Characterization of hydrodynamic and pollutant removal processes inside swales - a pilot study

Alexandre Fardel, Pierre Emmanuel Peyneau, Abdel Lakel, Béatrice Bechet, Claude Joannis, Fabrice Rodriguez

Characterization of hydrodynamic and pollutant removal processes inside swales – a pilot study

Caractérisation des processus hydrodynamiques et épuratoires au sein des noues - étude de noues pilote

Fardel A.[1, 2], Peyneau P.-E.[1], Lakel A.[2], Béchet B.[1], Joannis C.[1], Rodriguez F.[1]

[1]LUNAM, Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR), Département Géotechnique, Environnement, Risques naturels et Sciences de la Terre (GERS), Laboratoire Eau et Environnement (LEE), CS 4, 44344 Bouguenais, France
[2]Centre Scientifique et Technique du Bâtiment (CSTB), Aquasim, 11 rue Henri Picherit, 44300 Nantes, France
alexandre.fardel@cstb.fr

RÉSUMÉ

Les noues sont des ouvrages de gestion à la source des eaux pluviales dont la conception assure d'une part un écoulement horizontal et une infiltration verticale de l'eau dans le sol. Recueillant des eaux de ruissellement potentiellement chargées en polluants, leur implantation a pour objectif premier de limiter le débit de fuite à l'exutoire du bassin versant, mais elle participe également à l'épuration de ces eaux par décantation et filtration.
Le cadre technique de ce type d'ouvrage a déjà fait l'objet de nombreuses publications proposant une grande diversité de critères de conception lors de l'aménagement d'une noue. Néanmoins, ces critères méritent une attention supplémentaire quant à leurs impacts qualitatifs et quantitatifs sur les micropolluants dans le sol, les données disponibles dans la littérature n'étant pas très nombreuses.
Notre travail vise à étudier le lien entre le fonctionnement hydraulique et la performance épuratoire des noues, en contribuant à la définition et à la caractérisation des processus physiques et physico-chimiques contrôlant les flux d'eau et de polluants dans ces systèmes. D'un point de vue opérationnel, dans le cadre du projet Matriochkas, il s'agit d'établir la performance environnementale des noues. Cette communication présente le cahier des charges de l'instrumentation d'un pilote, dédié à la caractérisation de l'hydrodynamique et de la rétention de la charge polluante au sein d'une noue, ainsi que les premiers essais qui seront réalisés.

ABSTRACT

Swales are stormwater source control infrastructures that manage runoff in two dimensions. Generally, a first part of the volume discharged in a swale is conveyed as surface flow and the other is infiltrated underground. A swale traditionally aims at reducing and slowing runoff flows but swales can also decrease the load of sediment and other pollutants in urban runoff by promoting infiltration and sediment deposition.
The literature describes some design swales criteria but their effects on the quantity, the repartition and the speciation of pollutants in the soil remain unclear.
This study focuses on hydraulic and pollutant removal performances of swales and aims to define and characterize the physical and physicochemical processes governing water and pollutant flows in these unsaturated soil-water reactors. From an operative point of view, this work takes part in the Matriochkas project and consists in determining the environmental performances of swales. After a state of the art focusing on the swale pollution retention performance, the paper details some experimental specifications to build a pilot experiment to characterize hydrodynamics and pollutant removal within swales. First tests are expected to be realized before June 2016.

KEYWORDS

Experimental pilot, Hydrodynamics, Pollutant Removal, Runoff, Swale

1 INTRODUCTION

Urban stormwater runoff represents a significant source of potential environmental damages. However, implementation of several source control infrastructures at the catchment-scale could highly enhance its management. Particularly, building swales is fast-growing in urban landscapes because of their prospective efficient hydraulic and pollutant removal performances. A two-year pilot study will enable us to accurately characterize the process involved in their performances.

This study focuses on hydraulic and pollutant removal performances of swales and aims to define and characterize the role of hydrodynamic processes in the pollutant purification chemical processes in these unsaturated soil-water reactors. This work participates to the Matriochkas project, and would help practitioners to better know the environmental performances of swales. Firstly, this paper presents a state of the art focusing on the main issues of stormwater management, and the swales pollution retention performance in the context of source control facilities. Then, the paper details some experimental specifications to build a pilot experiment to characterize hydrodynamics and pollutant retention relations. First tests are expected to be realized before June 2016.

2 STATE OF THE ART

2.1 Consequences of urbanisation on stormwater runoff

Urbanisation of watersheds compromises stormwater runoff quality and quantity. On the one hand, products of industries modified the account balance of stormwater runoff sources of pollution resulting in increasing anthropogenic rejects of trace metals, organic matters, hydrocarbons and nutrients (Sansalone and Buchberger, 1997). On the other hand, urbanisation spreads over catchments impervious surfaces such as roofs and roads (Elliott and Trowsdale, 2007), contributing to:

- intensify both stormwater flow-rates and volumes which modifies storm hydrographs in developed areas (Liu et al., 2014),
- concentrate the deposits of potential washed off pollutants such as suspended solids (*i.e.*, main components of sediment load) (Ellis et al., 2006) and trace metals (Sabin et al., 2005),
- extend the part of nonpoint source pollution in the account balance of water pollution (Novotny and Olem, 1994; Tsihrintzis and Hamid, 1997).

Many studies characterized urban stormwater runoff quality through the contributions of sources of pollution (Aryal et al., 2010; Gromaire-Mertz et al., 1999; Sabin et al., 2005) and the physicochemical properties of its compounds, including their speciation (Lau and Stenstrom, 2005; Sansalone et al., 1998). All these works pointed out perturbations attributable to urbanisation. Moreover, comparisons with environmental standard qualities demonstrated that stormwater runoff can be highly contaminated by toxic substances (Zgheib et al., 2011a; Zhang et al., 2015). Two recent French studies focusing on stormwater quality of three distinct urban catchments with different land use patterns are in accordance with these conclusions (Gasperi et al., 2014; Zgheib et al., 2011b). Their authors observed high levels of contamination without significant differences between each site, knowing however that pollutant loads of several metals like As, Cr, Cu, Ni, Sr and Zn and organic micropollutants such as polycyclic aromatic hydrocarbons (PAHs) and polybrominated diphenyl ethers (PBDEs) may strongly depend on site features such as land use (Gasperi et al., 2014).

Furthermore, all these anthropogenic phenomena impact aquatic habitat quality (Cianfrani et al., 2006), soil quality (Werkenthin et al., 2014), underground water quality and quantity (Andersen et al., 2014), receiving waters quality (Beck and Birch, 2012) and they threaten human health and the environment (US-EPA, 2000). Simultaneously, urbanisation is still going on; proportion of people living in urban areas could thus reach 66% in 2050 (United Nations, 2014) partly thanks to the extension of current periurban areas (United Nations News Service, 2008). Therefore, solutions to cope with urbanisation consequences on stormwater runoff have been developed for several decades.

2.2 Development of stormwater source control facilities

Traditionally, stormwater runoff is channelled in sewer networks or stored in civil engineering structures such as open air or underground detention basins. These traditional approaches are struggling to keep pace with fast urbanisation (Bressy et al., 2014). Furthermore, they are expensive (Gromaire-Mertz et al., 1999), their focus is mainly on water quantity control (Zhou, 2014) and risks are concentrated in one centralized system.

New stormwater management practices have been set up for two decades in an attempt to regulate the urbanisation effects (Bressy et al., 2014; Elliott and Trowsdale, 2007). These major changes in drainage design take place in several developed countries. Several similar concepts group these facilities together and concern low impact development (LID) (Elliott and Trowsdale, 2007; US-EPA, 2000) and best management practice (BMP) (Clar et al., 2004) in the USA, sustainable urban drainage system (SUDS) in the UK (Woods-Ballard et al., 2015), water sensitive urban design (WSUD) in Australia (City of Melbourne & Melbourne Water, 2006) and *techniques alternatives* in France (Petrucci et al., 2013). All these sustainable applications promote Source Control (SC) management by developing facilities at very small scales (10^2-10^3 m²) to deal with catchment-scale problems (10^6-10^7 m²) (Petrucci et al., 2013). Structural functions range in scale from small infrastructures (*i.e.*, grassed swales, permeable pavements, rain gardens) to larger constructions (*i.e.*, detention and retention pond, artificial wetland). Small infrastructures are designed to filter and treat runoff from frequent rain events whereas larger devices (*i.e.,* detention and retention pond, artificial wetland) are designed to store high stormwater volumes to manage flood risk (Raja Segaran et al., 2014). Such solutions promote natural processes and natural water behaviour in the urban environment (Zhou, 2014). Therefore, these facilities are usually vegetated and ensure stormwater regulations in an efficient, economic, aesthetically and social way (Lucke et al., 2014).

2.3 Hydraulic and pollutant removal performances of swales

Implementation of swales is fast-growing in urban areas (Lucke et al., 2014). These SC infrastructures are often recommended as techniques to treat stormwater runoff from transportation infrastructures (Burkhard et al., 2000) and residential lots (Minnesota Pollution Control Agency, 2000). Low cost of implementation - an engineered swale costs three times less than a traditional stormwater infrastructure (US-EPA, 2000) - and quite good pollutant removal performance encourage the building of these places of biodiversity enhancement (Kazemi et al., 2011).

Structurally, swales are basic open channel systems that store and/or convey stormwater runoff from a limited drainage area (Storey et al., 2009) and provide some water quality treatment (Iowa Department of Natural Resources, 2009; Woods-Ballard et al., 2015). The ability of swales to reduce flow rates, regulate water volumes and remove pollutant load have been studied for thirty years. The effectiveness of swales seems quite good for pollutant trapping and both runoff volume and flow rates reduction (US-EPA, 2000). Indeed, there is considerable evidence in literature that pollutants such as total suspended solids (TSS) and trace elements (Fe, Zn, Pb, Cd, Cu) in both aqueous and particular phases are trapped in these BMP applications (Ackerman and Stein, 2008; Deletic and Fletcher, 2006; Ismail et al., 2014; Lucke et al., 2014; Roseen et al., 2009; Stagge and Davis, 2006; Stagge et al., 2012). All these field or pilot studies quantified the pollutant removal performances of swales through calculating the mean pollutant removal efficiency ratio (ER) (David et al., 2015) based on event mean concentrations (EMCs) or total masses. For instance, the overall results demonstrated mean TSS ER ranged from 44 % to 99 % and mean Cu ER ranged from 8 to 81 %. The lowest ranges of expected pollutant removal in swales concern nitrogen and phosphorus (Watershed Management Institute, 1997). Several studies found negative mean total phosphorus ER (Roseen et al., 2009; Stagge et al., 2012) and negative mean total nitrogen ER (Stagge et al., 2012; Yousef et al., 1987). Moreover, a modelling study (Grinden, 2014) and several field studies (Davis et al., 2012; Lucke et al., 2014; Toronto and Region Conservation Authority, 2008; Van Seters and Graham, 2014) have demonstrated the clear capacity of swales to reduce the outflow discharge during a runoff event.

Relationships between design criteria and global environmental performances are well characterized in literature. The design criteria for implementation of swales, including location, geometrical patterns, vegetation species, soil bed composition and additional equipment (check-dams, liner) may have a strong effect on their environmental performances (*i.e.*, hydraulic and pollutant removal performances). For instance, vegetation or grass enhances flow rate reduction, pollution removal and protection against erosion (Credit Valley Conservation and Toronto and Region Conservation, 2010). Moreover, studies demonstrated that some species of plants have a better capacity to assimilate pollutants than others (Leroy et al., 2015; Rycewicz-Borecki et al., 2016). In addition, the inclusion of check dams could greatly improve the swale ability to reduce runoff volume (Davis et al., 2012) and enhances water quality treatment (Stagge et al., 2012). Otherwise, Luke et al. (2014) focused on the relationships between both TSS pollutant removal and trapped sediment size fractions with swale length; they observed firstly that at least 70% of the end TSS ER was performed within the first longitudinal 10 m of 30 m swales and secondly that swales monitored in the study were not effective to capture particles finer than 20 µm.

The physical and physicochemical mechanisms responsible for the quite good performances of grass swales to reduce peak flows and to treat urban stormwater runoff (Davis et al., 2012; Lucke et al., 2014; Stagge et al., 2012) remain poorly understood. It is well known that swales reduce the load of sediment and other pollutants in urban runoff by promoting infiltration and sediment deposition. Sedimentation is the primary pollutant removal mechanism, followed by secondary mechanisms such as infiltration, adsorption, bioaccumulation (US-EPA, 2000) and phytoremediation (Leroy et al., 2015). To the authors' knowledge, very few studies have tried to bridge the gap between physical and physicochemical soil parameters and performances of swales. For instance, saturated hydraulic conductivity (K_s) seems to be crucial for pollutant removal efficiency. Indeed, a good calibration of K_s is by far the most important step to efficiently use TRAVA model (Deletic, 2001) and to obtain good predictions of the sediment behaviour in swales (Deletic and Fletcher, 2006). Another field and modelling study (Ahmed et al., 2014) underlines the importance to focus on K_s to calibrate a model that predicts the quantity of runoff infiltrated in the soil and its effect on the runoff depths still remained in the swales as surface flow. Therefore, conducting a new field and modelling study seems to be useful to entirely characterize the main mechanisms involved in the environmental performances of swales.

2.4 Study objective

The main objective of this research is to characterize the effects of water flows in soil on environmental performances of swales in order to develop an hydro-physicochemical model describing swale overall functioning. For this purpose, an empirical experimental approach associated to a simulation study is proposed. The experimental study will investigate the ability of two different experimental swales to reduce volumes, retard flows and treat pollutant load from simulated stormwater events. A special attention will be given to (1) the environmental performances of swales during frequent rain events which are suspected to produce the main part of the total annual pollutant load and to (2) the poorly characterized efficiency removals of several organic pollutants such as PAHs and pesticides. The first part of the study will supply useful data that will be compared with numerical simulations. The modelling study will use the HYDRUS-3D software (Simunek et al., 2012) which simulates water flow and solute transport in porous media (soils in this study). Using HYDRUS-3D will enable us to quantify overall environmental performances of swales through designing virtual swales and simulating distribution in the system. The results will provide a better understanding of swale environmental performances in urban landscapes to propose both appropriate design and efficient maintenance for future implementations.

In this paper, we present experimental specifications enabling us to define a methodology that will set up on the site before June 2016.

3 METHODOLOGY

3.1 Site description and pilot facility construction

The pilot site is at the *Centre Scientifique et Technique du Bâtiment* (CSTB), a French research center in Nantes (France). It is located in an oceanic climate zone with 16.7 °C annual average temperature and an annual average rainfall of 819.5 mm, with precipitation evenly dispersed throughout the year. A map of the campus is presented in Figure 1. The pilot will exactly belong to *Aquasim* which is the department of CSTB dedicated to water research.

After examination of possible areas for the pilot facility in the campus of the CSTB, it was decided to select a concrete open air box of 37.5 m^3 (5 x 5 x 1.5 m) as the experimental site; two reasons explain this choice: (i) it is close to a pond which can store stormwater from three different sources that will be used for simulating storm events in the facility (Figure 1); (ii) it can be divided in two equal volumes so that two swales can be monitored simultaneously. The two 5 m long swales will display distinct features to assess their relative performances. For instance, the two swales could display different soil beds, different geometrical patterns, different filter media depths and/or different species of plants. The bottom of the concrete box is impervious and infiltrated water can be collected in an outlet. In addition, regular and systematic swale maintenance is needed in order to ensure the swale performances and longevity. Therefore, several vegetation cutting and/or mowing sessions will be planned. Moreover, other swales could be built in a specific infrastructure dedicated to simulate the effect of a water table rising and located near the concrete box aforementioned. A schematization of the construction process is detailed in Figure 1.

3.2 Stormwater supply

The study will be conducted using stormwater runoff from a zinc coated steel roof of 2000 m² and from a service road. Stormwater runoff from the road could be diverted in a hydrocarbon separator before supplying the storage pond (Figure 1). The pilot facility will be fed by a storage tank and a detention pond of 200 m^3. Storing stormwater enables us to simulate several distinct storm events that are representative of frequent rain events and of severe weather phenomena observed in Nantes. Controlled runoff simulations were chosen for their reliability and because it is difficult to sample real time stormwater runoff events. Several values of inflow will be tested. Incoming runoff can enter into the swales along one of their sides or from the entrance of the channel. Experiments will be conducted between summer 2016 and summer 2018.

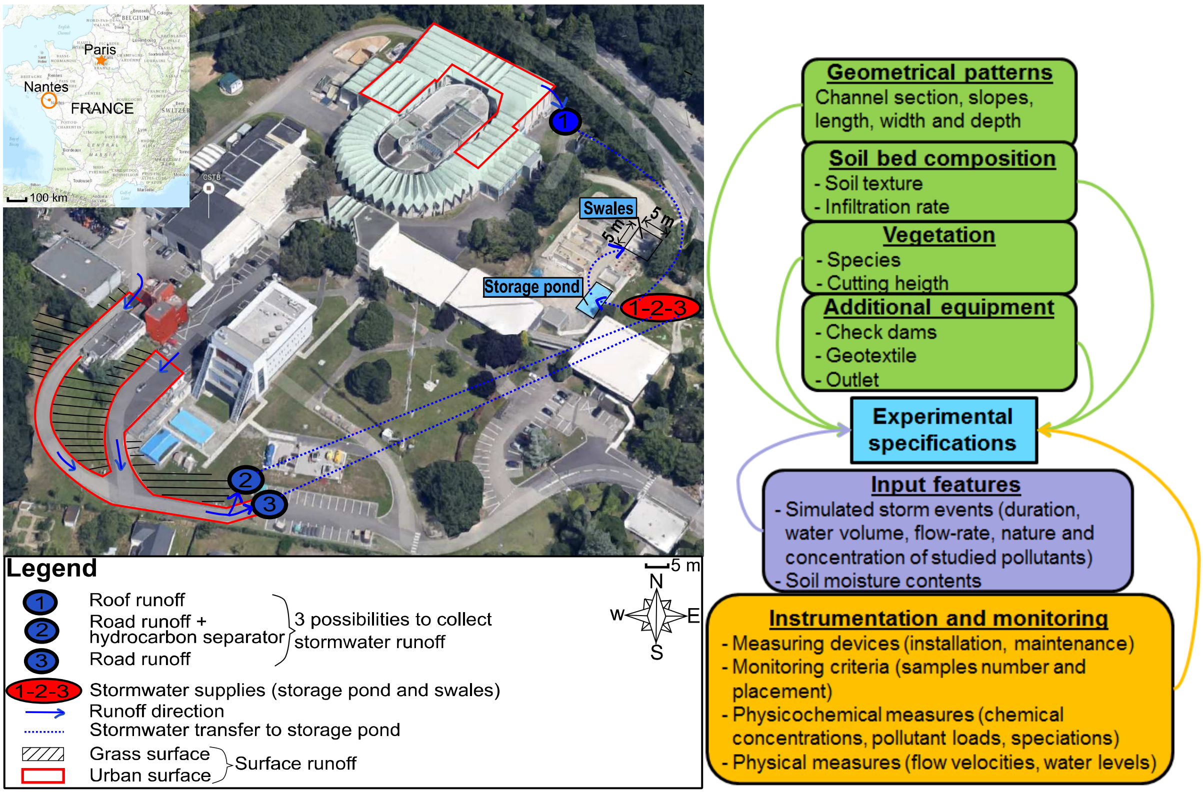

Figure 1. On the left: schematization of experimental site features, the pilot site belongs to *Aquasim* (modified from Google Maps). On the right: schematization of experimental specifications.

3.3 Hydraulic and physicochemical measures

Hydraulic quantities (*i.e.*, flow rate, water level and succion) and physicochemical quantities (*i.e.*, pollutant concentrations, pollutant masses and particle sizes) will be measured in the system. Various sensors will be embedded in the soil to explore soil water content, pressure and soil water quality. Installing porous cups in swales will enable to extract water from distinct soil depths. Flow rate will be measured with an adaptive flow meter; infiltrometry experiments will be performed to measure Ks.

Stormwater runoff samples from the roof and the road will be collected for preliminary analysis. TSS, turbidity, pH, volatile dry matter, chemical oxygen demand (COD), biological oxygen demand (BOD), phosphorus compounds (orthophosphate, total phosphorus), nitrogen compounds (total nitrogen, nitrate, total Kjeldahl nitrogen), trace metals (Zn, Pb, Cu, Cd, Fe, Ni), arsenic, PAHs and pesticides (diuron, glyphosate) will be analyzed. Results will help us to identify the detectable substances that may violate some environmental quality standards (*i.e.*, regulations about drinking water, water reuse, bathing water), and therefore to list pollutants that are interesting to be monitored in field experiments. Moreover, a special attention will be given to the first measures of PAHs and pesticides effluent concentrations; if some relevant substances cannot be detected, we will consider the possibility to add synthetic chemicals in the stored stormwater to study the effectiveness of swales to remove these toxic substances. In addition, batch tests could be realized in laboratory to characterize the adsorption kinetics of pollutants in soil to better calibrate the model that will be used.

4 EXPECTED RESULTS AND CONCLUSION

Implementation of the pilot and first tests are expected to be realized before June 2016. Thus, first comparisons with values found in the literature (such as pollutant ER) will be made.

Monitoring two experimental swales during two years will help us to efficiently determine environmental performances of swales. In addition, the overall study will enable us to characterize the effects of water flows in soil on these performances and to better understand the physical and physicochemical mechanisms involved.

LIST OF REFERENCES

Ackerman, D., and Stein, E.D. (2008). *Evaluating the effectiveness of best management practices using dynamic modeling*. J. Environ. Eng., 134(8), 628–639.

Ahmed, F., Natarajan, P., Gulliver, J.S., Weiss, P.T., and Nieber, J.L. (2014). *Assessing and improving pollution prevention by swales*. Center for Transportation Studies, University of Minnesota, Minneapolis, USA.

Andersen, D., Burns, R., Helmers, M., and Moody, L. (2014). *Vegetative Treatment System Impacts on Groundwater Quality*. Trans. ASABE, 57(2), 417–430.

Aryal, R., Vigneswaran, S., Kandasamy, J., and Naidu, R. (2010). *Urban stormwater quality and treatment*. Korean J. Chem. Eng., 27(5), 1343–1359.

Beck, H.J., and Birch, G.F. (2012). *Metals, nutrients and total suspended solids discharged during different flow conditions in highly urbanised catchments*. Environ. Monit. Assess., 184(2), 637–653.

Bressy, A., Gromaire, M.-C., Lorgeoux, C., Saad, M., Leroy, F., and Chebbo, G. (2014). *Efficiency of source control systems for reducing runoff pollutant loads: Feedback on experimental catchments within Paris conurbation*. Water Res., 57, 234–246.

Burkhard, R., Deletic, A., and Craig, A. (2000). *Techniques for water and wastewater management: a review of techniques and their integration in planning*. Urban Water, 2(3), 197–221.

Cianfrani, C.M., Hession, W.C., and Rizzo, D.M. (2006). *Watershed imperviousness impacts on stream channel condition in southeastern Pennsylvania*. J. Am. Water Resour. Assoc.,42(4), 941-956.

City of Melbourne & Melbourne Water (2006). *City of Melbourne WSUD Guidelines*. Melbourne, Australia.

Clar, M.L., Barfield, B.J., and O'Connor, T.P. (2004). *Vegetative Biofilters*. In : Stormwater Best Management Practice Design Guide, Vol.2. United States Environmental Protection Agency, Cincinnati, USA.

Credit Valley Conservation and Toronto and Region Conservation (2010). *Low Impact Development Stormwater Management Planning and Design Guide*. Ontario, Canada.

David, N., Leatherbarrow, J.E., Yee, D., and McKee, L.J. (2015). *Removal Efficiencies of a Bioretention System for Trace Metals, PCBs, PAHs, and Dioxins in a Semiarid Environment*. J. Environ. Eng., 141(6), 04014092.

Davis, A.P., Stagge, J.H., Jamil, E., and Kim, H. (2012). *Hydraulic performance of grass swales for managing highway runoff*. Water Res., 46, 6775–6786.

Deletic, A. (2001). *Modelling of water and sediment transport over grassed areas*. J. Hydrol., 248(1/4), 168–182.

Deletic, A., and Fletcher, T.D. (2006). *Performance of grass filters used for stormwater treatment—a field and modelling study*. J. Hydrol., 317(3/4), 261–275.

Elliott, A., and Trowsdale, S. (2007). *A review of models for low impact urban stormwater drainage*. Environ. Model. Softw., 22(3), 394–405.

Ellis, J.B., Marsalek, J., and Chocat, B. (2006). *97: Urban water quality*. In : Encyclopedia of Hydrological Sciences, M.G. Anderson (ed). John Wiley & Sons.

Gasperi, J., Sebastian, C., Ruban, V., Delamain, M., Percot, S., Wiest, L., Mirande, C., Caupos, E., Demare, D., Kessoo, M.D.K., et al. (2014). *Micropollutants in urban stormwater: occurrence, concentrations, and atmospheric contributions for a wide range of contaminants in three French catchments*. Environ. Sci. Pollut. Res., 21(8), 5267–5281.

Grinden, A. (2014). *Numerical Modeling of Combined Hydraulics and Infiltration in Grassed Swales*. Master's Thesis, Norwegian University of Science and Technology, Trondheim, Norway.

Gromaire-Mertz, M.-C., Garnaud, S., Gonzalez, A., and Chebbo, G. (1999). *Characterisation of urban runoff pollution in Paris*., Water Sci. Technol. 39(2), 1–8.

Iowa Department of Natural Resources (2009). *General Information for Vegetated Swale Systems*. Version 3. In: Iowa Stormwater Management Manual. Iowa Department of Natural Resources, Iowa, USA.

Ismail, A.F., Sapari, N., and Abdul Wahab, M.M. (2014). *Vegetative Swale for Treatment of Stormwater Runoff from Construction Site*. Pertanika J. Sci. Technol., 22(1), 55-64.

Kazemi, F., Beecham, S., and Gibbs, J. (2011). *Streetscape biodiversity and the role of bioretention swales in an Australian urban environment*. Landsc. Urban Plan., 101(2), 139–148.

Lau, S.-L., and Stenstrom, M.K. (2005). *Metals and PAHs adsorbed to street particles*. Water Res., 39(17), 4083–4092.

Leroy, M.-C., Legras, M., Marcotte, S., Moncond'huy, V., Machour, N., Le Derf, F., and Portet-Koltalo, F. (2015). *Assessment of PAH dissipation processes in large-scale outdoor mesocosms simulating vegetated road-side swales*. Sci. Total Environ., 520, 146–153.

Liu, W., Chen, W., and Peng, C. (2014). *Assessing the effectiveness of green infrastructures on urban flooding* *reduction: A community scale study*. Ecol. Model., 291, 6–14.

Lucke, T., Mohamed, M., and Tindale, N. (2014). *Pollutant Removal and Hydraulic Reduction Performance of Field Grassed Swales during Runoff Simulation Experiments*. Water, 6, 1887–1904.

Minnesota Pollution Control Agency (2000). *Best Management Practices for stormwater systems*. Minnesota, USA.

Novotny, V., and Olem, H. (1994). *Water Quality: Prevention, Identification, and Management of Diffuse Pollution*. Van Nostrand Reinhold, New York.

Petrucci, G., Rioust, E., Deroubaix, J.-F., and Tassin, B. (2013). *Do stormwater source control policies deliver the right hydrologic outcomes?* J. Hydrol., 485, 188–200.

Raja Segaran, R., Lewis, M., and Ostendorf, B. (2014). *Stormwater quality improvement potential of an urbanised catchment using water sensitive retrofits into public parks*. Urban For. Urban Green., 13(2), 315–324.

Roseen, R.M., Ballestero, T.P., Houle, J.J., Avellaneda, P., Briggs, J., Fowler, G., and Wildey, R. (2009). *Seasonal performance variations for storm-water management systems in cold climate conditions*. J. Environ. Eng., 135(3), 128-137.

Rycewicz-Borecki, M., McLean, J.E., and Dupont, R.R. (2016). *Bioaccumulation of copper, lead, and zinc in six macrophyte species grown in simulated stormwater bioretention systems*. J. Environ. Manage., 166, 267–275.

Sabin, L.D., Lim, J.H., Stolzenbach, K.D., and Schiff, K.C. (2005). *Contribution of trace metals from atmospheric deposition to stormwater runoff in a small impervious urban catchment*. Water Res., 39(16), 3929–3937.

Sansalone, J.J., and Buchberger, S. (1997). *Partitioning and First Flush of Metals in Urban Roadway Storm* Water. J. Environ. Eng., 123(2), 134–143.

Sansalone, J.J., Koran, J., Smithson, J., and Buchberger, S. (1998). *Physical Characteristics of Urban Roadway Solids Transported during Rain Events*. J. Environ. Eng., 124(5), 427–440.

Simunek, J., Van Genuchten, M.T., and Sejna, M. (2012). *The HYDRUS software package for simulating two and three-dimensional movement of water, heat, and multiple solutes in variably-saturated media*. Technical manual, 1.

Stagge, J.H., and Davis, A.P. (2006). *Water Quality Benefits of Grass Swales in Managing Highway Runoff*. Proc. Water Environ. Fed. 2006, 5518–5527.

Stagge, J.H., Davis, A.P., Jamil, E., and Kim, H. (2012). *Performance of grass swales for improving water quality from highway runoff*. Water Res., 46(20), 6731–6742.

Storey, B.J., Li, M.-H., McFalls, J.A., and Yi, Y.-J. (2009). *Stormwater Treatment With Vegetated Buffers*. Texas Transportation Institute, The Texas A&M University System, College Station, USA.

Toronto and Region Conservation Authority (2008). *Performance Evaluation of Permeable Pavement and a Bioretention Swale*. King City, Ontario (USA), Seneca College.

Tsihrintzis, V.A., and Hamid, R. (1997). *Modeling and management of urban stormwater runoff quality: a review*. Water Resour. Manag., 11, 136–164.

United Nations (2014). *World urbanization prospects: the 2014 revision : highlights*. Population Division, Department of Economic and Social Affairs, United Nations.

United Nations News Service (2008). *UN News - Half of global population will live in cities by end of this year, predicts UN*. United Nations. Available online at http://www.un.org/apps/news/story.asp?NewsID=25762

US-EPA (2000). *Low Impact Development A Literature Review*. United States Environmental Protection Agency, USA.

Van Seters, T. and Graham, C. (2014). *Performance Evaluation of a Bioretention System - Earth Rangers, Vaughan*. Toronto and Region Conservation's Sustainable Technologies Evaluation Program, Toronto, Ontario, Canada.

Watershed Management Institute (1997). *Operation, Maintenance, and Management of Stormwater Management Systems*. In cooperation with Office of Water of the United States Environmental Protection Agency, Washington D.C., USA.

Werkenthin, M., Kluge, B., and Wessolek, G. (2014). *Metals in European roadside soils and soil* solution – A review. Environ. Pollut., 189, 98–110.

Woods-Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R., and Kellagher, R. (2015). *The SUDS manual*. Ciria, London, UK.

Yousef, Y.A., Hvitved-Jacobsen, T., Wanielista, M.P., and Harper, H.H. (1987). *Removal of contaminants in highway runoff flowing through swales*. Sci. Total Environ., 59, 391–399.

Zgheib, S., Moilleron, R., Saad, M., and Chebbo, G. (2011a). *Partition of pollution between dissolved and particulate phases: What about emerging substances in urban stormwater catchments?* Water Res., 45(2), 913–925.

Zgheib, S., Moilleron, R., and Chebbo, G. (2011b). *Influence of the land use pattern on the concentrations and fluxes of priority pollutants in urban stormwater*. Water Sci. Technol., 64(7), 1450-1458.

Zhang, K., Randelovic, A., Aguiar, L.M., Page, D., McCarthy, D.T., and Deletic, A. (2015). *Methodologies for Pre-*

Validation of Biofilters and Wetlands for Stormwater Treatment. PLOS ONE, 10(5).

Zhou, Q. (2014). *A Review of Sustainable Urban Drainage Systems Considering the Climate Change and Urbanization Impacts*. Water, 6, 976–992.