Modelling & Software 96 (2017) 158–171

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

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

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ARTICLE INFO

Article history:
Received 9 October 2016
Received in revised form
8 June 2017
Accepted 29 June 2017

Keywords:
Integrated modelling
Traffic-related pollutants
Spatially-distributed modelling
OpenLISEM
SWMM
Urban stormwater

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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http://dx.doi.org/10.1016/j.envsoft.2017.06.047
1364-8152/

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