Enhanced Bioretention Cell Modeling: Moving from Water Balances to Hydrograph Production

Modélisation améliorée des cellules de biorétention: passer des bilans hydriques à la production d'hydrogrammes

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RÉSUMÉ

Au cours des dix dernières années, les systèmes de biorétention sont devenus la principale mesure de contrôle des eaux pluviales. Bien que ces systèmes aient donné de bons résultats dans de nombreuses études de terrain menées à l'échelle du site, on en sait moins sur leur impact sur le bassin versant. La modélisation de la biorétention offre un moyen d'élargir l'échelle au bassin versant plus vaste. Toutefois, les modèles hydrologiques doivent d'abord être améliorés à l'échelle du site afin de fournir des estimations fiables de leur performance à l'échelle du bassin versant. Actuellement, les modèles hydrologiques capables de simuler la biorétention se basent en grande partie sur des paramètres agrégés et des simplifications qui ne tiennent pas pleinement compte des processus hydrologiques fondamentaux (en particulier les processus sol-eau). DRAINMOD est un modèle de drainage agricole qui s'est révélé intéressant pour les systèmes de biorétention. Il utilise la courbe caractéristique sol-eau pour obtenir des bilans hydriques quotidiens détaillés sur une période continue (progrès par rapport à la plupart des autres modèles en biorétention). Pour cette étude, DRAINMOD a été recodé pour mettre au point DRAINMOD-Urban qui permet des entrées et sorties à haute résolution temporelle, se rapprochant davantage des temps de déplacement des systèmes urbains. Voici les résultats de la modélisation : (1) Si DRAINMOD-Urban peut effectivement produire des hydrogrammes, (2) comment les paramètres calibrés pour le modèle original de DRAINMOD peuvent-ils se transposer au modèle DRAINMOD-Urban et (3) comment les résultats de ce modèle amélioré, DRAINMOD-Urban, peuvent-ils être comparés avec des modèles de biorétention avec des paramètres simplifiés et agrégés.

ABSTRACT

Over the last decade, bioretention systems have become a leading stormwater control measure. Although these systems have performed well in many site-scale field studies, less is known about how these systems impact the watershed. Modelling of bioretention provides an avenue for such scaling to the larger watershed. However, hydrologic models must first be improved at the site scale to provide reliable estimations of their performance at the watershed scale. Currently, hydrologic models capable of simulating bioretention largely consist of lumped parameters and simplifications that do not fully account for fundamental hydrologic processes (in particular soil-water processes). DRAINMOD is an agricultural drainage model that has shown promise when applied to bioretention systems by using the soil-water characteristic curve to obtain detailed daily water balances over a continuous time-period (advances over most other models for bioretention). For this study, DRAINMOD has been recoded to develop DRAINMOD-Urban which allows high temporal resolution inputs and outputs, more closely matching the travel times of urban systems. Resulting modelling revealed: (1) if DRAINMOD-Urban can effectively produce hydrographs, (2) how parameters calibrated for the original DRAINMOD model translate to DRAINMOD-Urban, and (3) how the performance of this enhanced model, DRAINMOD-Urban, compares to simplistic, lumped-parameter bioretention models.

KEYWORDS

Bioretention, DRAINMOD, Hydrology, Modelling, Stormwater

1 INTRODUCTION

Modelling of bioretention allows designers to better optimize the function of bioretention cells, provide guidance for design standards, and scale local impacts to the larger watershed. Using models, potential benefits of implementation can be quantified prior to investing large amounts of time and money into a given project or watershed restoration effort. Improved modelling at the site-scale must be achieved before watershed effects can be fully understood.

Existing models applied to bioretention use simplifications that do not fully account for fundamental hydrologic processes. Many early bioretention models lacked long-term, continuous simulation which ignored the effect of antecedent moisture conditions in the soil, an important consideration that affects the infiltration capabilities of the system (Davis et al., 2011; Heasom et al., 2006). Further, many models use infiltration processes that assume uniform saturation of the media, while field measurements confirm bioretention systems are variably saturated and unsaturated during and following rain events (Brown et al., 2013). Another limitation of current bioretention models is that many are never calibrated with underdrains despite this being a common design feature.

DRAINMOD is an agricultural drainage model that has shown promise when applied to bioretention systems (Brown et al., 2013, Hathaway et a., 2014, Winston et al., 2016). It has the capability of using the soil-water characteristic curve (SWCC) to obtain detailed water balances over a continuous, long-term time-period (improvements over other models for bioretention that assume field capacity). For instance, Brown et al. (2013) showed that calculating the total volume drained using the SWCC compared to assuming a moisture content of saturation minus field capacity created very large errors (-6017 to -14% different), especially at high water table depths. Therefore, the SWCC is a better parameter to use in determining infiltration through bioretention systems since the water level is often near the surface. Because DRAINMOD was designed for agricultural purposes, it currently cannot accommodate the rapid response time of an urban runoff hydrograph, instead aggregating data to a daily timeframe. For this study, DRAINMOD has been recoded to create a bioretention-specific model (DRAINMOD-Urban) that will allow high temporal resolution inputs and outputs, more closely matching the travel times of urban systems.

The objective of this research was to evaluate if DRAINMOD-Urban can produce accurate output hydrographs compared to measured data for a bioretention cell in Ohio, USA. Then, DRAINMOD and DRAINMOD-Urban simulations were compared to determine if improvements in site-scale modelling were realized. In future work, these site-scale improvements will be expanded to a watershed scale model to explore bioretention benefits to the watershed hydrology.

2 MATERIALS AND METHODS

2.1 Site Descriptions

A bioretention site located near Cleveland, Ohio, USA, from a study by Winston et al. (2016) was chosen to calibrate the new DRAINMOD-Urban model. The Ursuline College (UC) cell had a surface area of 182 m^2 and treated stormwater runoff from a 3600 m^2, 77% impervious drainage area made up primarily of parking lot. The cell was filled with typical bioretention media (87% sand, 4% silt, 9% clay). Cleveland, OH, USA, has a humid, continental climate (Köppen Dfa) with cold winters.

2.2 DRAINMOD modifications

DRAINMOD was re-coded to better represent the rapid response time of an urban runoff hydrograph. The original DRAINMOD accepted hourly precipitation inputs as the finest time-scale available. The original model also provided a “Contributing Area Runoff” function but did not allow for input of measured runoff entering the bioretention system from the drainage area. DRAINMOD-Urban was created to allow 1-minute precipitation inputs and 1-minute runoff/inflow from the drainage area. The outputs [infiltration, drainage (outflow), runoff (overflow), ET, and seepage (exfiltration)] are also at 1-minute intervals. This can be used to examine the hydrograph of each water balance component, which was not possible in the previous version of the model.

2.3 Original DRAINMOD Calibration Procedure

The Winston et al. (2016) study, found that 34 out of 50 storm events (68%) produced no drainage or overflow at UC. Thus, the remaining drainage and overflow events were used to calibrate and validate the drainage (outflow) and runoff (overflow) from the system. The original DRAINMOD was parameterized based on the known design configuration and characteristics of the UC cell. The model parameters that could not be measured, such as the piezometric head of the contributing aquifer and thickness of the restricting layer, were used as calibration parameters. These parameters were changed to maximize the goodness-of-fit tests, namely the Nash-Sutcliffe Efficiency (NSE) parameter, for the volumes of each water balance component across all storm events.

2.4 DRAINMOD-Urban Calibration Procedure

The calibrated design configuration and soil parameters used for the original DRAINMOD simulation of the UC cell were not modified for the initial DRAINMOD-Urban simulation (these may change in future efforts). Measured precipitation was input to the model on a 1-minute interval. The inflow at UC consisted of sheet flow that was unable to be measured, so the estimated runoff hydrograph from the drainage area was developed using the USEPA Storm Water Management Model (SWMM). This 1-minute interval inflow was also input into DRAINMOD-Urban. This initial simulation for the UC cell produced 1-minute drainage (outflow) and runoff (overflow) for the same storm events as those of Winston et al. (2016).

Next, Nash-Sutcliffe Efficiency (NSE) was calculated for each individual event to describe model fit for each hydrograph and cumulatively for all storm events which provided an overall NSE value for each simulation. Parameters such as the drainage coefficient, saturated hydraulic conductivity, piezometric head of the aquifer, and thickness of the restricting layer were adjusted in DRAINMOD-Urban to optimize the NSE. A visual assessment of each drainage (outflow) and runoff (overflow) hydrograph was also used to determine optimum model calibration.

3 RESULTS AND DISCUSSION

3.1 Original DRAINMOD Results

The calibrated DRAINMOD model produced high NSE values, 0.94 for drainage and 0.97 for overflow for the UC bioretention cell (Winston et al., 2016). The values during the validation period were 0.98 for drainage and 0.73 for overflow. The overflow NSE is likely lower during validation due to a small number of overflow events during that period. This suggests excellent performance of the model when data are aggregated and comparisons of modelled versus measured data are based on total event volumes of overflow and drainage.

3.2 DRAINMOD-Urban Results

To test the model's ability to predict hydrology at a finer scale (1-minute versus daily), output from DRAINMOD-Urban was compared to the observed data. Examples of initial DRAINMOD-Urban outputs versus measured hydrographs are shown in Figures 1a and 1b. Some outflow events showed lack of correlation with the timing and duration of the event while others showed discrepancies in volume and peak flow rates. Many events were affected by restricted drainage capacity which caused a plateau effect (Figure 1a). Reasonable prediction of runoff timing for events with overflow was observed for DRAINMOD-Urban but much higher peak flows were modelled than measured. The individual event NSEs ranged from -1.00 to 0.66 with a cumulative NSE of 0.41 for drainage (with a range of -7.57 to -0.05 and a cumulative -1.55 NSE for overflow). This suggested that further calibration of the model was needed as there were fine-scale processes not well-represented by the model.

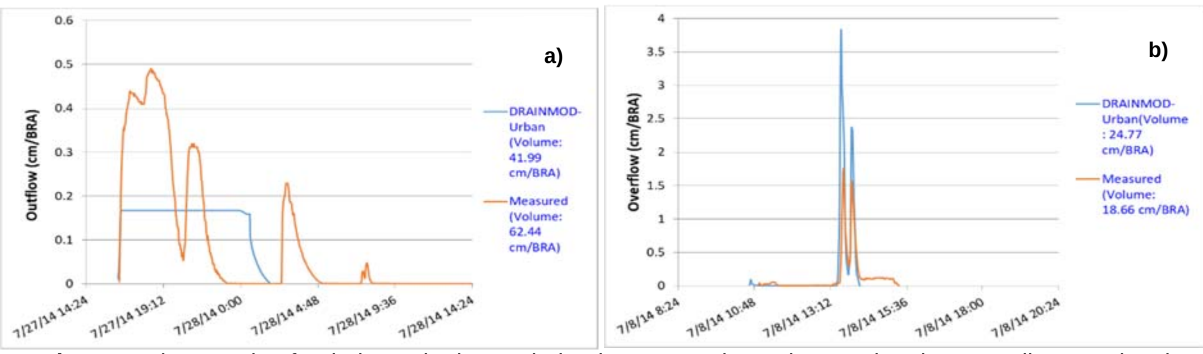

Figure 1. a) Example of a drainage hydrograph that has overestimated event duration as well as restricted drainage creating a plateau effect and underestimated volume predicted by DRAINMOD-Urban b) Example of an overflow hydrograph that shows good correspondence with duration and time to peak but DRAINMOD-Urban overestimated the flow volume and peak flow rate

To calibrate the DRAINMOD-Urban model to the measured hydrographs, the drainage coefficient, saturated hydraulic conductivity, and seepage parameters were adjusted until improvement in hydrograph peak flow, timing and duration were evident (Figures 2a and 2b). The individual event NSEs ranged from -1.37 to 0.86 with a cumulative NSE of 0.65 for drainage (with a range of -0.19 to 0.92 and a cumulative 0.2 NSE for overflow). These NSE values indicate a good fit (a perfect fit would have an NSE value of 1) between measured and modelled drainage data, especially over a fine temporal scale. The NSE was noticeably smaller for overflow events, and examination of the hydrographs still shows overestimation of peak flows by DRAINMOD-Urban. It is important to note that the NSE parameter emphasizes matching the peak of the hydrograph; therefore, visual assessment of each hydrograph was performed to ensure a good fit in addition to the NSE parameter.

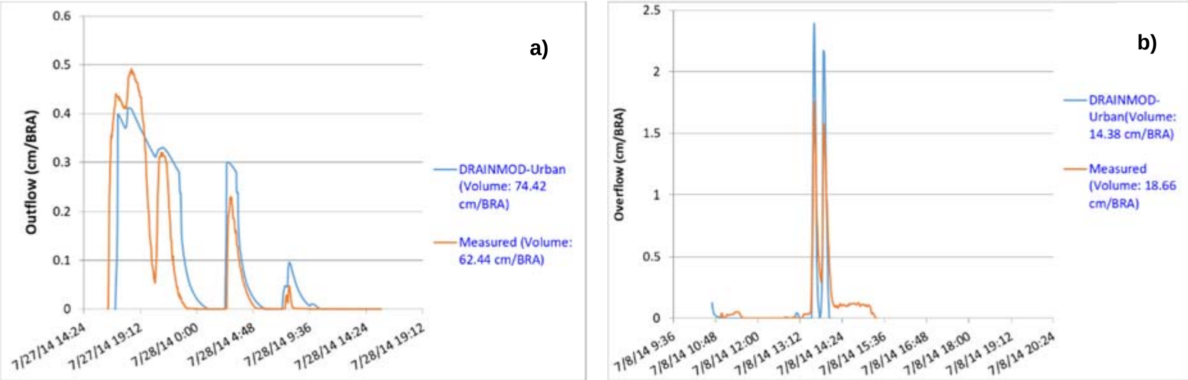

Figure 2 a) Example of a drainage hydrograph that has good correlation of modelled and measured data with respect to event duration, peak flows and flow volume (compare with Figure 1a); b) Example of an overflow hydrograph that shows good correspondence with duration and time to peak and improved peak flows (compare with Figure 1b)

4 CONCLUSIONS

This study shows the strong influence of scale in model performance. When a very accurate bioretention model was disaggregated to a finer time scale, performance suffered. When data are aggregated, these issues are not critical, but become important when accurate outflow hydrographs are desired to understand how bioretention functions when combined at the watershed scale, that is, when there is a need to understand how individual site scale hydrographs are combined at the system level. Although NSE values for the hydrographs from DRAINMOD-Urban were lower than original DRAINMOD results due to the higher level of detail, it is hypothesized DRAINMOD-Urban will outperform other common bioretention models due to improved representation of fundamental hydrologic processes. Ultimately, we hope to show that DRAINMOD-Urban is well-suited to modelling the flashy nature of urban bioretention while considering the influence of antecedent soil moisture, underdrain configuration, and unsaturated flow conditions in the media.

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