Hydraulic modelling of constructed reed-bed wetlands for stormwater treatment

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ABSTRACT
The reed-bed filter, widely used to treat wastewater, is adapted here to treat stormwater. Modelling such systems poses problems linked tothe unsteady-state behaviour, itself a consequence of the flow variability during storm events. Under those conditions, hydraulic head variations play an important role in the infiltration processes. The goal of this study is thus to develop simplified models which can be used for the sizing and design configuration of constructed reed-bed wetlands for CSO treatment. The paper proposes five models based on Darcy and Richards approaches, but also accounting for evapotranspiration and capillarity. Those models have been validated against data for a field biofiltration systemslocated at Monash University Car park. Two models based on the concept of barrier filters and simplified Richards equations seem to perform well with good experimental agreement obtained.These conceptual models were then applied to catchments in Lyon and Nantes (France), in order to test whether such simplified models can be feasibly applied to optimise the key design and sizing parameters for constructed reed-bed wetlands. Real inflow time series data collected on these sites were used to develop and test the models. Models have shown to be sensitive to drainage layer and diverted weir level.

KEYWORDS
Capillarity; Hydraulic modelling; Infiltration; Reed-bed wetland; Stormwater

INTRODUCTION
The most common sewer networks in many countries, including France, are combined systems, receiving both domestic wastewater and stormwater in the same combined pipe. During wet period, flow rates increase significantly and the amount of water to be treated can exceed the capacity of the WWTP, causing overflows though Combined Sewer Overflow structures (CSOs). Significant pollutant loads are therefore directly discharged to receiving water bodies. Consequently, there is increasing pressure to treat these combined sewer overflows. The development of extensive systems based on constructed wetland technology with vegetation has been shown to be an effective stormwater pollution control measure, with the potential for integration into a range of stormwater treatment and recycling systems (Uhl and Dittmer, 2005; Hatt et al. 2006). In this kind of system, hydraulic behavior plays an important role, particularly in the control of the infiltration capacity which impacts the pollutant removal, the overflow frequency (Carlton et al., 2001; Hatt et al. 2006) as well

as oxygen renewal. Dynamic models developed for CSO treatment by vertical flow constructed wetlands (VFCW) (Dittmer et al., 2005; Henrichs et al., 2007, 2009) are powerful in describing processes within the system but are generally too complicated to be used easily for design purposes.

This paper proposes an approach based on simplified hydraulic modelling of filter in order to improve the sizing of extensive wetland systems for CSO treatment according to rain event and sewer system characteristics. Investigations are carried out in the framework of the SEGTEUP (Extensive systems for stormwater treatment and management in urban areas) national French project in collaboration with Monash University (Australia). The reed-bed filter, widely used to treat wastewater (based on the principle of aerobic biological treatment – Molle et al., 2005) is adapted here to treat stormwater discharges. To model such a system, however, the main problem remains the unsteady-state functioning of the VFCW due to the variability of flows during the storm event. Under these conditions, hydraulic head variations play an important role on the infiltration processes (Beach et al., 2005). The goal of this sutdy is to develop simplified models in for the sizing and design of VFCWs for CSO treatment.

The paper aims to : i) compare five proposed models (including the model based on the approach used in MUSIC, the Australian model; eWater, 2009)against experimental data published by Lewis et al. (2008) and Hatt et al. (2009); ii) to assess the ability of such simplified models to identify optimal sizing and design parameters, taking into account the consequences of climate change (impact on the storm event and then on the variability of the CSO discharge) and the sewer system characteristics.

METHODS AND EXPERIMENTAL DATA

Presentation of models

In the modelling of hydrological cycles (relevant to the modelling of reed-bed filtration) there are four methods that are applicable to the modelling of biofilters (She and Pang, 2010):

- Curve Methods: This relies upon empirical data curves to simulate outflow,
- Physical models for groundwater applications: These are field equations solved for unsaturated flow,
- Analytical models: These models treat biofilters as combinations of linear storage reservoirs (with separate storages for the ponding zone and the filter media zone),
- Water-balance models: This views the biofilter as a set of storages with flows between them that are restricted by laws (such as Darcy’s Law).

In addition, the steady-state infiltration rate that a porous matter biofilter can accommodate is dependent upon the following four characteristics (Beach et al., 2005) :

- The hydraulic conductivity of the filter media (also considering the effects of the thickness of the filter);
- The height of the ponding above the filter driving the flow;
- The thickness of the biomat (layer of biomass that can potentially hinder water infiltration);
- Moisture tension of the subsoil (suction potential of unsaturated soil).

This paper deals with water-balance models and how they can be used to better model VFCW systems. The thickness of the biomat is not considered in the developed models as it is regarded as very case-specific and thus too complicated to model without detailed site-specific information. In addition to this a continuity equation-based model ensures that the amount of the water is conserved and there is no loss or gain in all the water in the system. However, to model this in the system requires an accurate representation of the storages. The model in this case is viewed as volume storages (that are linearly proportional to height) that are separated by barriers. These barriers govern the flows between the storages and therefore the parameters of these barriers provide the inputs for the physical laws which determine the flows between the storages. With this however arises a problem; the filter acts both as a storage and a barrier. This problem is approached in two main different ways in the proposed models:

- The filter is not considered as storage but only as a barrier.
- The filter is considered as a storage with a maximum inflow governed by Darcy's Law (Darcy, 1856) and an outflow that considers the saturation level of the filter according to a modified form of Richard's equation (Daly et al., 2009).

The most accurate way of modelling this dual barrier/storage property is to undertake finite element modelling over the modelling period in both vertical and horizontal directions. However due to the computing power required for this, this was not considered an option for the simplified model needed in the SEGTEUP project.

Five models are tested in this study. All models take into account evapotranspiration losses. Compartments taken into account are reminded on Fig. 1

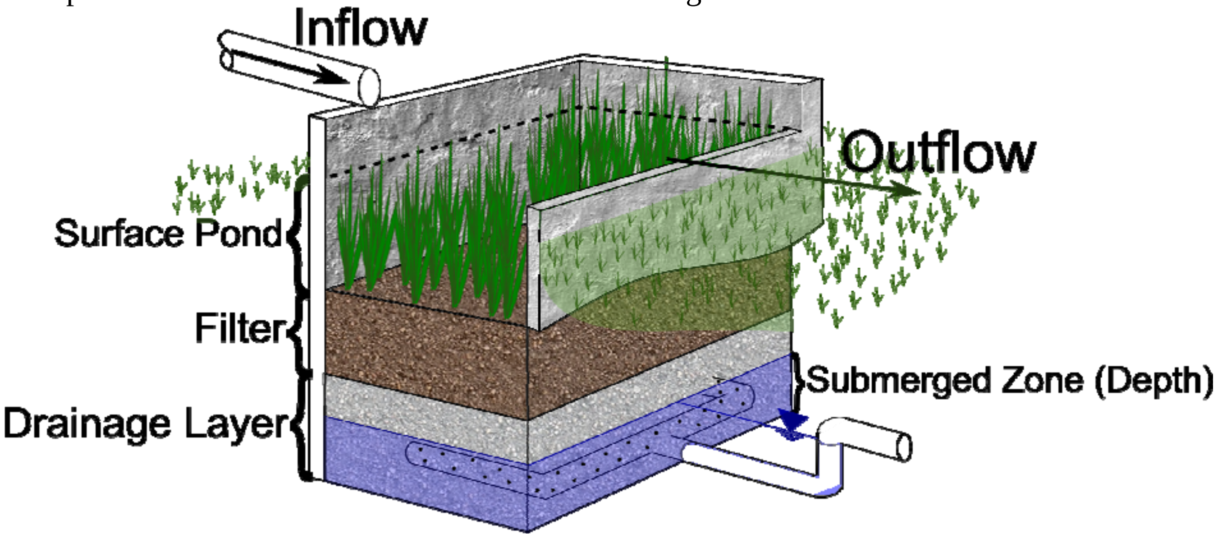

Figure 1. Simplified sketch of the VFCW with key compartments

The reed-bed filtration models that have been developed are listed below:

- SEGTEUP I labeled SI: A simple model using three layers: surface pond, filter layer and drainage zone, with the flows in the latter two being determined by Darcy's Law.
- SEGTEUP II labeled SII: This model uses two storages, surface pond and drainage zone separated by the filter as the controlling factor for the flow between the two storages.
- SEGTEUP III labeled SIII: This model functions in the same way as the previous one(S II) with the addition of capillary flow from the submerged layer to the filter (from which the evapotranspiration is now taken). This model uses a similar approach to the modelling of capillarity flows as used in the Australian software MUSIC version-4 package (e-Water, 2009).
- SEGTEUP IV labeled SIV: This model functions in the same way as S IIIexcept that the filter can store water within its porosity and the flow through it is governed by Darcy's law and a simplified infiltration equation based upon Richards' Law and capillarity is used to recharge the filter store from which evapotranspiration (factored according to season and plant type) is taken. This model inherits the infiltration equations from MUSIC version 4.

- SEGTEUP V labeled SV: This model functions in the same way as S IVexcept that the evapotranspiration is a constant value factored only by soil moisture store (like MUSIC) as opposed to a base ET values that changes with timestep. It should be noted that for intellectual property reasons that the equations inherited from MUSIC shall not be published under a separate licence and have only been written into the above software for research purposes only. Therefore the software with MUSIC-based equations or default values will not be released to the public.

Figure 2 shows an example of SIV model.

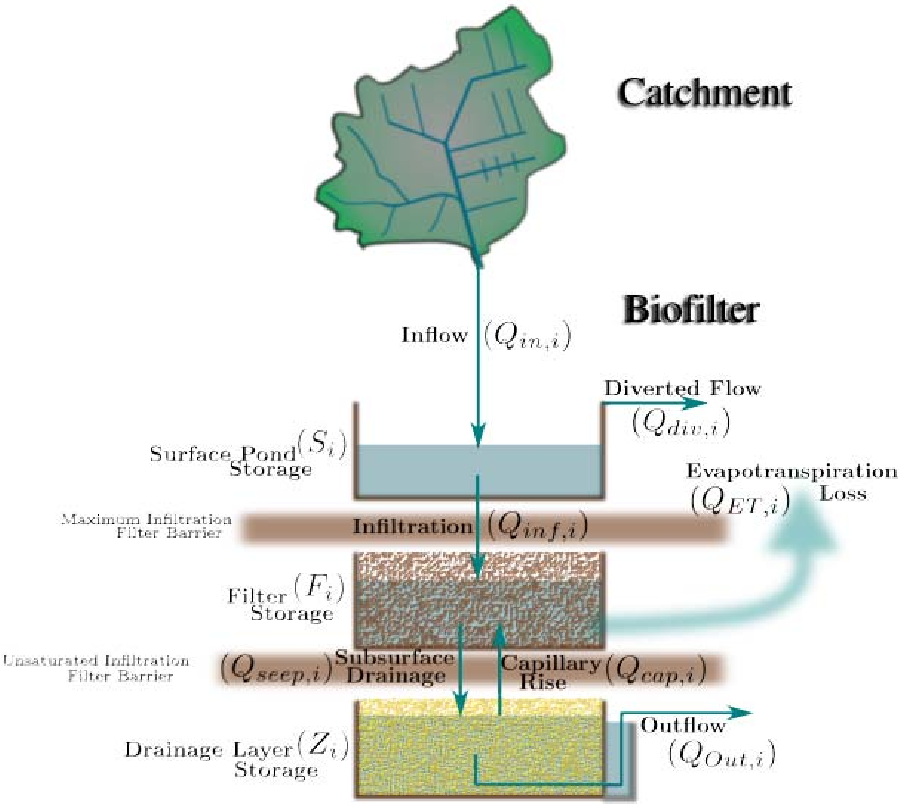

Figure 2. Schematic and conceptual outlay of the model S IV

These models have been calibrated and verified in two main ways:

- MUSIC Comparison: A comparison has been undertaken to compare results with MUSIC version 4.00.9, a well-established Australian conceptual stormwater modelling tool. Since this is a commercially used product this is considered a reference point for similar models. It should be noted that for the purpose of this research project alone a clone of MUSIC was made for comparison. This allowed the alteration of the model's function to study its effect on its performance.
- Real data validation: Data presented in a paper published by Lewis et al. (2008) has been used to determine how the model functions with respect to real biofilters. The model results are compared with the observed data using the Nash-Sutcliffe coefficient of efficiency. This modelling has been event-based as the duration of data in this not long enough to be considered climatic. This data is the most accurate calibration of the model, however gives no long term perspective of its function.

Experimental data for the validation – Lewis et al., 2008

The study site was a biofilter located on the Clayton campus of Monash University (Australia). Runoff from the top level of a multi-level car park (approximately 0.45 ha) drains into two 15 kL pre-treatment sedimentation tanks. This water then passes into a biofiltration system which contains three separate cells, each with a different filter media, each 1.5 m wide, 10 m long, and 0.7 m deep (0.5 m of filter media plus a 200 mm drainage layer).The top biofilter surface is 1% of the catchment area(Figure 1). The filter media had a hydraulic conductivity of 35mm/hr, 110mm/hr and 50mm/hr for cells 1, 2 and 3 respectively as per the measurements over time taken by Lewis et al. (2008) in the first 6 months of 2007. Each cell was densely planted (20 plants/m^2) with ephemeral native rushes and sedges renowned for their nutrient removal properties and extensive root systems (Read et al., 2008, 2010). The following species were planted:*Carex appressa, Carex tereticaulis, Lomandra longifolia, Isolepis nedosa, Caleocephalus lacteus, and Juncus spp.* An overflow weir allowed water to pond to a depth of 250 mm. Perforated 100 mm PVC pipes were installed in the drainage layer of each cell to collect treated water. The sides and bottom of the biofiltration system were sealed to prevent exfiltration to the surrounding soil in order to track mass balance in the system.

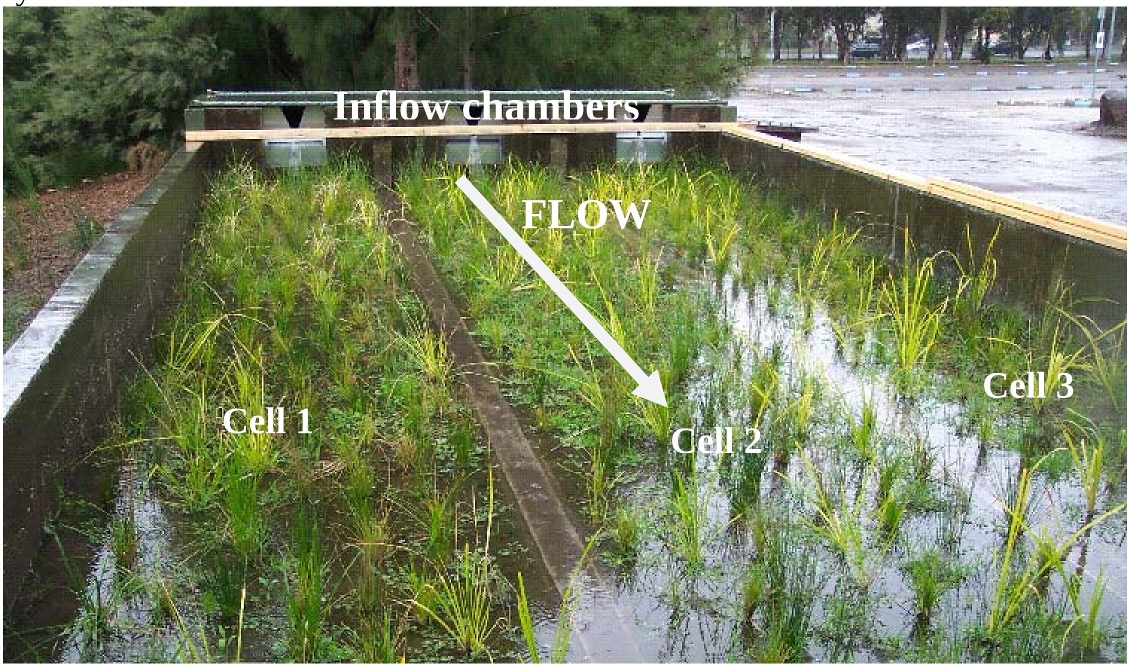

Figure 3. The Clayton biofiltration system (Lewis et al., 2008)

Further properties of the Monash carpark biofilter can be found in Lewis et al. (2008) and Hatt et al. (2009).

RESULTS AND DISCUSSION

Validation of models

Figure 4 shows that the biofilter experiences very rapid responses to inflows, producing outflow hydrographs which seem greater than the measured media permeability over time (as reported in Lewis et al., 2008) would allow. This may be due to preferential flow paths within the system or to spatial variation in the hydraulic head with more water being present near the inlet. This may also cause variation in the permeability over the biofilter. In addition to this it results in less attenuation due to small flows only saturating the portion of the biofilter near to the inlet and therefore the water passes through more quickly leaving the other part of the filter dry. With the low permeability in the model and the maximum timestep of one minute, none of the models are very sensitive to the time step. With Nash-Sutcliffe coefficients of around 0.7, modelsSIII and SIV seem to provide the best representation of the transfer of water through the reed-bed filter.

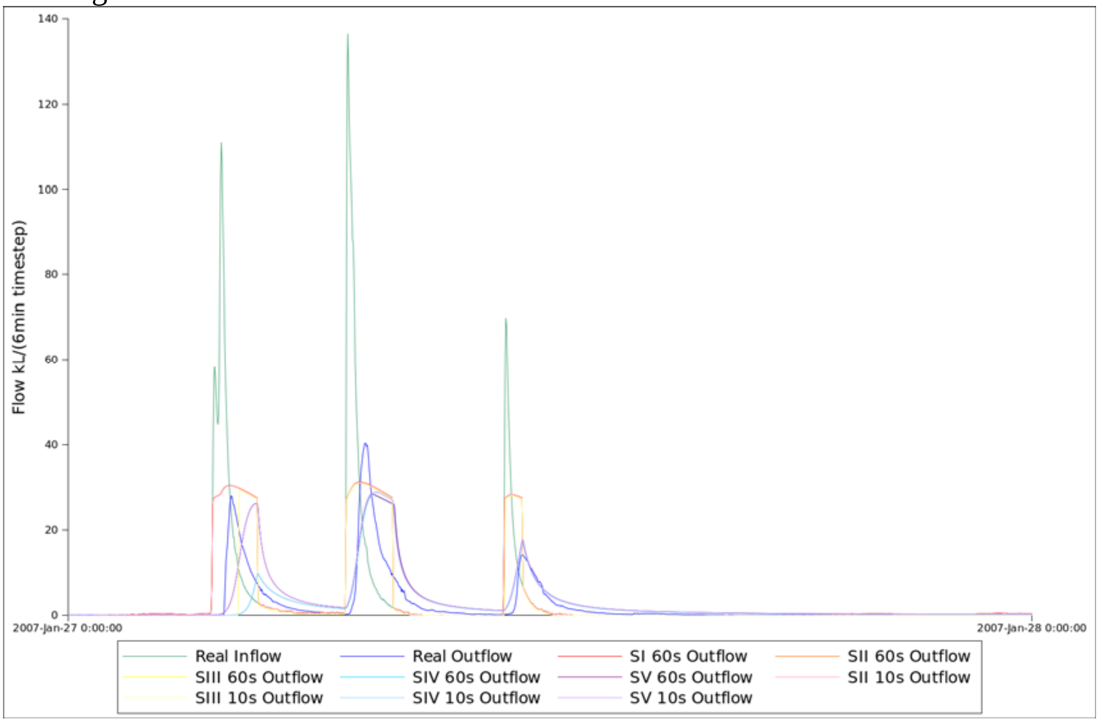

Figure 4. Comparison between simulated and experimental outflows for cell 3

Application of the models to determine key design and sizing parameters

The developed conceptual models have been applied to a subcatchment within theRézé catchment(close to Nantes, France)and to anothers inYzeron, Ecully and Chassieu (the later three are close to Lyon, France and represent a part of Field Observatory in Urbane Drainage sites– OTHU – www.othu.org), in order to evaluate the ability of these simplified models to test the key parameters for VFCW design and sizing. Real inflow time series data collected at these sites have been used. The surface area of the biofilter in each case is assumed to be 2% of the active area (total impermeable area within the catchment) as recommended by the FAWB Adoption Guidelines (FAWB, 2009). The default sizing and design parameters are indicated in figure 5.

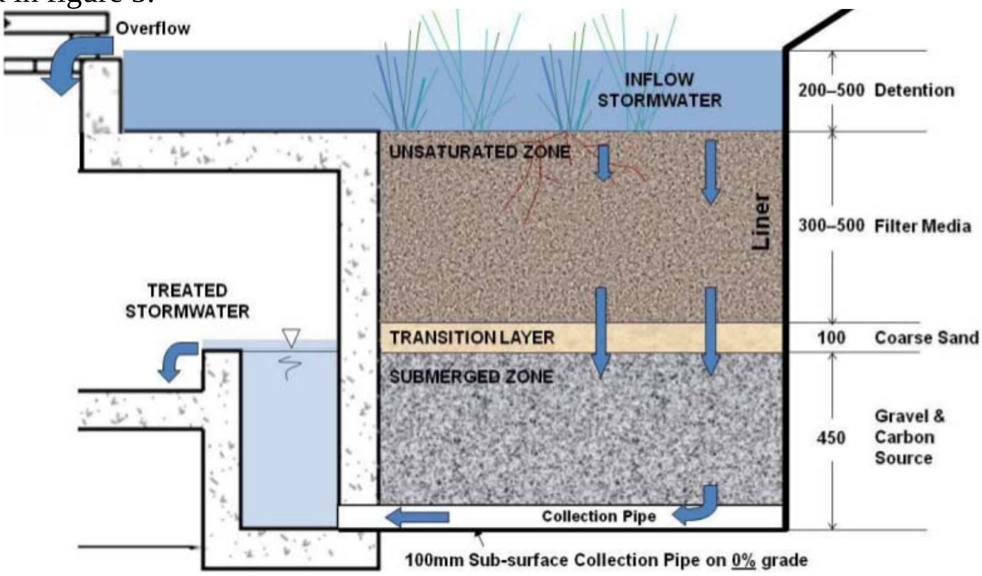

Figure 5. Illustration outlining the advised dimensions of a constructed stormwater biofilter (FAWB, 2009).

Some sizing parameters are followed by means of the validated simplified models. Table 1 shows values of diversion volumes, the storage level, the filter level and the drainage layer. Just under 1 year for Yzeron and 10 yearsof inflows recorded at each catchment is used to test those parameters.

Table 1. Mean values of the data and of the characteristic parameters of the simulated filter

	Rézé – filterarea = 342 m^2		Yzeron – filter area = 660 m^2	
	Model SIII	Model SIV	Model SIII	Model SIV
Inflow volume (L)	122		4655	
Surface storage level (mm)	0.24	1.44	18	88
Diversion volume (L)	1	3	167	800
Drainage layer (mm)	556	347	678	424
Outflow volume (L)	110	111	4468	3836

CONCLUSIONS AND PERSPECTIVES

This paper was focused on the hydraulic modelling of constructed reed-bed wetlands accounting for evapotranspiration and capillary. Darcy and simplified Richards' approaches have been used to govern the fundamental phenomena. Five models have been proposed. Two models (SIII and SIV) based on the concept of barrier filters and simplified Richards equations seem to perform well with good experimental agreement obtained. However, peaks are not well represented because of two main reasons:

- Spatial variation and preferential flow paths within the biofilter is an explanation considered for the variation in peak timings and the variation in permeability at different flow events;
- It is important to model evapotranspiration effectively as this greatly affects the flow patterns of the first flow after a dry spell. This is particularly important for catchments with generally dry weather and large rainfall events in between them.

The representation of the capillarity and unsatured flow such as modelled in MUSIC software seems useful.However it poses problems with extra large timesteps and large permeabilities. The simplified approaches adopted show real potential for being applied to the design and sizing constructed reed-bed filter parameters, taking into account long time series data as well as climate change and characteristics of catchments.

The SEGTEUP data will be used to further validate the proposed approaches. Following this, we will investigate integrating these validated simplified models into theFrench CANOE software package in order to give some recommendations on the key design and sizing parameters of constructed reed-bed wetlands for the purpose of treating CSOs discharges.

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