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Evaluation of catchment connectivity and storm runoff in flat terrain subject to urbanisation

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Abstract

Contributing Catchment Area Analysis (CCAA) is a spatial analysis technique that allows estimation of the hydrological connectivity of relatively flat catchments and the effect of relief depressions on the catchment rainfall-runoff relationship for individual rainfall events. CCAA of the Southern River catchment, Western Australia, showed that catchment contributing area varied from less than 20% to more than 60% of total catchment area for various rainfall events. Such variability was attributed to a compensating effect of relief depressions. CCAA was further applied to analyse the impact of urbanisation on the catchment rainfall-runoff relationship. It was demonstrated that the change in land use resulted in much greater catchment volumetric runoff than expected simply as a result of the increase in proportion of impervious urban surfaces. As urbanisation leads to an increase in catchment hydrological connectivity, the catchment contributing area to the river flow also becomes greater. This effect was more evident for the most frequent rainfall events, when an increase in contributing area was responsible for a 30–100% increase in total volumetric runoff. The impact of urbanisation was greatest in sandy catchments, which were largely disconnected in the pre-development conditions.

1 Introduction

Evaluation of the rainfall-runoff relationship within a catchment presents a challenge, particularly when there is an additional need to predict the effect of changing land use on this relationship.

Urbanisation has a profound effect on a catchment water balance and hydrological regime. Increasing impervious surfaces alters the pathway by which rainwater is transferred to surface water networks and groundwater systems. It is broadly accepted that due to the impact of impervious surfaces, urbanisation leads to an increase in runoff from individual storm events and annual runoff (Grove et al., 2001; Jennings and Jar-

HESSD

6, 6721–6758, 2009

nagian 2002). It has also been reported that urbanisation increases the magnitude of peak runoff and the rate of hydrograph rise and recession, but reduces the lag time between rainfall and runoff response, as well as the mean residence time of stream flow (Burns et al., 2005; Rose and Peters, 2001).

The magnitude of this impact is dependent on the proportion of urban development to the total catchment area and the intensity of rainfall events. The greatest effect on stormwater yields was found in medium and low intensity rainfall events rather than in extreme rainfall conditions (Niehoff et al., 2002; Camorani et al., 2005).

The effects of urbanisation on catchment runoff are particularly significant in areas affected by inundation, which may occur in flat terrain and may be associated with a shallow groundwater table. In such cases, large volumes of water, previously stored in the landscape or lost to evaporation, are required to be drained. Under such conditions, variations in rainfall-runoff relationship are not only affected by impervious surfaces and alteration of the rain water pathways, but also by an increase in catchment area, contributing to the river flow. In other words, urbanisation may alter and increase hydrological connectivity within the catchment.

The study presented here is part of a larger project which aims to develop a decision support tool to facilitate catchment urbanisation within water sensitive environments. The overall focus of the project is to quantify the impacts associated with urban development on surface water, groundwater and wetlands water balance. This paper examines the effect of catchment connectivity on catchment volumetric runoff associated with a single rainfall event. Peak flow, flooding and other details of discharge hydrographs fall outside the scope of the reported analysis.

The following sections provide a description of the studied catchment; details of the methodology developed for the catchment connectivity analysis; and the model outcomes for a number of scenarios, including catchment urbanisation.

HESSD
6, 6721–6758, 2009

2 Case-study

Perth, the capital city of Western Australia, is experiencing fast growth, with urbanisation of greenfield sites leading to substantial environmental challenges. The Southern River catchment is one of the fastest developing regions where urban expansion is challenged by shallow groundwater tables, high nutrient concentrations in surface and groundwater, seasonal inundation, presence of conservation wetlands, and proximity to a groundwater supply area and to the Swan-Canning Estuary. Such complex environmental settings necessitate great care when altering catchment land and water management.

The Southern River catchment (155 km^2) is located near the eastern edge of the Perth basin adjacent to the Darling Scarp in the east as shown in Fig. 1. The elevated upland area in the south-east (approximately 41 km^2) includes the upper reaches of the Neerigen Brook and Wungong Creek below the Wungong Water Supply Dam. The rest of the Southern River catchment is mainly a flat low-lying area underlined by Quaternary fluvial and aeolian deposits 20–60 m in thickness. The Quaternary deposit consists of aeolian Bassendean Sand, occurring in the west, and the Guildford Formation, predominantly clays of alluvial origin, outcropping within the eastern part of the catchment adjacent to the Darling Scarp. Low surface gradient and limited drainage capacity cause inundation and the establishment of wetlands.

There are two major land uses in the low-lying part of the catchment: urban and semi-rural. The currently urbanised areas include suburban housing and infrastructure on the northern and eastern boundaries of the catchment, covering less than 30 km^2. The remaining rural part of the Southern River catchment includes the state forest area in the hills, remnant vegetation and cleared land used for hobby horticultural and livestock farming as illustrated in Fig. 2.

Typically for a Mediterranean-style climate, more than 80% annual rain falls during the winter months, while the summer months are usually dry and warm. While the average annual rainfall (1889–2006) is 891 mm, there exists an overall long-term reduction

HESSD
6, 6721–6758, 2009

in annual rainfall (Fig. 3).

The average annual discharge of the Southern River at the outflow from the catchment is approximately 13 GL/year. A monthly water balance was estimated to evaluate changes in river flow in response to rainfall, and some observations can be summarised as follows:

- Autumn and early winter rainfalls do not result in a significant increase in the river flow when monthly volumetric runoff coefficient is less than 2%. It is believed that during this period the substantial storage capacity of the deep sandy soils and wetlands allows the accumulation of rain water with little stormwater yields. In the analysis presented in the following section, this period will be referred to as the "storage recovery stage".

- The Southern River flow increases significantly during late winter and early spring when monthly volumetric runoff coefficient is greater than 25%. The analysis of the river discharge data for 1997–2006 shows that the increase in the flow rate occurs when the cumulative rainfall during the year reaches 360–400 mm. At this stage the catchment storage is largely filled and the stormwater yield increases. This period will be referred to as the "storage deficiency stage". During summer, when evaporative losses exceed rainfall, the "storage depletion stage" occurs.

We suggest that some of the variation in catchment volumetric runoff coefficients during dry and wet periods may be attributed to greater hydraulic connectivity of the catchment during the storage deficiency stage and therefore a greater area contributing to the river flow during this stage.

The effect of the catchment connectivity on catchment volumetric runoff before and after urbanisation was investigated using a model named Catchment Contributing Area Analysis (CCAA).

HESSD
6, 6721–6758, 2009

3 Methodology

CCAA is a GIS-based spatial analysis technique, which produces two major outcomes:

- the sub-catchment area contributing to river flow in response to an individual rainfall event, and
- the total volumetric runoff generated during a single rainfall event.

Analysis of distributed runoff was based on USDA runoff curves numbers (USDA, 1986), which utilised the spatial information on land cover and soil types. The Arc Hydro toolset (Maidment, 2002) was applied for a Digital Elevation Model (DEM) interpretation to define the hydrological network and sub-catchment connectivity. Spatial analysis technique was implemented using ArcGIS9.2 (ESRI, 2009) and the Python scripting language (Python Software Foundation, 2009).

CCAA includes a number of steps, as Fig. 4 illustrates.

3.1 Definition of hydrological response units

The spatial information utilised for analysis included: two broad soil classes (clay and sand), a DEM and six land cover classes ("cleared land", "grass", "road", "rooftop", "trees" and "water").

The land cover classes were defined using both raster and vector spatial data set reflecting information for 2004. Maximum likelihood classification of the digital aerial photography clearly discerned three broad classes: "grass", "trees or water" and "rooftops or roads or cleared". Additional spatial data were used to further separate these classes:

- A map of existing water bodies was used to separate "trees" and "water" classes.
- A road centreline vector data set enabled the assignment of "road" to cells within 4 m of a road centreline.

– Cadastral data were employed to delineate the “rooftops” class in urban areas.

– The cells which were initially classified as “rooftops” or “roads” or “cleared” but fell outside the 4 m distance from a road centreline and the urban areas, were re-classified as “cleared land”.

The two soil classes, sand and clay, were delineated based on an environmental geology map (Western Australian Department of Industry and Resources), making the maximum twelve number of hydrological response units (six land use classes and two soil classes).

3.2 Estimation of daily volumetric runoff

The USDA Curve Number (CN) method was employed to estimate runoff from individual storm events for the twelve delineated hydrological response units. Daily rainfall was assumed to be an individual storm event. The Curve Numbers were selected according to soil type and land cover. As a result, CN varies from 30, representing highly permeable soils with natural woody vegetation cover, to 98, for roads and rooftops.

Under current conditions soil type, vegetation cover, impervious surfaces and superficial storages are constants. However the CN was varied to account for different soil conditions in summer, with possible infiltration (storage recovery stage), and winter, when groundwater levels rise and infiltration capacity is limited (storage deficiency stage). For simulations of summer conditions, CN estimation accounts for only the soil infiltration rate based on soil type – sandy soils infiltrated freely and did not produce much runoff. For winter conditions the CN was increased to simulate a limit to infiltration due to reduction in available storage. To ensure the consistency of these seasonal variations across the model domain, each CN was increased to an average between its original value and the maximum CN of 98. An example of CN spatial distribution within the catchment during storage recovery stage is illustrated on Fig. 5a.

The developed model of runoff was not fitted by estimating and varying CN spatially on an event basis to closely match with river records. Instead, the values of CN are

all determined a priori and the model as a whole is validated for current conditions by comparing CCAA estimates of total runoff estimated from river hydrograph records.

Simulation of new urban development included the addition of impervious area within the proposed development area and elimination of the predevelopment surface depressions. CN values were selected in accordance with the USDA procedure resulting in an average estimate for each soil type and potential housing density. In order to reflect the commonly adopted practice in the region, roof runoff in areas proposed for development was expected to be conveyed to urban waterways in subsurface drains and further to the river. As a result, CN value was higher in comparison with existing urban areas, indicated in Figs. 2 and 5a. In this paper, only the case related to medium density development is discussed (Fig. 5b).

3.3 Estimation of catchment retention capacity and connectivity

A raster DEM was used to delineate sub-catchments, individual relief depressions and depressions storage capacity (V_i). The raster DEM was built from 1 m contour data and spot heights of ground surface (1:2000 Digital Topographic data from Western Australia Department of Land Information). A hydrology data set, containing known drains and rivers, was used to enforce drainage in the DEM using the Arc Hydro toolset (Maidment, 2002). The DEM was then "filled", allowing catchments and their connectivity to be derived, as shown in Fig. 6.

Derived relief depressions which have potential to store water were attributed with a total storage capacity (V_i), defined as the volume of a depression limited by a minimum surface height which indicates the level of the water outflow from the depression. An additional attribute defined the presence or absence of a surface water channel.

Within the adopted methodology, the runoff (q_i) generated in an individual relief depression (i) and estimated using CN values was compared to the depression storage capacity (V_i). When q_i exceeds V_i the surplus ($\Delta_i = q_i - V_i$) was added to channel flow and then to the neighbouring relief depression in accordance with the defined hydrological connectivity between those depressions.

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Sequentially the storage capacity (V_{i+1}) in the receiving depression ($i+1$) was compared with the sum of two characteristics: the runoff generated within this depression (q_{i+1}) and the runoff surplus generated in the depression (i) positioned upgradient, Δ_i. If $(q_{i+1}+\Delta_i)>V_{i+1}$, the surplus ($\Delta_{i+1}$) was further directed to the next hydrologically connected depression.

Only relief depressions which cumulatively contribute to the stream network were identified as the catchment contributing area (A_{cc}). This approach allowed estimation of the cumulative volumetric runoff from the sub-catchments and at the outflow from the entire catchment.

The analysis was undertaken for two antecedent conditions: (a) the case when stormwater infiltration to groundwater storage is possible, simulating catchment response for "storage recovery stage", and (b) the case when stormwater infiltration to groundwater storage is limited, which simulates the catchment response for "storage deficiency stage". This condition of available storage is implicit in selecting CN.

A range of rainfall events was selected for analysis, reflecting a typical 24 h duration of rainfall for specified periods of recurrence typical for the Perth region: 48 mm (1 year), 62 mm (2 years), 76 mm (5 years), 85 mm (10 years), 99 mm (20 years), 118 mm (50 years) and 134 mm (100 years). More common rainfall events (<48 mm) and other randomly selected events were included to show a representative range of daily rainfall for model simulation. The range also included the highest daily rainfall event recorded in the area since 1889 of 147 mm.

The model validation was based on comparison, for a number of individual daily rainfall events, of the simulated volumetric runoff to the measured total river discharge at the outflow from the catchment, generated by a single rainfall event.

HESSD
6, 6721–6758, 2009

4 Historical data review

4.1 Rainfall data

Given the approach addressed single rainfall events, further analyses were undertaken to establish if this approach is suitable for local historical rainfall patterns. Rainfall data for the period between 1889 to 2006 were available at two meteorological stations shown in Fig. 2.

The record of the river discharge indicates that rainfall events less than 5 mm produce low runoff. Rainfall historical data review (Table 1) shows that on average there are 52 rainfall events greater than or equal to 5 mm during each year. These data suggest that over the winter period between May and September statistically up to 10 daily rainfall events greater than 5 mm may occur during each month. Figure 7 shows the historical trend in decline of the number of rainfall events, and for all those greater than 5 mm.

The variation in the daily rainfall data collected at two locations within the catchment is noticeable. The standard deviation between the long-term daily rainfall records at the two local weather stations is consistent and equal to 5 mm for the entire data set, irrespective of the rainfall range. As a result, a standard deviation of 5 mm was used in further analysis for all rainfall events in order to reflect the high spatial variation in rainfall.

4.2 Catchment volumetric runoff

Historical flow rate data analysed in this study were acquired on an hourly basis over the period 1997–2006. The hydrograph analysis indicated that the duration of a flow event in response to an individual daily rainfall event varied between 24 h in the summer and about 7 days in the late winter. A total of 51 rainfall events between 1997 and 2004 which met the condition that there were no rain events within the seven following days were selected for further analysis. This allows assumption that the river discharge measured at the gauging station is generated by the identified rainfall event. Using

HESSD
6, 6721–6758, 2009

hydrograph data, the volume of the river discharge was estimated for each of these events. The events were further separated into two groups based on the time of the event and the cumulative rainfall up to the date of the event to identify the storage recovery and storage deficiency conditions. As stated earlier, the cumulative rainfall threshold was 400 mm.

The gauging station used in this study is located within the urban area and the initial stage of each hydro-event reflects the quick discharge from 6.6 km^2 of the local urban area. The concentration time for urban discharge was found to be 2–3 h, and a well-defined flow peak was recorded at this time for all available hydrographs. Such circumstances allow approximate estimation of volumetric runoff generated within the urban area, based on hydrograph separation. The cumulative volume associated with urban stormwater discharge was then compared with the hourly rainfall data recorded at the nearest meteorological station.

The calculation for volumetric runoff contains errors related to the measurement of the river stage height which is further translated into river discharge, and uncertainty associated with rainfall distribution within the catchment.

The errors estimated for the instantaneous flow measurement at the gauging station are ±25% for flow rates greater than 500 L/s, ±10% for the flow range 50–500 L/s and up to ±500% for low flows <50L/s, due to siltation and plant growth. The latter corresponds to summer baseflow. For all considered events the flow was above 50 L/s, while the high flow rates (Q>500L/s) were recorded during some events in the late winter during the storage deficiency stage. Based on these considerations, an overall error related to the flow measurements was estimated to be ±20%.

5 Modelling results

Figures 8 and 11 show the relationship between the individual daily rainfalls and associated volumetric runoff for both field data and model simulation outcomes. The results of the CCAA model show a good correlation with the observed data, both for

the catchment and urban volumetric runoff (Table 2).

Both the observed data and the modelled results demonstrate that the catchment runoff differs for events occurring during the storage recovery stage and the storage deficiency stage. The catchment runoff generated by a similar rainfall event varies by more than a factor of two for the two hydrological conditions. Figure 9 indicates that such variations are related to a combination of two factors: (a) increase in the runoff coefficient (1.5–4.4 times) and (b) increase in the catchment area contributing to the river flow (up to 2.2 times).

The catchment contributing area (A_{cc}) for selected rainfall events during the storage recovery stage and storage deficiency stage are shown in Fig. 10. A_{cc} is as low as 13% of the total catchment area for low rainfall events (5 mm) but not more than 75% of the total area even under extreme rainfall events. This is partly due to a compensation effect of the large wetland in the west of the catchment which provides an internal drainage zone for the sub-catchment under all range of the considered daily rainfall intensity.

The observed volumetric runoff from the urban area shows a more scattered distribution as illustrated by Fig. 11. The CCAA results generally reproduced the lowest range of the observed volumetric runoff. This suggests that the modelling approach adopted to simulate urban runoff is sufficient to reproduce the lower range of urban volumetric runoff, and as such, does not overestimate the real fluxes which occur in urbanised areas.

6 Effect of variation in catchment contributing area on volumetric runoff

The volumetric runoff is commonly defined as a product of catchment area (A) and runoff coefficient (RO). The runoff coefficient in turn is a measure of a catchment response to a given rainfall intensity and is dependent on the catchment land cover, land use, soil moisture and topography. Both runoff coefficient and total volumetric runoff for a given catchment are generally greater for higher rainfall intensity.

The analysis undertaken for the Southern River catchment indicates that an increase in rainfall intensity results in greater catchment connectivity and therefore an increase in the catchment contributing area. Thus, in this case, both factors (A and RO) are contributing to the increase in total volumetric runoff. Since the paper investigates the former (A_{cc}), the effect of variation in a catchment contributing area on total volumetric runoff was estimated for a number of cases. These included variation in rainfall intensity, availability of catchment storage (storage recovery and storage depletion stages) and soil types. The pre-urbanisation and post-urbanisation conditions were also considered.

The variation in total volumetric runoff ΔQ_{a_b} between two scenarios a and b can be expressed as follows (see Fig. 12):

$$\Delta Q_{a_b} = Q_b - Q_a = \left(A_a RO_b + \Delta A_{a_b} RO_{\Delta A}\right) - A_a RO_a = A_a(RO_b - RO_a) + \Delta A_{a_b} RO_{\Delta A}, \quad (1)$$

where Q_a and Q_b are total volumetric runoff for scenarios a and b, $\Delta A_{a_b}=A_a-A_b$ is a change in the contributing area between scenarios a and b, and RO_a and RO_b are average volumetric runoff coefficients in areas A_a and A_b during scenarios a and b, and $RO_{\Delta A}$ is the volumetric runoff coefficient in the area ΔA_{a_b} during scenario b. Two resulting members of Eq. (1) describe the variation in runoff from area A_a as $A_a(RO_b-RO_a)$ and volumetric runoff generated within an additional area ΔA_{a_b}, as $\Delta A_{a_b} RO_{\Delta A}$.

The effect of variation in the catchment contributing area (δ_{a_b}) between two scenarios a and b on the variation in the total volumetric runoff can then be estimated as:

$$\delta_{a_b} = \frac{\Delta A_{a_b} \times RO_{\Delta A}}{\Delta Q_{a_b}} = \frac{Q_{\Delta A}}{\Delta Q_{a_b}} (\%), \quad (2)$$

where $Q_{\Delta A}$ is the volumetric runoff generated within the area ΔA_{a_b}.

The method described in Sect. 4 allows estimation of both Q and A for any given sub-catchment, rainfall intensity and for a number of scenarios. Accordingly, $Q_{\Delta A}$ and ΔQ_{a_b} were estimated for a number of cases.

HESSD
6, 6721–6758, 2009

6.1 Effect of catchment contribution area on the volumetric runoff for various rainfall intensities

As shown in Fig. 9 the area of the catchment (A) contributing to the total volumetric runoff (Q) in the Southern River catchment increases for higher intensity rainfall events. In order to estimate the effect of increasing contributing catchment area ΔA on volumetric runoff, δ_{RF}, A and Q for various rainfall intensities were compared with A_{5mm} and Q_{5mm}, which relates to the catchment response of the 5 mm rainfall event as a minimum considered in CCAA. For this case, Eq. (2) was adopted as follows:

$$\delta_{RF} = \frac{Q_{\Delta Ai_5mm}}{\Delta Q_{i_5mm}}(\%) . \quad (3)$$

The estimation was undertaken for the entire catchment and also for two sub-catchments. These sub-catchments in pre-development conditions are characterised by semi-rural land-use, flat topography, but different soil types; one occurs in the area of clay rich soil (15 km^2) and the other in the area of sandy soil (49 km^2) (Fig. 1).

The results are demonstrated in Fig. 13 where the runoff volume (Fig. 13a and b) and relative contribution of A_{cc} (Fig. 13c and d) are shown for varying rainfalls. They suggest that the effect of the changing in a catchment contributing area is most significant for more frequent rainfall events <14 mm, which comprise 82% of annual daily rainfall. For these events, up to a 60% increase in the catchment volumetric runoff is due to increase in A_{cc} alone (Fig. 13d1). The A_{cc} effect is noticeably greater during the storage recovery stage (Fig. 13c1) relative to its effect during storage deficiency stage (Fig. 13d1).

In the sub-catchment with clay soil (Guilford Formation) the effect of increasing catchment contributing area dominates for rainfall events <60 mm during the storage recovery stage (Fig. 13c2). In this case, the increase in volumetric runoff is attributed to A_{cc} variation by more than 50% (and up to 100%). During the storage deficiency stage A_{cc} effect is limited to less then 20%, with a greater effect related to the less intensive rainfall events <14 mm (Fig. 13d2).

HESSD
6, 6721–6758, 2009

In the sub-catchment with sandy soil (Bassendean Sand), the impact of the catchment contributing area dominates the increase in total volumetric runoff during storage recovery stage for rainfall greater than 20 mm (Fig. 13c3). For these cases, the increase in the total volumetric runoff is more than 50% attributed to A_{cc} increase. However it appears that the A_{cc} effect has no impact on the total volumetric runoff for lower rainfall intensities. During the storage deficiency stage A_{cc} contribution within sandy sub-catchments is also significant and is greater than 40% for most rainfall events (Fig. 13d3).

Therefore catchment contributing area effect on total volumetric runoff appears to be greater for the most frequent rainfall events and during early winter (storage recovery stage) and in the catchments with sandy soils.

6.2 Effect of catchment contribution area on the volumetric runoff as result of catchment storage availability

The results indicated that the area of catchment contributing to the total volumetric runoff for equal rainfall events is greater during the storage deficiency stage (Fig. 9). The effect of the increasing catchment contributing area (δ_{St}) between the two hydrological stages can be estimated as:

$$\delta_{St} = \frac{Q_{\Delta A}}{\Delta Q_{D_R}}(\%), \quad (4)$$

where $Q_{\Delta A}$ is the volumetric runoff generated at the storage deficiency stage within the area $\Delta A = A_D - A_R$ for a given rainfall event; and $\Delta Q_{D_R} = Q_D - Q_R$ is the variation in the total volumetric runoff between storage deficiency (D) and storage recovery (R) stages for the same intensity rainfall event.

The outcomes are illustrated by Fig. 14. At the catchment scale the effect of increasing A_{cc} is greatest during the most frequent rainfall events (5 and 7 mm) (Fig. 14b) when the total flow response to increasing rainfall is changing most rapidly (Fig. 14a), but overall it is approximately 20%.

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The effect of the storage availability on volumetric runoff generation in sub-catchments is particularly profound where the sandy soil occurs. An increase of up to 92% is observed for volumetric runoff due to catchment contributing area variation for the most frequent rainfall events (<25mm covering 93% of all daily rainfall events). In the sub-catchment with clay soils the A_{cc} effect is also greater for more frequent events, but is generally lower than in the other considered cases for rainfall greater than 30 mm.

7 Effect of effect of catchment urbanisation on the volumetric runoff

The CCAA methodology was applied for estimation of the impact of urban development on river volumetric runoff. The area designated for urbanisation in the Southern River catchment is 64 km^2 (Figs. 1 and 5). The new development will include residential areas of various densities and some light industrial and commercial establishments.

As stated previously CCAA results generally reproduced the lowest range of the observed volumetric runoff and therefore the results are likely to be conservative with respect to potential changes in the volumetric runoff resulting from catchment urbanisation. The analysis was undertaken under the assumption that the development is fully completed.

The analysis determined that urbanisation increases the total volumetric runoff in the entire catchment and in the individual sub-catchments (Fig. 15a and b). The cumulative impact of urbanisation on the catchment volumetric runoff under individual rainfall events was estimated to be up to 25%. The variations were greater for the storage recovery stage and particularly evident in the sandy sub-catchments, where the volumetric runoff was estimated to be up to 3.5-fold greater in comparison with pre-development conditions (Fig. 15a). However the impact of urbanisation here was only evident for the rainfall events greater than 10 mm.

Similarly to the previous analysis, the effect of the increasing catchment contributing area (δ_U) on the increase in total volumetric runoff between predevelopment (nU) and

HESSD
6, 6721–6758, 2009

post-development (U) conditions was estimated as:

$$\delta_U = \frac{Q_{\Delta A}}{\Delta Q_{U_nU}}(\%), \quad (5)$$

where $Q_{\Delta A}$ is the volumetric runoff which is likely to be generated after urbanisation within the area $\Delta A = A_U - A_{nU}$ for a given rainfall event; and $\Delta Q_{U_nU} = Q_U - Q_{nU}$ is the variation in the total volumetric runoff between predevelopment conditions and post-development conditions for the same intensity rainfall event.

Figure 15 shows that the contributing area increased not only for the most frequent rainfall events in the entire catchment, but also in the individual sub-catchments. Once again the catchment contributing area increase was particularly evident in sandy sub-catchment during the storage deficiency stage, where A_{cc} increased 4-fold compared with pre-development conditions (Fig. 15d).

The effect of the catchment contributing area was significant during both hydrological stages for the entire catchment and for the sub-catchments (Fig. 15e and f). The results of the analysis confirm the previously reported evidence that urbanisation may increase the total volumetric runoff for individual storm events. However in a flat sandy catchment the increase in total volumetric runoff as a result of urbanisation is also related to the increase in the catchment contributing area, which may cause up to 100% stormwater yield increase.

8 Conclusions

The developed method for CCAA provides an insightful, yet simple tool for the evaluation of event-based catchment response to individual rainfall events and the introduction of new urban development in water sensitive environments such as in the Southern River Catchment, Western Australia. The method was implemented as a GIS-based model which allowed simulating the hydrological connectivity of flat catchments and volumetric runoff related to individual rainfall events. Model outputs provide a good

HESSD
6, 6721–6758, 2009

correlation with the observed volumetric catchment runoff, and were applied to the rainfall-runoff characterisation of an individual sub-catchment with specific land use and land cover characteristics (e.g. urban, geology, during storage recovery or storage deficiency stages of the catchment hydrological cycle).

The analyses suggest that the effect of variation in catchment contributing area on volumetric runoff under individual rainfall events can be significant, particularly for the most frequent rainfall events (<40mm). For those events, up to 50% increase in the total volumetric runoff during higher intensity rainfall events can be associated with greater hydrological connectivity within the catchment. Similarly it was shown that A_{cc} for the same rainfall event is greater when rainfall infiltration is limited, e.g. during the storage deficiency stage of the annual hydrological cycle.

The urbanisation of the Southern River catchment is likely to cause an increase in runoff from the newly urbanised area, which is not only related to variation in rainfall/runoff response under new land cover conditions, but also to a higher degree of catchment hydrological connection resulting from the urban development. The effect of urbanisation on the catchment total volumetric runoff was estimated to be greater for the most frequent rainfall events and during autumn and early winter, the storage recovery stage of the annual hydrological cycle. The impact of urbanisation is particularly evident in sandy catchments, which are largely disconnected in pre-development conditions.

The analysis showed that catchment surface depressions are important relief elements which influence the catchment response to rainfall events and the rainfall-runoff relationship. The inclusion of these features in the hydrological analysis becomes particularly important when land use changes are considered. However, a hydrological models typically deploy larger computational cells, which in this case would miss some of the features found to be important for estimation of the rainfall-runoff dynamics of this catchment.

The limitation of the approach in its current form is that it does not allow for estimation of flow rates, including sub-daily peak flow. It is also not suitable for analysing

HESSD
6, 6721–6758, 2009

a sequence of storm events, which may have a similar effect to a large single event. To address this, the addition of channel flow routing to the method is required. Since the modelling is based on independent daily rainfall events, peak flow would be still outside of the scope of the expanded method.

Glossary

Catchment Contributing Area Analysis (CCAA)	The GIS-based methodology developed to define (a) catchment area contributing to river flow during an individual rainfall event and (b) total volumetric runoff generated during the event
Catchment Contributing Area (A_{cc})	Catchment area contributing to river flow during an individual rainfall event
Catchment Volumetric Runoff (Q)	Total storm yield generated in a catchment during an individual rainfall event
Daily Rainfall Event (RF)	Total daily rainfall
Effect of Catchment Contributing Area on variation in Catchment Volumetric Runoff (δ)	Proportion of a total volumetric runoff associated with variation in the Catchment Contributing Area and Catchment Volumetric Runoff
Number of rainfall events a year (NRF) *Runoff Coefficient (RO)*	Number of daily records per year A measure of catchment area response to a given rainfall intensity, dependant on the catchment land cover, land use, soil moisture and topography.
Storage deficiency stage	The period in the Southern River hydrological cycle when the storage in shallow groundwater and wetlands is filled to full capacity (normally occurs when the annual rainfall is greater than 400 mm)
Storage recovery stage	The period in the Southern River hydrological cycle when the storage in shallow groundwater and wetlands is recovering (normally occurs in the beginning of a wet season limited by the time when annual rainfall reaches 400 mm)
Total storage capacity of a relief depression (V_l)	Volume of an individual relief depression which is limited by the lowest elevation point that allows overflow to the surrounding surfaces

HESSD
6, 6721–6758, 2009

USDA Curve Number (CN)	A parameter that controls a non-linear equation to convert storm rainfall to storm runoff, based on soil type, plant cover, impervious surfaces and hydrologic condition
Variation in the Catchment Contributing Area between two scenarios (ΔA)	Increase in catchment area contributing to river flow between two scenarios
Variation in Volumetric Runoff between two scenarios (ΔQ)	Increase in volumetric runoff between two scenarios

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Table 1. Rainfall statistics for 1889–2006 in Southern River catchment showing number of rain days per year; annual average rainfall in the area is 891 mm, maximum and minimum recorded annual rainfall are 1371 mm and 499 mm, respectively.

Number of rain days		Rainfall Intensity (mm/day)				
		<5	5–10	10–20	20–40	>40
Annual average	106	54	21	19	10	2
Annual maximum	163	95	35	35	18	7
Annual minimum	69	27	9	8	3	0

Table 2. Statistics of modelled and observed volumetric runoff data.

Statistical measures	Storage recovery stage	Storage deficiency stage
Scaled mean sum of residuals	0.04	0.06
Scaled root mean fraction square	0.63	0.13
Scaled root mean square	0.05	0.08
Coefficient of determination	0.89	0.82
Correlation coefficient	0.98	0.96

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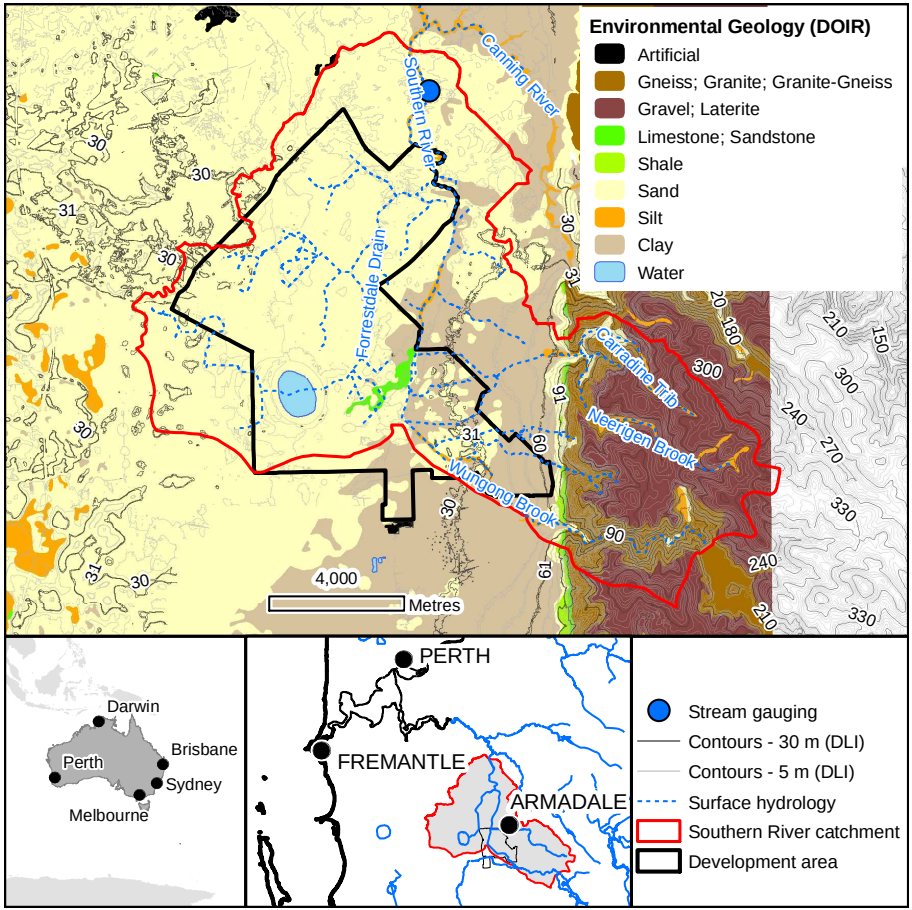

Fig. 1. Location, topography and geology map.

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Evaluation of catchment connectivity and storm runoff

O. V. Barron et al.

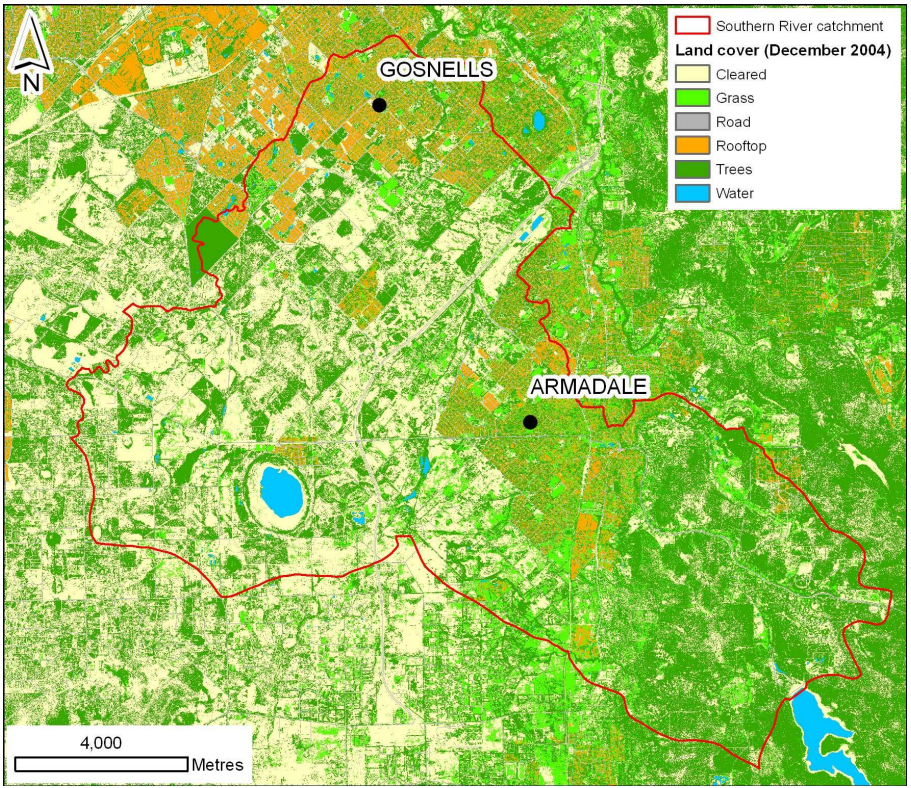

Fig. 2. Land cover map; meteorological stations at Gosnells and Armadale are marked.

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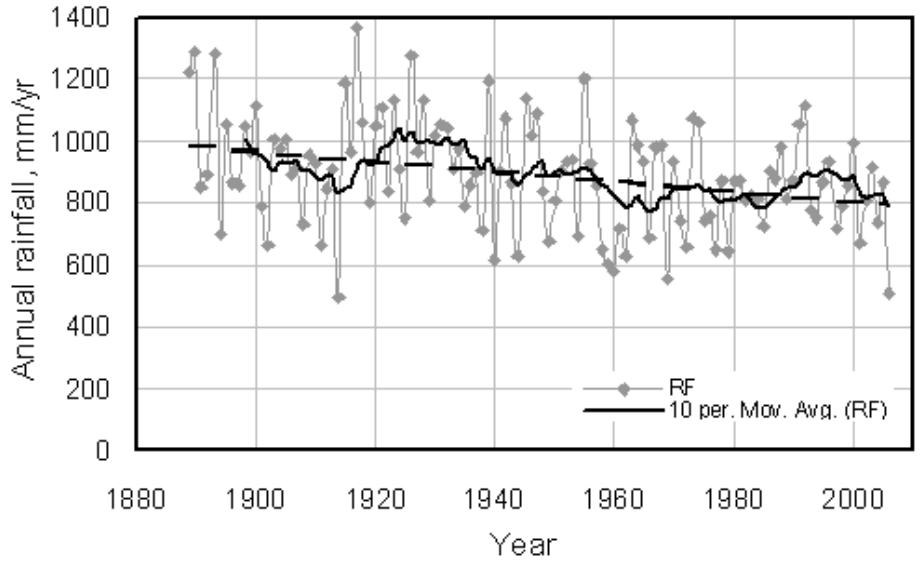

Fig. 3. Annual rainfall at Armadale meteorological station.

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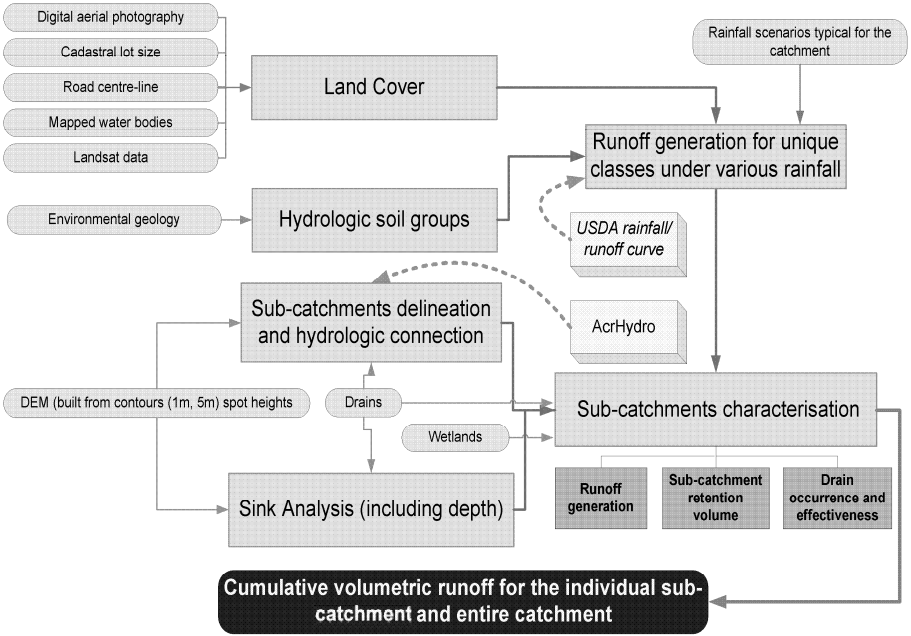

Fig. 4. Framework for Catchment Contributing Area Analysis.

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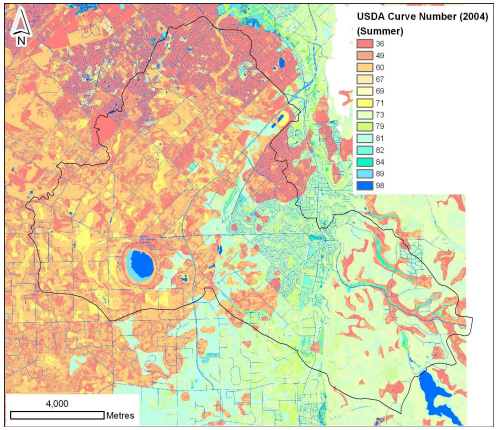
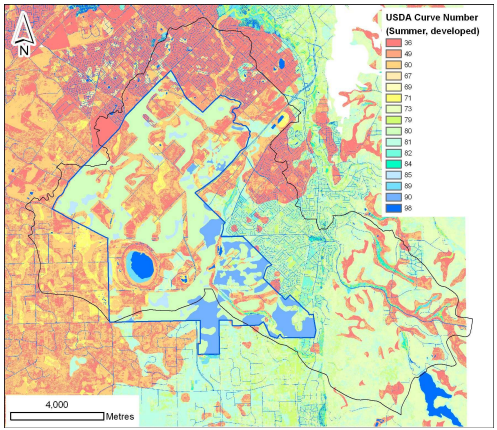


(a)



(b)

Fig. 5. USDA Curves applied to the volumetric runoff analysis for **(a)** predevelopment and **(b)** post-development conditions.

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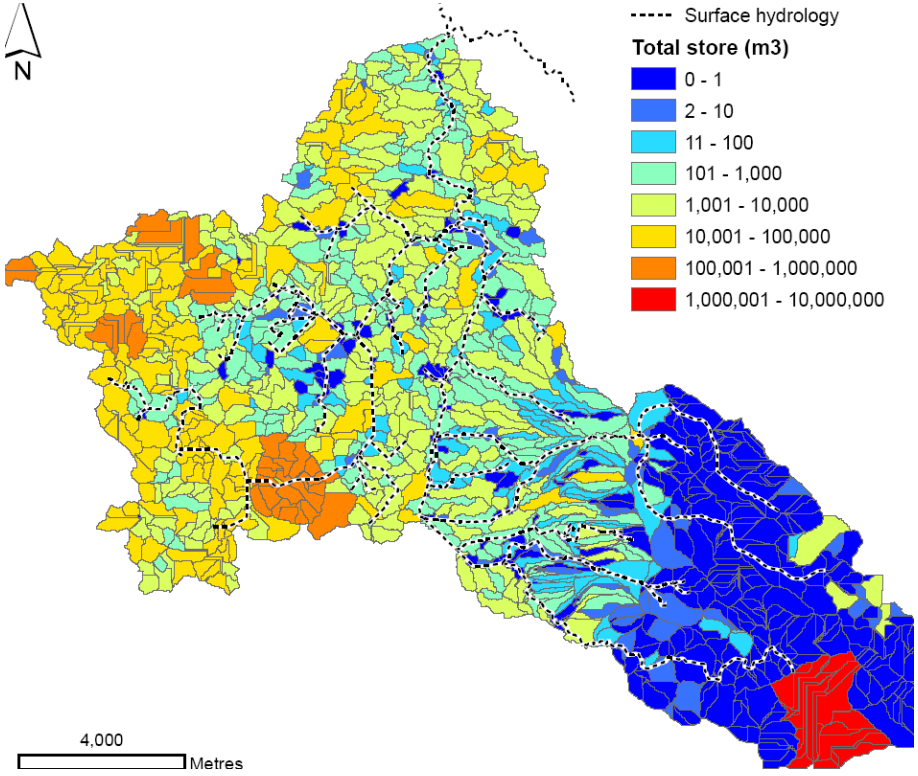

Fig. 6. Stream network and retention volumes in identified surface depressions.

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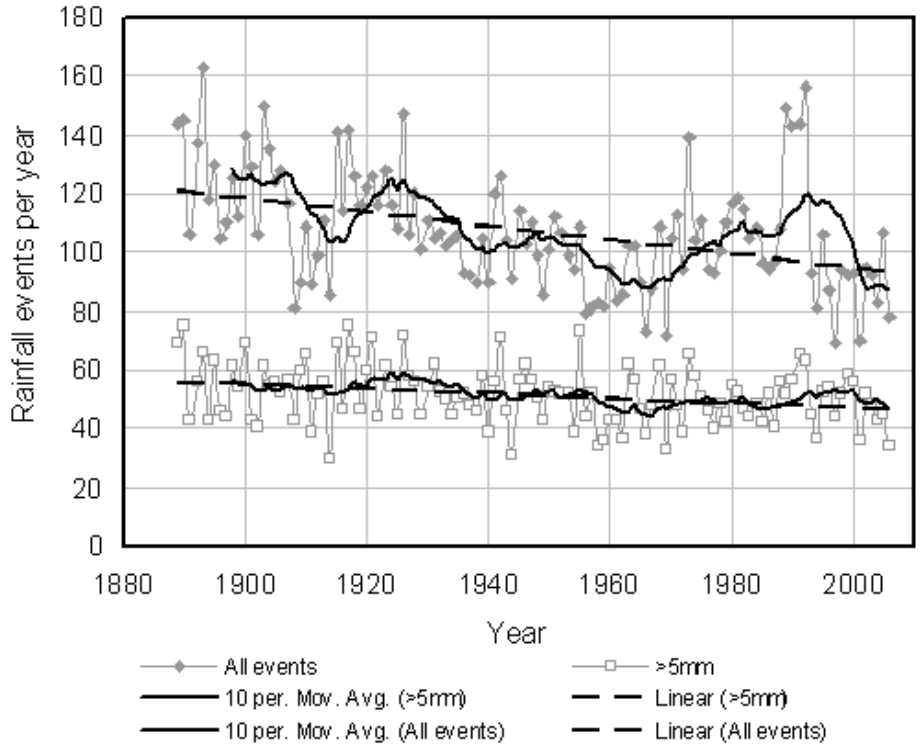

Fig. 7. Variation in frequency of rainfall events over 1889–2006: all rainfall events and the events greater than 5 mm.

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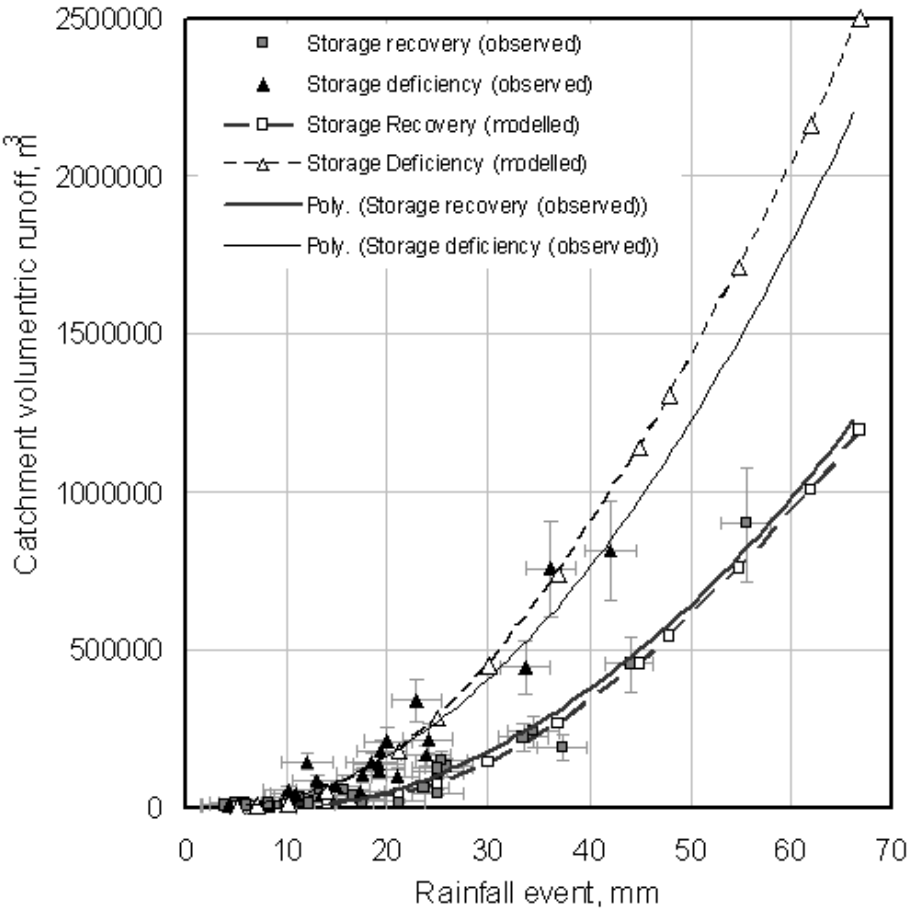

Fig. 8. Catchment volumetric runoff (modelled and observed) during storage recovery and storage deficiency stages.

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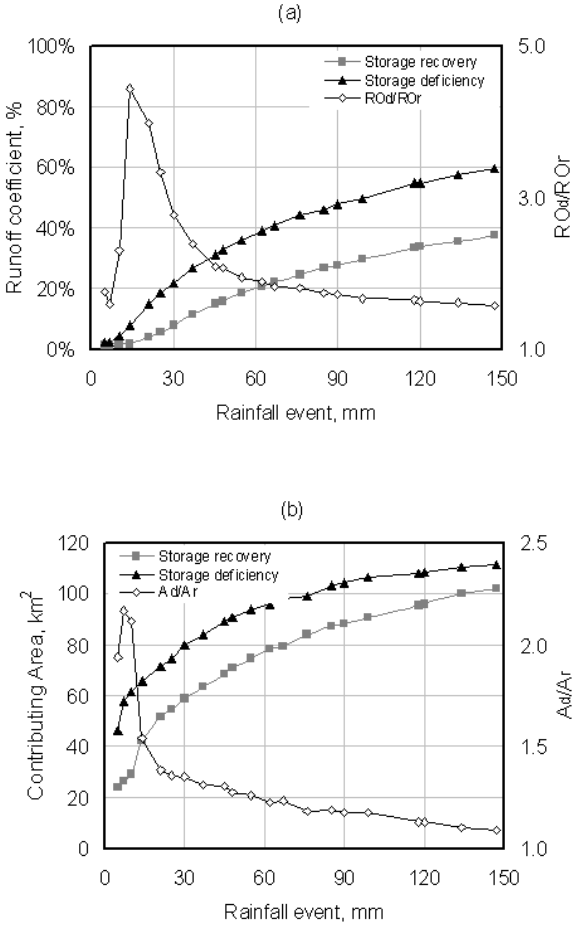

Fig. 9. Variation in **(a)** catchment runoff coefficient and **(b)** contributing areas (RO_d and RO_r are runoff coefficients under storage deficiency and storage recover stages, respectively, and Ad and Ar are contributing areas during those stages).

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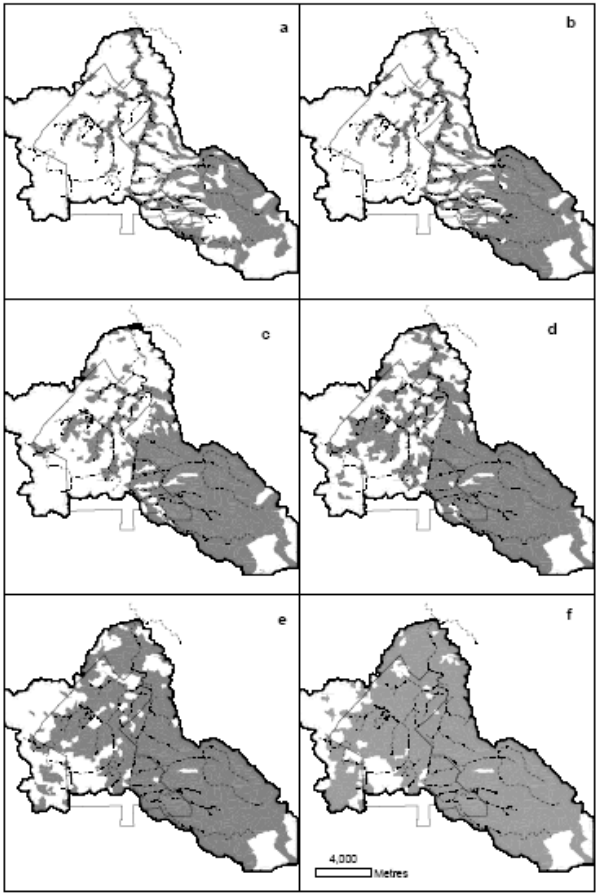

Fig. 10. Contributing catchments during the storage recovery stage under **(a)** 10 mm, **(b)** 48 mm, **(c)** 137 mm rainfall event; and during the storage deficiency stage under (a) 10 mm, (b) 48 mm, (c) 137 mm rainfall event.

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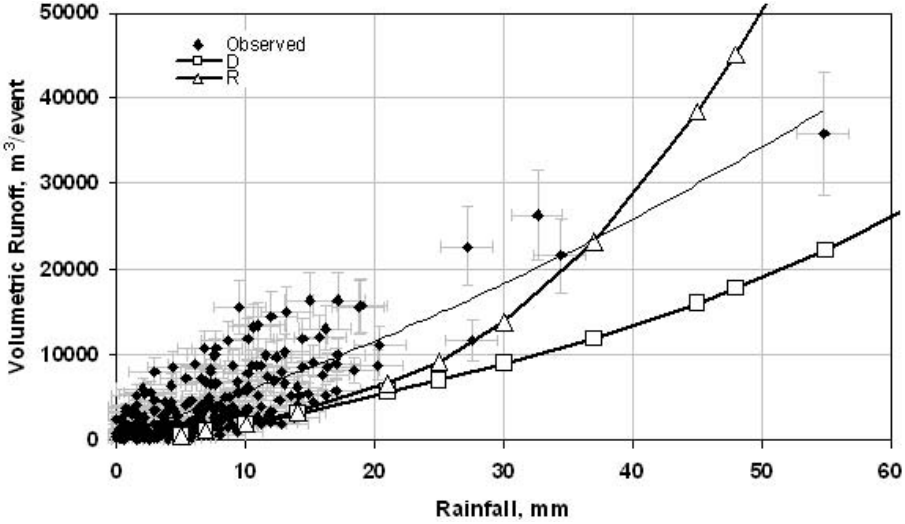

Fig. 11. Urban volumetric runoff (in legend: *D* – storage deficiency stage; *R* – storage recovery stage).

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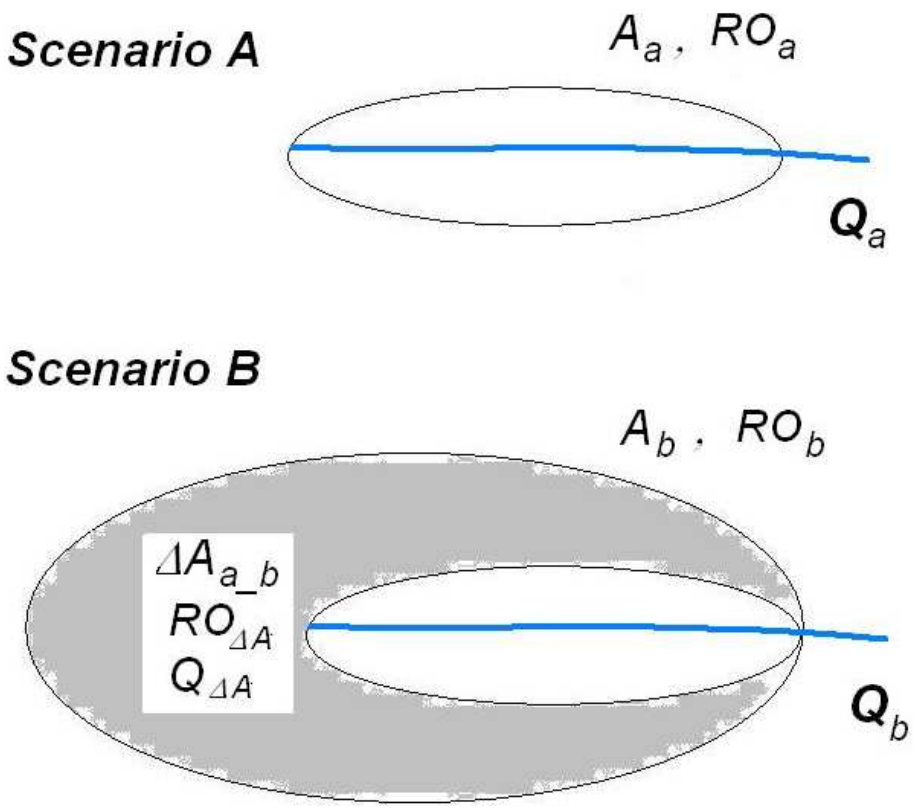

Fig. 12. Illustration for CA effect estimation with the references to Eqs. (1) and (2).

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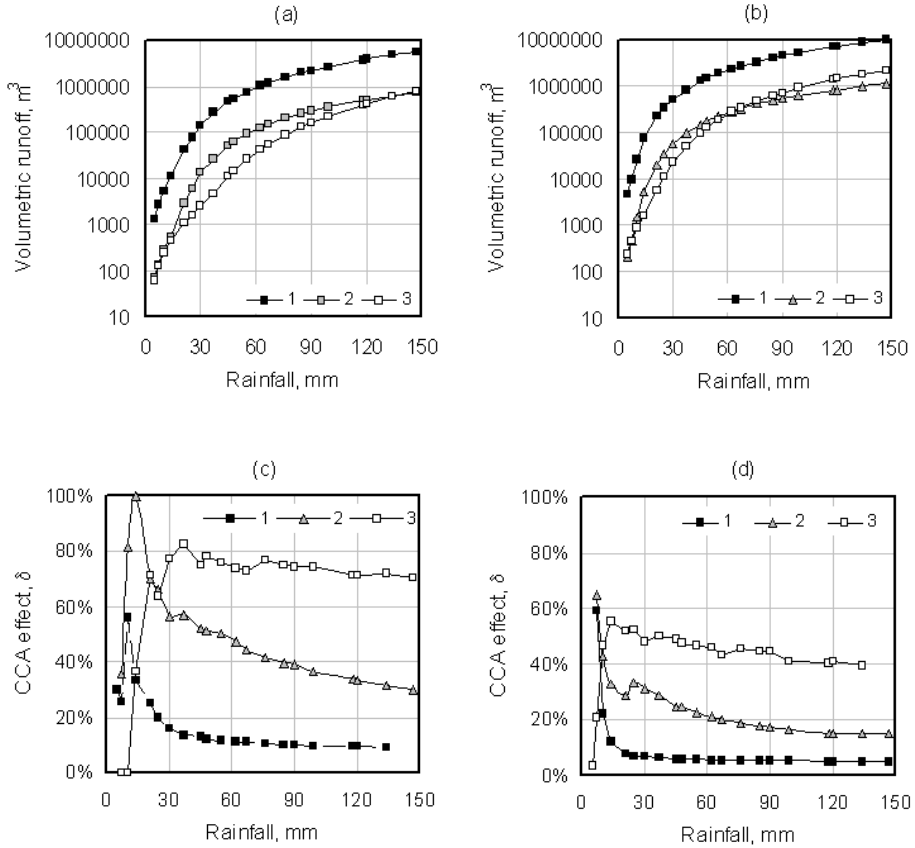

Fig. 13. Variation in **(a, b)** the volumetric runoff and **(c, d)** the effect of the catchment contributing area during the storage recovery stage (a, c) and storage deficiency stage (b, c) for the entire catchment (1), sub-catchment with clay soil (2) and sub-catchment with sandy soil (3).

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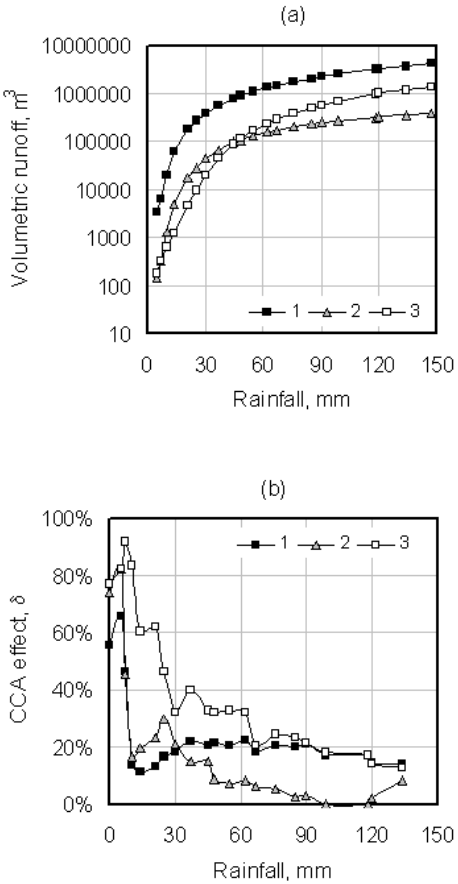

Fig. 14. Variation of the total volumetric runoff between two hydrological stages (storage recovery and storage deficiency) for the entire catchment (1), sub-catchment with clay soil (2) and sub-catchment with sandy soil (3).

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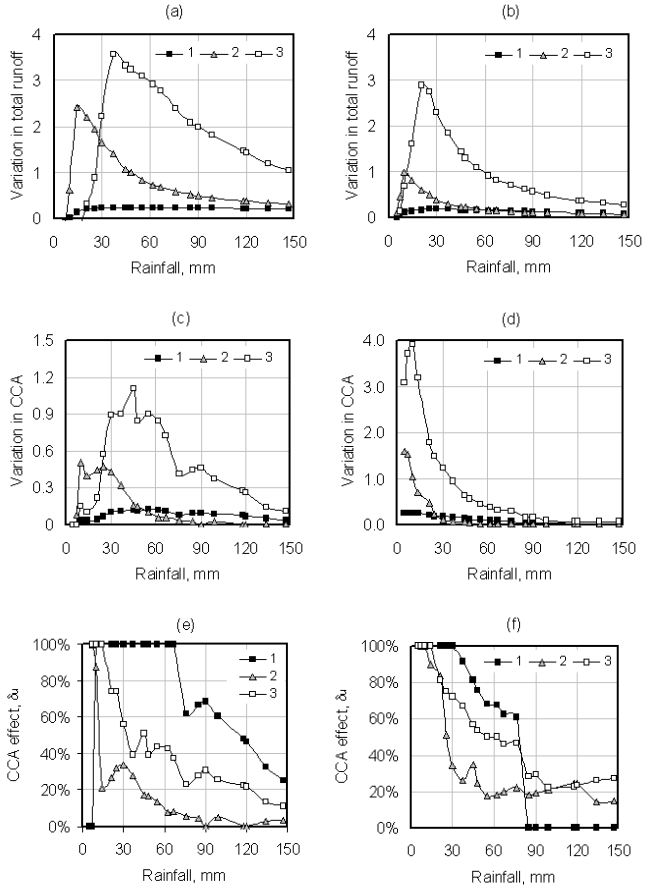

Fig. 15. Effect of urbanisation on **(a, b)** the total volumetric runoff, **(c, d)** the catchment contributing area and **(e, f)** the effect of the increase in catchment contributing area on volumetric runoff during the storage recovery stage (a, c, e) and storage deficiency stage (b, d, f) for the entire runoff (1), sub-catchment with clay soil (2) and sub-catchment with sandy soil (3).

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