A new model for stormwater infiltration systems

La modélisation de la performance des systèmes d'infiltration des eaux pluviales ; une nouvelle méthode

Authors - Browne, D., Deletic, A., Mudd, G. and Fletcher, T.D.

Institute for Sustainable Water Resources, Department of Civil Engineering

Monash University VIC 3800, Australia

Dale.Browne@eng.monash.edu.au

Corresponding author: Dale Browne, Dale.Browne@eng.monash.edu.au

RESUME

Les systèmes d'infiltration sont largement utilisés en tant que mesure de contrôle efficace pour les eaux pluviales. Cependant, la plupart des méthodes et modèles utilisés pour la conception n'approximent que grossièrement les procédés physiques complexes d'écoulement. Des modèles d'écoulement sophistiqués à saturation variable sont disponibles, mais rarement utilisés en raison de leur complexité et des conditions aux limites souvent restrictives. Cet article décrit le développement et la mise à l'épreuve d'un modèle capable de simuler des processus d'écoulements saturés et insaturés à 2 dimensions. Il tient compte de la profondeur dans un volume de stockage poreux, de l'humidité des sols environnants et de l'interaction entre le volume de stockage et le sol. Le modèle combine de façon innovatrice une méthode reposant sur l'humidité du sol avec un flux de Darcy à travers une zone saturée, permettant ainsi l'utilisation d'une solution numérique simple et non-itérative. Les données observées en laboratoire sur des installations d'essai sont bien approchées par le modèle, qui procède à un calibrage des propriétés du sol en fonction de la profondeur de stockage, facilement mesurable dans les systèmes d'infiltration, et de l'humidité du sol.

ABSTRACT

Infiltration systems are widely used as an effective stormwater control measure. However, most methods and models used for design only roughly approximate the complex physical flow processes. Sophisticated variably saturated flow models are available but rarely used due to their complexity and often restrictive boundary conditions. This paper describes the development and testing of a model that can simulate 2-Dimensional saturated and unsaturated flow processes taking into account the depth in a porous storage, surrounding soil moistures and the interaction between the storage and soil. The model innovatively combines a soil moisture based method with Darcy flow through a saturated zone, enabling a simple non-iterative numerical solution to be used. The model produces a good fit to observed data from a 2-Dimensional laboratory test rig, calibrating the soil properties to storage depth, which is easily measured for infiltration systems, and soil moisture.

KEYWORDS

Infiltration, stormwater, Richards equation, unsaturated flow

1 INTRODUCTION - BACKGROUND AND AIMS OF THE WORK

A wide range of infiltration systems, such as infiltration trenches, soakaways, infiltration basins, and bioretention are widely used as effective stormwater control systems (Argue and Pezzaniti 2003; Dechesne et al. 2005; Fujita 1994; Urbonas 1994). They typically consist of a hole or trench filled with a filter media such as gravel or sand. They can also be built as swales or basins placed over a porous soil such as sandy loam. They divert stormwater to the groundwater, reducing the quantity and frequency of downstream flows and restoring a more natural hydrological regime to receiving waters in urban areas. Infiltration systems have a small footprint and can be readily retrofitted into almost any urban area as demonstrated by the subsurface systems widely implemented in Tokyo (Fujita 1994) and recently constructed street tree systems in Melbourne (2006).

However, infiltration systems have a chequered history with many stories of both successes and failures (Furumai et al. 2005; Lindsey et al. 1992; Mikkelsen et al. 1996). Most failures can be attributed to design and construction issues and clogging (Le Coustumer et al. 2007; Lindsey et al. 1992), highlighting the importance of accurate design and upstream pre-treatment of sediment.

Typical infiltration system design guidelines and methods specify an emptying time for design events and use simple empirical equations to estimate this time (Argue and Pezzaniti 2003; Francey 2005; Mikkelsen et al. 1996). However, the behaviour of the system for a range of events including smaller high frequency events (Wong et al. 2005) over a long period of time is of greatest interest to mitigate downstream hydrological and water quality impacts. The capacity of a system to achieve specified flow, load and concentration targets can be predicted using stormwater system simulation models. These models often assume a constant infiltration rate (Wong et al. 2005), with an implicit assumption of steady-state, saturated conditions. However, these would not commonly occur in practice. Ponding with flows into unsaturated soils, influenced by the depth of ponding and antecedent moisture content would be more common. This is particularly the case if guidelines for drainage rates and groundwater clearances are observed (Winogradoff 2002), ensuring the system is able to design freely and preventing the development of steady state saturated conditions. One model that considers the effects of storage levels and clogging on infiltration is that of Dechesne (2005) who assumed a clogging layer acted as the system control and obtained good calibration results for clogged systems. This model is however limited in that antecedent moisture conditions must be assumed as an input constant and it is effective only where the clogging layer acts as the control. More sophisticated models of soil moisture flow are readily available such as Seep/W (Krahn 2004) and SWAP (Kroes and Van Dam 2003) but rarely applied to stormwater infiltration systems due to their complexity, lengthy run times and expertise and data requirements.

Given the substantial investments being made in these systems around the world, there is a need for a rigorous model of infiltration systems that accurately simulates hydraulic behaviour and performance and the physical flow processes. The purpose of this research is to develop such a model. The model focuses on accurate representation of the primary hydraulic processes of storage and flow into variably saturated surrounding soils within a framework that is simpler than most existing variably saturated flow models. Pollutant transport processes and the effects of vegetation are not yet considered. The effects of clogging have not yet but will be taken into account. This model will facilitate the evaluation of existing simpler methods and enable infiltration systems to be designed with greater confidence.

2 METHODS

2.1 Model Development

2.1.1 Conceptualisation and governing equations

A stormwater infiltration system typically consists of a storage which may either be a surface ponding area or a gravel-filled trench that temporarily retains storm water, allowing infiltration into the surrounding soil to occur, Figure 1. Water infiltrates into the surrounding soil, eventually reaching the underlying groundwater table. Flows through the soil are initially unsaturated with a saturated zone forming around the storage after prolonged ponding. It was assumed that a 2-Dimensional modelling approach would be adequate since the majority of these systems are built as long, narrow systems (although this is not always the case for small soakaways and some basins). Therefore, a 2D model was proposed that contains three major blocks representing: (1) the storage, (2) the saturated soil zone (near the storage), and (3) the unsaturated soil zone.

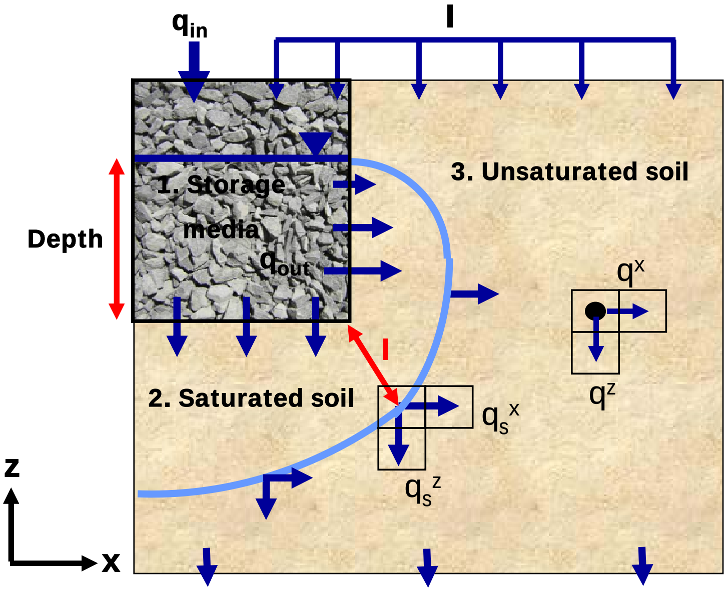

Figure 1 Conceptualisation of a stormwater infiltration system in 2D

The **storage** is simulated using a reservoir equation, considering inflows, outflows to the surrounding soil and the resulting change in depth.

$$\frac{dDepth}{dt} = \frac{q_{in} + I - q_{out}}{n}$$

Eq. 1 Storage equation

Where the inflow data series are q_{in}, stormwater inflow rate ($m^3/s/m^2$) and I, rainfall intensity (m/s length). *Depth* is water depth in the storage (m), *n* is the porosity of the storage media and q_{out} is the outflow rate ($m^3/s/m^2$), the sum of outflows through the bottom and sides of the storage divided by the storage surface area (Figure 1).

Flow through **unsaturated** soils can be simulated using Richard’s equation (Richards 1931) describing flow in the unsaturated zone, see Eq. 2 and Eq. 3. Richards equation is derived by substituting the Darcy flux into the equation for continuity of mass.

$$\frac{\partial \theta}{\partial t} = \frac{\partial \left(D(\theta) \frac{\partial \theta}{\partial x} \right)}{\partial x}$$

Eq. 2 Richards Eq. for horizontal flow

$$\frac{\partial \theta}{\partial t} = \frac{\partial \left(D(\theta) \frac{\partial \theta}{\partial z} + K(\theta) \right)}{\partial z}$$

Eq. 3 Richards Eq. for vertical flow

where θ is soil moisture, $K(\theta)$ is unsaturated hydraulic conductivity (m/s), $D(\theta)$ is diffusivity (m^2/s), x is distance in horizontal direction (m), z is distance in vertical direction (m) (positive upwards) and t is time (s). A van Genuchten model in conjunction with the Mualem pore distribution model, fixing lambda to 0.5, was used for the soil characteristic curves (van Genuchten 1980). The Darcy flux is also calculated throughout the unsaturated zone in both directions, q_x and q_z, see Figure 1.

The soil moisture based form of Richards equation is applicable for unsaturated or just saturated soils but not pressurised conditions (Celia et al. 1990). This limitation was overcome using a simplified Darcy's law approach to approximate flows through a **saturated zone** surrounding the storage. Saturated flows are assumed to be steady state for a moment in time with inflows and outflows being equal, ignoring diffusion and lag time. The flow through this zone is driven by the pressure differential between the depth of water in the storage and the pressures in the adjacent unsaturated soil. The flow at the saturated/unsaturated interface is calculated using Darcy's Law:

$$q_s = -K_s \frac{Depth + z}{l}$$

Eq. 4 Saturated flow

where q_s is the total flow rate through the saturated/unsaturated zone boundary that can be divided into its components in the x and z direction (Figure 1), K_s is saturated hydraulic conductivity, l is the shortest distance from the storage to the saturated/unsaturated boundary (Figure 1). Since there is no change in moisture content throughout the saturated zone, the inflows and outflows to the saturated zone must be equal. This is expressed through a simple continuity equation to determine outflows from the storage to the saturated zone.

2.1.2 Boundary conditions

The input parameters into the Van-Genuchten soil model are the saturated moisture content, θ_s, residual moisture content, θ_r, curve fitting parameters α, n, and the saturated hydraulic conductivity, Ks. These are defined or calibrated by the user.

The time series inputs to the model are rainfall and stormwater inflows. A time variable storage depth can be specified instead with the model calculating the flow rate required to achieve the specified depth. The storage acts as a highly flexible switching flux/head boundary condition in two dimensions, avoiding the need to set soil boundary conditions a-priori. If the inflow rate is less than the outflow rate, a flux boundary is applied to the soil. If the inflow rate exceeds the outflow rate or the depth in the storage is greater than zero, a head boundary condition is applied with the flow rates through the bottom and side of the storage influenced by the depth of ponding.

2.1.3 Numerical solution

A fully explicit non-iterative approach was used. The soil moisture based form of Richards equation (Eq. 2 and Eq. 3) was solved for vertical and horizontal directions sequentially, similar to the approach used by Tuteja (2004). The saturated zone equations were also solved explicitly. Conversely, popular pressure head based variably saturated flow codes use implicit, iterative solutions requiring multiple calculations for each timestep to ensure mass conservation with Celia's method (1990). They may experience convergence failures and long run times with high flow rates into very dry conditions, as can be expected for infiltration systems. The explicit solution will require smaller timesteps, being limited by the ratio of temporal to spatial discretisation, but it is hypothesised that it will enable a faster solution than a comparable implicit iterative method.

The modelled region is discretised using a simple finite difference scheme with a series of layers, *i*, in the vertical direction and pixels, *p* in the horizontal direction. The thickness of both is variable. Soil moistures, pressure heads, hydraulic conductivities and diffusivities are evaluated at the centre of a given pixel layer while fluxes are evaluated at the boundaries.

An adaptive time stepping method first proposed by Staple (1966) was adopted to accommodate the range of conditions from dry periods to sudden storms with rapid flows and saturation over dry soils. Staple’s criterion for stability, “r”, assuming a fixed layer thickness, and the resulting formulation for maximum timestep used here are:

$$\frac{D_{\max}(t)\Delta t}{(\Delta z)^2} \le r \qquad Min\left[\Delta t^{i,p}_{\max} = r\frac{(\Delta z)^2}{D^{i,p}(t)}\right] \qquad \Delta t(t+1) = \Delta t(t) + F.[\Delta t(t) - \Delta t(t-1)]$$

Eq. 5a Staple’s criterion Eq. 6b Maximum timestep 7c New timestep size (t+1)

Where D_{max} is maximum diffusivity at any node, Δt is timestep size, Δz is layer thickness and *r* the stability criterion. *z* is the thickness for a given pixel layer. $\Delta t^{i,p}_{max}$ is maximum timestep size and $D^{i,p}$ diffusivity at a given pixel layer for the previous timestep. *F* is a multiplier to accelerate the change in timestep. Values of *r* in the range 0.15 to 0.3 used by Staple (1966) were found here to be satisfactory with a sandy loam soil. The next timestep is forward predicted explicitly based on the change in timestep size to the previous timestep and using a multiplier to keep pace with non-linearly changing conditions.

2.2 Model testing

The accuracy of the numerical model was tested in 1D for unsaturated and ponded conditions using simulations of unsaturated flow used to validate Hydrus (Kool and van Genuchten 1991) and Phillip’s analytical models for ponded infiltration (Philip 1957). Good results were obtained for both unsaturated flow simulation and the saturated zone approximation at a range of depths.

The model was then tested using data obtained from experiments conducted in a two dimensional experimental rig at Monash University (Siriwardene et al. 2006) representing a 2D slice of a long infiltration trench, as shown in Figure 2. The rig is 2.1 x 2.0 x 0.25 m and is filled with a sandy loam to represent the surrounding soil around an infiltration system. The upper left corner (0.5 x 0.8 m) is filled with a gravel storage media. Water is introduced into the laboratory infiltration system via a sprinkler. Experiments were carried out with constant water level and with filling and draining to specified levels to simulate multiple rainfall events, initially with clean water then with sediments introduced until clogging occurred. Only data for clean water was used for the calibration to establish baseline hydraulic parameters.

Measured inflow rates were used as inputs, while 5 of the parameters needed for construction of the soil characteristic curves (listed in 2.1.2) were calibrated. The calibration was done using the optimisation tool PEST, widely used in groundwater modelling (Doherty 2004). The model was optimised for measured depths in the soakaway (A). For field infiltration systems, this is a much more practical observation data set than the outflow rate commonly used in calibration of laboratory column tests. The model was also calibrated by optimising for both depth and soil moisture (B) measured at a selected probe, 1.56 m from the left and 0.9 m from the bottom of the test rig. Although soil moisture is not so commonly measured, this was undertaken to determine whether a better calibration could be obtained given more extensive data

Figure 2: 2D laboratory infiltration system

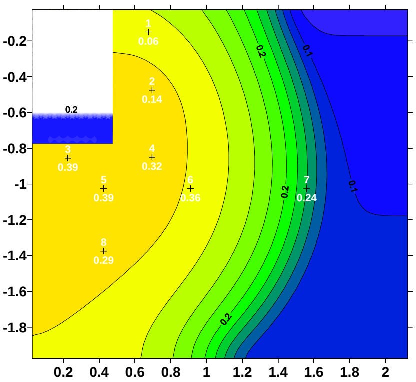

Figure 3: Soil Moistures 2D plot

3 RESULTS AND DISCUSSION

Figure 3 shows the typical model outputs for soil moisture in 2D. Figure 4 and Figure 5 show the measured versus modelled soil moistures at the point used for calibration and depths in the soakaway for both calibration runs. Moisture contents at other points were also checked.

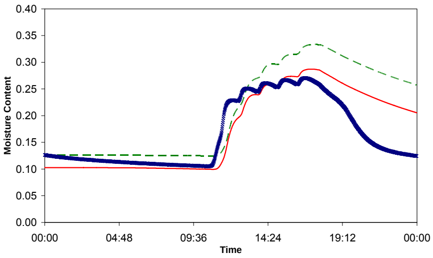

Figure 4 Modelled vs measured moisture content

······ Observed (Probe 7)

—— Modelled (A)

—·— Modelled (B)

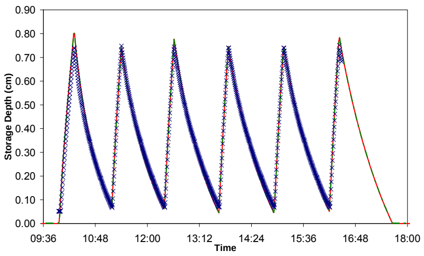

Figure 5 Modelled vs measured storage depth

······ Observed (Probe 7)

—— Modelled (A)

—·— Modelled (B)

For calibrations using only the depth data, results matched very well for depth (the modelled results match almost exactly) but were fairly poor for moisture content. Incorporating moisture content data significantly improved the fit to moisture contents at the calibration point and other observed points while the fit to depths was still very good. Inspection of the 2D profile (Figure 3) show a steep moisture content profile near Probe 7 so the fit achieved can be considered to be very good.

The results indicate that the model is able to reproduce the conditions observed in the 2D laboratory rig, both in terms of depths in the storage and moisture contents in the surrounding soils. This gives confidence that the model is simulating the physical processes including both outflows from the infiltration system and antecedent moisture conditions reasonably well.

The calibration results have important implications for field monitoring, indicating that it is highly desirable to measure soil properties such as the saturated moisture content and monitor field moisture contents as well as storage depths for filling and draining conditions to obtain a good calibration and minimise the uncertainty of estimated parameters.

However, the results presented here are a preliminary calibration of the model. Further soils tests are being undertaken in a laboratory to more accurately estimate the soil characteristic curves. Finally sensitivity analyse of the model is planned for the near future.

4 CONCLUSIONS

A new model of stormwater infiltration systems was developed incorporating storage, saturated and unsaturated zone models. The model simulates the physical processes of outflow from an infiltration system more precisely than models commonly used in the design process for infiltration systems, allowing simulation of varying outflow rates from an infiltration system as the depth in the storage and antecedent soil moistures change. The explicit solution is significantly simpler than existing pressure based variably saturated flow codes. It overcomes the main problem associated with soil moisture based models by using a simple Darcian flow method for a saturated zone around the storage. Adaptive time-stepping efficiently handles the broad range of wet and dry conditions encountered for infiltration systems. The model was shown to be able to reproduce observed conditions in a 2D laboratory experiment, giving confidence in the models ability to simulate field conditions.

It was also found that it is useful to obtain data for saturated moisture content and field moisture content data to obtain a good calibration fit for unsaturated soil properties. This would enable field data from simple filling and draining tests to be used to determine soil parameters, minimising the need for time consuming and expensive laboratory soils tests.

Clearly much remains to be done, firstly to undertake simulations of laboratory and field conditions over longer periods and compare results with observed data. These simulations could then be compared with predictions based on simple approximate methods and standard assumptions to evaluate their adequacy for predicting the hydraulic behaviour of infiltration systems. Further testing and sensitivity analysis is also planned.

Another area that is yet to be addressed is the issue of clogging and this is to be implemented into the model, using data obtained from clogging experiments in the 2D laboratory rig and a model of clogging under development (Siriwardene et al. 2006).

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