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Modeling of a lot scale rainwater tank system in XP-SWMM: A case study in Western Sydney, Australia

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ABSTRACT

Lot scale rainwater tank system modeling is often used in sustainable urban storm water management, particularly to estimate the reduction in the storm water run-off and pollutant wash-off at the lot scale. These rainwater tank models often cannot be adequately calibrated and validated due to limited availability of observed rainwater tank quantity and quality data. This paper presents calibration and validation of a lot scale rainwater tank system model using XP-SWMM utilizing data collected from two rainwater tank systems located in Western Sydney, Australia. The modeling considers run-off peak and volume in and out of the rainwater tank system and also a number of water quality parameters (Total Phosphorus (TP), Total Nitrogen (TN) and Total Solids (TS)). It has been found that XP-SWMM can be used successfully to develop a lot scale rainwater system model within an acceptable error margin. It has been shown that TP and TS can be predicted more accurately than TN using the developed model. In addition, it was found that a significant reduction in storm water run-off discharge can be achieved as a result of the rainwater tank up to about one year average recurrence interval rainfall event. The model parameter set assembled in this study can be used for developing lot scale rainwater tank system models at other locations in the Western Sydney region and in other parts of Australia with necessary adjustments for the local site characteristics.

1. Introduction

Urbanization affects urban water cycle in many different ways, such as increased run-off volume, flow velocity, pollutant build-up and wash-off, water demand, compaction of soils, and modification to vegetation (Elliot and Trowsdale, 2007). In the last two decades, various sustainable urban storm water management approaches have been developed, known as Low Impact Development (LID), Sustainable Drainage Systems (SuDS) and Water Sensitive Urban Design (WSUD). As a part of these new urban storm water management approaches, computer-based storm water modeling is frequently adopted to assess the impacts of urbanization on the existing storm water networks and receiving waters. During the last 50 years, urban storm water modeling has evolved from simplistic manual ‘street drainage’ design to a more holistic design method incorporating On-Site Detention (OSD), various WSUD elements, water demand, catchment as well as site scale modeling (Hardy, 2009; Makropoulos et al., 2008; Mitchell et al., 2007, 2001). Urban storm water quantity, quality and transport modeling remain a developing field, due to the complexity of the processes involved and scarcity of the observed data (Ahyerre et al., 1998; James, 1993; Marsili-Libelli and Giusti, 2007).

Rainwater tank systems have become an integrated part of the sustainable urban storm water management and there have been notable research studies on various aspects of rainwater tank systems. Mitchell et al. (2007) investigated the impact of computational time step, initial storage level and the length of simulation period on the accuracy of the storage, yield and reliability relationship of a rainwater tank behavior model. Coombes et al. (2002) argued for the use of a continuous simulation model for rainwater tank systems, whilst Hardy et al. (2007) indicated that continuous simulation would give a better

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indication of ‘the operation and performance of volume sensitive systems’ even on a lot scale (or otherwise known as site scale). Ward et al. (2010) also suggested adoption of continuous simulation approach in modeling rainwater tank system. Most of the previous studies on rainwater tank systems emphasized on the yield and reliability aspects of the system (Khastagir and Jayasuriya, 2010; Palla et al., 2011). There has been limited study on the impact of rainwater tank system on the reduction of urban storm water run-off and pollutant load calibrated to real world scenarios on a lot scale, especially models calibrated to measured inflow, outflow, storage and water quality characteristics in the tank. The majority of the models use a potential incorrect hypothetical run-off coefficient of 0.9 as identified in van der Sterren et al. (2012) and therefore a detailed calibration of rainwater tanks on a lot scale has been conducted in this study to shed more light on modeling lot scale rainwater tank systems.

In the development of rainwater tank system models, continuously recorded water quantity and quality data are often too limited to adequately calibrate and validate rainwater tank system models. These data are scarce and often unavailable for public use (Cowell and O’Loughlin, 1989; O’Loughlin, 2008), especially at a lot scale. This paper focuses on the calibration and validation of a lot scale rainwater tank system model using Expert Software Storm Water Management Modeling (XP-SWMM) utilizing a year-long continuously monitored data of on-site rainfall, tank water and pollutant levels. This paper also examines the sensitivity of the inputs and model parameters on the model outputs.

2. Materials and methods

2.1. Software selection

In this paper, the objective of the modeling task is to simulate the behavior of a lot scale rainwater tank system covering both the water quantity and quality aspects. The model presented in this paper considers the run-off peak and volume in and out of the rainwater tank system and also a number of water quality parameters including total phosphorus (TP), total nitrogen (TN) and total solids (TS). A suitable software had to be selected for this purpose.

There are a number of commercial programs available to model lot scale drainage systems on a continuous basis and therefore the selection of the appropriate software for a given modeling task is essential (Refsgaard et al., 2005). A comparison of the available software has been conducted by many researchers (Elliot and Trowsdale, 2007; Hardy, 2009; Nix, 1994; Obropta and Kardos, 2007; Singh, 1995; Tsihrintzis and Hamid, 1997; van der Sterren, 2012; van der Sterren et al., 2008; Zhao, 2001; Zoppou, 2001), which formed the basis of the selection of the most appropriate software. The software was selected based on three perspectives: design engineer, research and scale. The design engineers perspective focused on evaluating the cost, training maintenance of the program; acceptability; ease of use; versatility; compatibility and ongoing support and trouble shooting. The research perspective evaluated the software for calibration and validation methods; and continuous and event based simulation methods. The scale perspective evaluated the program based on the scale of the modeling, such as lot scale, neighborhood scale and catchment scale. For this study, XP-SWMM was selected as it allows for the modeling of storm water quality and quantity on a lot scale, is quite affordable and user-friendly as explained in van der Sterren et al. (2008).

The XP-SWMM engine is based on the Extran, Transport and Storage treatment modules of the USEPA SWMM4 engine. The program utilises a finite-difference engine that solves the 1 dimensional St Venant equations and an adaptive time step for its hydraulic computations. The model requires a rainfall time series as well as site configurations and pipe sizes. These data were obtained from detailed site testing as discussed in Section 3.

2.2. Error identification methods

Any modeling exercise should aim to minimize the associated errors. Common errors that can occur within a modeling exercise are random or systematic errors in the input data including errors due to non-optimal data values and errors due to incomplete or biased model structure (Abbott et al., 1996). In this study, the errors in the recorded data were minimized by implementing the best practices during sample collection, storage and testing as presented in van der Sterren et al. (2012, 2013). The random and systematic errors in the input data were minimized using appropriate ranges for each parameter and by ensuring that measurable parameters were quantified and checked on-site. Errors due to non-optimal values were minimized by uncertainty analysis, calibration and validation as discussed in this paper. The error due to incomplete model structure was beyond the scope of this study, as the adopted software was a standard industry software program (i.e. XP-SWMM).

2.3. Adopted modeling procedure

In the first step of the modeling task (see Fig. 1), an initial sensitivity analysis was conducted using random sampling from individual model input and parameter distributions as suggested by Helton et al. (2006). A normal distribution, as suggested by Freni and Mannina (2010), was adopted for each of the parameters and ten random values were generated for each parameter. In addition, the automated sensitivity analysis in XP-SWMM was used to confirm the findings, with a variation of ±25%. This procedure assisted in identifying the most sensitive parameters for the model and thereby allowing calibration to focus on these particular parameters (Blasone et al., 2008; Engel et al., 2007; Helton et al., 2006).

After initial sensitivity analysis, calibration was carried out, which focused on the most sensitive parameter to the least sensitive parameter, one at a time. The results of the calibration were evaluated using the depth of run-off, volume and instantaneous peak flow from the rainwater tank system including the roof catchment. In addition, the routed peak flows through the down pipe were evaluated with the relative error (RE) (Eq. A-1), square root error (SRE) (Eq. A-22, the root mean square error (RMSE) (Eq. A-3) and Nash-Sutcliffe efficiency (E) (Eq. A-4) (Nash and Sutcliffe, 1970). The levels within the tank were recorded on a weekly basis and compared to the modeled tank levels using a level based RMSE (Eq. A-5) and correlation equation (Eq. A-6). It should be noted here that use of a number of different statistics are intended to evaluate different aspects of the model fit. For example, RE and RMSE provide an overall error magnitude and the smaller these values are the better the model is and E provides an indication whether the model prediction is better than the simple averaging.

The calibration was followed by a two-step verification analysis as suggested by Kleidorfer et al. (2009), which included split-sample and proxy-basin validation. The split sample validation test was used to calibrate and validate the model using the data collected on Site 1. The dataset is divided and partly used for