AN ALTERNATIVE APPROACH TO MODELLING STORMWATER RUNOFF FROM SMALL URBAN CATCHMENTS

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ABSTRACT
The inability of current stormwater quality models in reproducing historical pollutographs accurately and reliably has prompted the need to introduce alternative approaches to simulate stormwater runoff from urban catchments. In view of the increasing popularity of designing urban stormwater systems using the Water Sensitive Urban Design (WSUD) approach, it is also essential to adopt a modelling approach that enables differentiation between the various sources of pollutants such as roofs, roads and other impervious surfaces. Using data from small urban catchments in Sydney, this research attempts to improve the accuracy of stormwater runoff predictions by adopting a more process-based approach. This resulting runoff model will be enhanced to simulate stormwater runoff quality, subsequently serving as an important tool in urban catchment management studies. Other findings from the modelling exercise include the necessity of adopting a finer resolution in which rainfall is to be recorded and the inferiority of the plane and gutter approach compared to a simplified diagonal approach in conceptualising the catchment.

KEYWORDS
Kinematic hydrology, modelling, stormwater, urban drainage, runoff.

1. INTRODUCTION

Recent periods of drought coupled with rapid urban development in Sydney have lead to significant strains on the urban water cycle. The concept of Water Sensitive Urban Design (WSUD) thus has gained popularity as increased efforts are invested into providing more sustainable use of water and improving the water quality to pre-development conditions (www.melbournewater.com.au). In light of this integrated best management practice approach to urban stormwater management, there exists a need to investigate the contribution of individual surfaces such as roofs and roads to urban pollution in order to facilitate the implementation of the appropriate WSUD applications. Unfortunately, consideration of the available literature indicates that little is known about the spatial and temporal distribution of pollutants on these surfaces especially for roofs. Furthermore, simulation models lack capabilities for modelling the intricate nature of urban drainage systems with a high degree of accuracy, particularly with respect to stormwater quality (Cheah, 2006). Therefore, a research project has been formulated to address these issues.

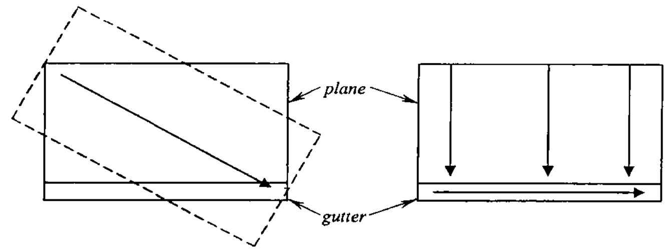
Most of the existing simulation models were developed initially for runoff quantity simulations. Consequently, their hydrologic components were not suited to the purpose of simulating stormwater quality. Furthermore, these simulation models are neither capable of differentiating the sources of pollutants nor able to reproduce the historical pollutographs accurately and reliably. As noted by Huber (1992), this can be attributed to the fact that water quality processes such as the entrainment and erosion mechanisms of pollutants from surfaces are poorly understood. Hence, most water quality models are either simple conceptual models, or empirical expressions that require extensive calibration and might not be applicable for catchment conditions other than those where they were formulated in. This was further highlighted by Jewell and Adrian (1981) and Nix (1994) who commented on the lack of effort from the modelling community in improving the underlying formulations of the existing models. As a result, a more advanced approach has to be developed to overcome some of these perceived shortcomings and that would replicate the underlying physical processes occurring during a rainfall storm event.

The purpose of this paper is to present an approach currently being investigated for improving the accuracy of stormwater runoff predictions by adopting a process-based approach found in kinematic hydrology. The developed model was applied to two impervious urban catchments located in Sydney with field gauging stations maintained by the University of New South Wales. This runoff model will subsequently be enhanced to simulate stormwater runoff quality for different impervious surfaces.

2. MODEL SETUP

2.1. Conceptualising the catchment

Having identified the objectives of the modelling exercise, the study catchment was first conceptualised as a rectangular element. Two alternative ways of simulating runoff flowing over a catchment surface have been investigated in this study. These two alternatives are illustrated in Figure 1. The first alternative is a simplified diagonal approach used by Hogan (2000). The second alternative is the plane and gutter approach introduced by Deletic *et al.* (1997), which is a more realistic representation of the pathway taken by the runoff. Investigation into the advantage of adopting one approach over the other is reported herein.



(a) Simplified Diagonal Approach (b) Plane & Gutter Approach

Fig. 1. Conceptualising Runoff Flow over the Catchment

2.2. Kinematic wave theory

Early studies conducted to investigate overland flow from impervious surfaces include work carried out by Horton (1933) and Izzard (1946) but it was Lighthill and Whitham (1955) who first developed the kinematic wave theory. This theory is a well-accepted tool for modelling a wide variety of hydrologic processes (Singh, 1996) and its usefulness was documented in studies such as those by Henderson and Wooding (1964) and Ball (1994).

The basis of the use of the kinematic wave theory for runoff estimation is the application and use of hydraulics as the foundation for the hydrological model. Using the assumption that the gravitational and frictional forces are dominant, the equations of continuity and motion for flow over a wide surface that neither converges nor diverges can be expressed as follow:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = i_e \quad (1)$$

$$q = \alpha y^{\beta} \quad (2)$$

where q is the flow rate per unit width of the catchment surface ($m^3/s/m$), y is the depth of flow (m), i_e is the effective rainfall intensity (m/s), ∂x is the space step (m), ∂t is the time step (s) and α and β are coefficients dependent on the flow conditions. Since Manning's equation is used in this case to describe flow over the surface, the values of the coefficients can be determined as:

$$\alpha = \frac{\sqrt{S_o}}{n_p} \tag{3}$$

$$\beta = \frac{5}{3} \tag{4}$$

where S_o is the longitudinal slope of the surface and n_p is the Manning's n for the plane surface. Equations 1 to 4 were used to simulate the overland flow on a plane surface. In addition, the following boundary and initial conditions were assumed:

$$y(0,t) = 0 \qquad 0 \le t \le T \tag{5}$$

$$y(x,0) = 0 \qquad 0 \le x \le L \tag{6}$$

where T is the storm duration (s) and L is the length of the overland flow plane (m). These assumptions are reasonable for an initially dry surface (Singh, 1996).

For gutter flow, similar equations were derived based on the model proposed by Izzard (1946) for simulating the hydraulics of flow in a gutter collecting runoff along the edge of a plane surface. The following equations were employed:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = i_e W_g + q_L \tag{7}$$

$$Q = \alpha H^{\beta} \tag{8}$$

where Q is the gutter flow rate (m^3/s), A is the cross section area (m^2), q_L is the unit inflow from the plane surface (m^2/s), W_g is the gutter width (m) and H is the flow depth by the kerb (m). The values of α and β are defined differently for the case of a gutter flow:

$$\alpha = \frac{0.375F\sqrt{S_o}\,z_g}{n_g} \tag{9}$$

$$\beta = \frac{8}{3} \tag{10}$$

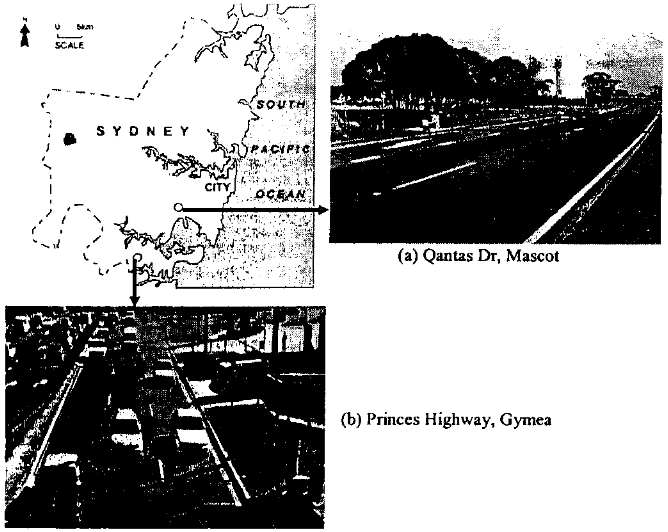
where F is a flow correction factor, z_g is the reciprocal of cross slope and n_g is the Manning's n for the gutter. Equations 9 and 10 are of the same form as Izzard's formula and give better results for shallow flow in a triangular cross section channel compared to the normal Manning's expression (Clarke *et al.*, 1981). These expressions have been recommended for use in analysing flow within gutters in Australian Rainfall and Runoff (Pilgrim, 1997). The suggested value for F is 0.9 for simple triangular channels and 0.8 for gutter sections. On the other hand, the range of Manning's n considered is 0.01 to 0.013, as suggested by Woolhiser (1975) for concrete or asphalt surfaces.

2.3. Numerical solution algorithm

Solution of the kinematic wave equations for the general case of temporally varying rainfall patterns requires the application of numerical techniques (Ball and Ferguson, 1994). A four-point implicit method known as the Preissmann scheme (Preissmann, 1961) was thus used in this study.

3. CASE STUDY

Two urban catchments located in the suburbs of Sydney were selected, namely Mascot and Gymea. These catchments generally consist of impervious road surfaces and are hydraulically isolated from other land uses. Field gauging instrumentations were installed and maintained by the University of New South Wales at both sites respectively. The criteria of the selection of these locations were discussed by Ball *et al.* (1994). A location map for both catchments is presented as Figure 2.



(a) Qantas Dr, Mascot

(b) Princes Highway, Gymea

Fig. 2. Location Map for Catchments

3.1. Qantas Dr, Mascot

This site is located near to the intersection of Qantas Drive and Link Road, Mascot. It is approximately ten kilometres south of Sydney CBD and about five kilometres south-west of the University of New South Wales. It backs directly onto a security area controlled by the Federal Airports Corporation (FAC) and is used by Qantas Airways for their customs holding area. This small catchment with an area of $242m^2$ includes two lanes of west bound traffic and a left turning lane for vehicles turning into Link Road. As a major arterial road, the average daily traffic exceeds 30,000 vehicles (RTA, 2003). The discharge of stormwater from the asphalt road passes through a rated flume located at the edge of the kerb, with the precipitation rain gauge, data logger, and automated grab sampler all installed in the nearby vicinity.

3.2. Princes Highway, Gymea

The Gymea catchment, which has an area of $380m^2$, is located along the Princes Highway, south-west of Sydney CBD. This catchment consists of three lanes of north bound traffic with additional runoff coming off a service station driveway. Similar to the Mascot site, it is also a major road artery with high traffic volume. The runoff site is at the overhead pedestrian bridge near the Gardens Avenue intersection and across the road from Gymea High School. Field equipment is housed under the pedestrian bridge ramp whereas the rain gauge is located on the top of the steel barrier of the same bridge.

3.3. Storm events

The resulting hydrological model based on the kinematic wave theory was tested using 9 storm events from the Mascot catchment, spanning from 13/11/1993 to 16/5/1997, and another 9 storm events from the Gymea catchment, spanning from 5/1/1998 to 15/2/1998. A range of storm events was selected, with a minimum rainfall depth of 1mm and a maximum of 8.2mm. These storm events are typical of the many frequent storm events that occur in the Sydney region.

4. CATCHMENT MODELLING

4.1. Calibration

Calibration was undertaken by systematically adjusting values of the control parameters until the monitored catchment performance was replicated. The focus was first on replicating the runoff volume and then secondly the peak runoff rate. For measuring the goodness of fit between the simulated and recorded hydrographs, the following criteria were used:

- Relative error (RE) between the predicted and recorded hydrograph volumes (V_p and V_r) defined as:

$$\varepsilon_V = \frac{V_p - V_r}{V_r} \qquad (11)$$

- Relative error (RE) between the predicted and recorded peak flows (Q_p and Q_r) defined as:

$$\varepsilon_Q = \frac{Q_p - Q_r}{Q_r} \qquad (12)$$

- Root Mean Square Error (RMSE), which gives an indication of the average departure of the prediction from the recorded values and is defined by:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Q_p(i) - Q_r(i)\right)^2} \qquad (13)$$

For the catchment at Mascot, Events 7 and 8 were used as calibration events whereas Events 1 and 3 were used for the Gymea catchment. Lower RE and RMSE values indicate a better fit between the predicted and recorded hydrographs.

4.2. Simulation results

Shown in Figures 3 and 4 are typical comparisons between the recorded and simulated hydrographs. As indicated by the simulated hydrographs shown in these figures, the predictions obtained from the simulation model adequately replicate the recorded hydrographs. This assumption is verified further when all the events are considered; details of these results are presented in Tables 1 and 2. Within these tables, results are shown for the two alternative modelling approaches being considered.

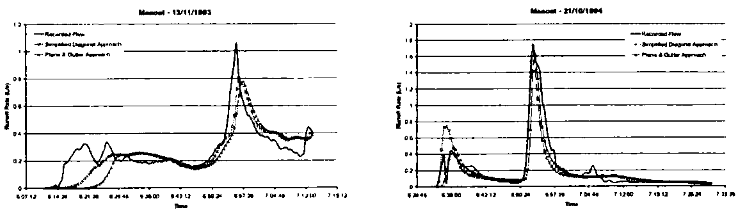


Fig. 3. Hydrographs for the Mascot Catchment

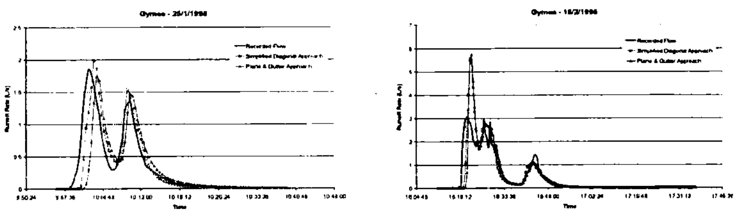


Fig. 4. Hydrographs for the Gymea Catchment

Table 1: Simulation Results for the Mascot Catchment

Event	Date	Rainfall Depth (mm)	Interevent dry period (hrs)	RE for Runoff Volume		RE for Peak Runoff		RMSE	
				S.D.(1)	P & G(2)	S.D.(1)	P & G(2)	S.D.(1)	P & G(2)
1	13/11/93	4.8	250	-6.5%	-12.5%	-23.8%	-26.5%	0.1101	0.1435
2	18/11/93	5.8	92.5	-7.8%	-11.4%	-11.1%	-14.3%	0.0901	0.1138
3	19/10/94	2.4	195.5	0.8%	-4.6%	5.7%	3.1%	0.0795	0.1072
4	21/10/94	2.8	2	-6.3%	-9.4%	-0.2%	-6.1%	0.1442	0.1214
5	28/11/94	8.2	197.5	-1.6%	-4.0%	-8.1%	-9.0%	0.2339	0.2686
6	8/12/94	2	212	0.5%	-7.4%	54.4%	43.8%	0.0473	0.0423
7	23/03/97	1	156.5	6.0%	-4.6%	23.0%	7.2%	0.0689	0.0583
8	5/05/97	4.4	885.5	0.4%	-1.7%	-12.8%	-13.7%	0.2860	0.3212
9	16/05/97	3.6	111	-2.5%	-4.4%	13.5%	13.1%	0.1056	0.1108

(1) Simplified Diagonal Approach
(2) Plane and Gutter Approach

Table 2: Simulation Results for the Gymea Catchment

Event	Date	Rainfall Depth (mm)	Interevent dry period (hrs)	RE for Runoff Volume		RE for Peak Runoff		RMSE	
				S.D.(1)	P & G(2)	S.D.(1)	P & G(2)	S.D.(1)	P & G(2)
1	5/01/98	6.8	44.5	-0.3%	-0.8%	17.4%	13.7%	0.1749	0.2316
2	20/01/98	1.8	18.5	-7.7%	-19.0%	-18.4%	-35.0%	0.1528	0.2528
3	25/01/98	5	0.5	0.8%	-0.3%	10.2%	5.5%	0.2725	0.3537
4	25/01/98	2.8	17.5	-3.7%	-6.0%	6.9%	-6.4%	0.2038	0.3614
5	7/02/98	1.4	74	-9.3%	-22.2%	-60.6%	-82.6%	0.1305	0.1899
6	10/02/98	4	14.5	-13.6%	-16.7%	-23.5%	-23.9%	0.1590	0.2037
7	15/02/98	7.4	123	0.0%	0.2%	80.8%	87.1%	0.4918	0.5625
8	15/02/98	3.2	1	-4.2%	-9.3%	17.6%	10.5%	0.2796	0.4420
9	15/02/98	1.4	3	-3.4%	-11.9%	-3.6%	-10.9%	0.1580	0.2541

(1) Simplified Diagonal Approach
(2) Plane and Gutter Approach

5. DISCUSSIONS

A comparison between the simulated runoff hydrographs for the two alternative approaches has been undertaken. Among the distinctive features of the hydrograph using the plane and gutter approach is the delay present at the beginning of the simulated runoff hydrograph. Against expectations, the simplified diagonal approach consistently produced better runoff predictions compared to the plane and gutter approach. This will have implications for the setup of the water quality model. However, the case might not be the same if a larger catchment is modelled as the lag introduced by the plane and gutter approach will come into play with the longer catchment response time expected from the larger catchment.

Table 3: Comparison of Results from Both Catchments

		RE for Runoff Volume		RE for Peak Runoff		RMSE	
		S.D.	P & G	S.D.	P & G	S.D.	P & G
Mascot	MEAN	-1.89%	-6.67%	4.52%	-0.27%	0.1295	0.1430
	VAR	0.20%	0.14%	5.55%	4.21%	0.0064	0.0086
Gymea	MEAN	-4.60%	-9.55%	2.97%	-4.65%	0.2248	0.3169
	VAR	0.23%	0.72%	14.75%	20.62%	0.0128	0.0154

Drawn in Table 3 is a comparison of the simulation results from both catchments. Overall, the model results derived for the Mascot catchment fared better than the Gymea catchment, primarily because of the uncertainty in defining the latter catchment boundary where additional runoff is introduced by the adjacent service station driveway. Nevertheless, a similar trend is observed in regard to the two alternative simulation approaches.

It was found also that for small events, which produced rainfall depths less than 1mm, the modelling results contained large errors. This can be attributed to the small runoff volume recorded. Omitting these events from the analysis, the difference between the recorded and the predicted hydrograph volume, as shown in Figure 5, ranges from -22.2% to 6.0%, which is within the acceptable accuracy range of ±30% quoted by Schilling and Fuchs (1986).

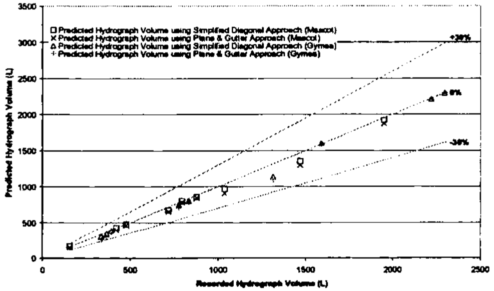


Fig. 5. Comparison of Predicted and Recorded Hydrograph Volume

The shapes of the hydrographs produced using either simulation approach are similar but both are unable to reproduce the variability of the original recorded hydrographs, mainly due to the averaging of rainfall intensity. From this modelling exercise, it is apparent that the dominant variable affecting the final results is the rainfall component. Hence, good quality rainfall data is vital in order to obtain reliable and accurate runoff predictions. It is also important to note the validity of the assumption that the recorded rainfall at the gauge is representative of the rainfall that occurred over the catchment. Considering the relatively small size of the catchments and the location of the pluviometer outside of the catchment, it might be necessary to incorporate spatial variability into the hydrological model. Another aspect that is of concern is the resolution in which the rainfall was recorded. Even though rainfall data for certain storm events were recorded to half a minute, the rest are only accurate to the minute. Yet, the catchment response times for both study catchments were determined to be just fraction of a minute, using the following equations:

$$u = \alpha y^{\beta - 1} \tag{14}$$

$$c = \beta u \tag{15}$$

where c is the wave speed and u is the flow velocity on the surface. In other words, the lag between the rainfall occurrence and its influence upon runoff is small. Adopting a larger temporal resolution for the rainfall records will lead to errors. This is also discussed in Ball and Alexander (2006).

6. CONCLUSIONS

An approach for simulating runoff quantity from impervious urban surfaces is presented in this paper. The model is based on the widely used kinematic wave theory and tested with historical data from two monitored catchments in Sydney, which are Qantas Dr, Mascot and Princes Highway, Gymea. It is found that a reasonable fit can be achieved between the simulated hydrographs and the recorded hydrographs for majority of the storm events. The simplified diagonal approach produced better predictions than the more realistic plane and gutter approach, probably due to the comparatively small size of these catchments and corresponding quick response catchment time. There is also a need to adopt a finer resolution for the rainfall records as a loss of variability in the simulated hydrographs is noticeable.

This modelling exercise will be extended to simulate runoff from roof surfaces with additional field data to be collected during the remainder of the study period to supplement the existing data. Also, the runoff quantity model will be enhanced further to simulate runoff quality, thus serving as a useful tool for urban catchment management and to facilitate the implementation of WSUD applications.

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