

# South East Queensland Catchment Modelling for Stormwater Harvesting Research: Instrumentation and Hydrological Model Calibration and Validation

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The Urban Water Security Research Alliance (UWSRA) is a \$50 million partnership over five years between the Queensland Government, CSIRO's Water for a Healthy Country Flagship, Griffith University and The University of Queensland. The Alliance has been formed to address South-East Queensland's emerging urban water issues with a focus on water security and recycling. The program will bring new research capacity to South-East Queensland tailored to tackling existing and anticipated future issues to inform the implementation of the Water Strategy.

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## Cover Photograph:

Description: Gauged catchment  
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## FOREWORD

Water is fundamental to our quality of life, to economic growth and to the environment. With its booming economy and growing population, Australia's South East Queensland (SEQ) region faces increasing pressure on its water resources. These pressures are compounded by the impact of climate variability and accelerating climate change.

The Urban Water Security Research Alliance, through targeted, multidisciplinary research initiatives, has been formed to address the region's emerging urban water issues.

As the largest regionally focused urban water research program in Australia, the Alliance is focused on water security and recycling, but will align research where appropriate with other water research programs such as those of other SEQ water agencies, CSIRO's Water for a Healthy Country National Research Flagship, Water Quality Research Australia, eWater CRC and the Water Services Association of Australia (WSAA).

The Alliance is a partnership between the Queensland Government, CSIRO's Water for a Healthy Country National Research Flagship, The University of Queensland and Griffith University. It brings new research capacity to SEQ, tailored to tackling existing and anticipated future risks, assumptions and uncertainties facing water supply strategy. It is a \$50 million partnership over five years.

Alliance research is examining fundamental issues necessary to deliver the region's water needs, including:

- ensuring the reliability and safety of recycled water systems.
- advising on infrastructure and technology for the recycling of wastewater and stormwater.
- building scientific knowledge into the management of health and safety risks in the water supply system.
- increasing community confidence in the future of water supply.

This report is part of a series summarising the output from the Urban Water Security Research Alliance. All reports and additional information about the Alliance can be found at <http://www.urbanwateralliance.org.au/about.html>.



**Chris Davis**

Chair, Urban Water Security Research Alliance

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## EXECUTIVE SUMMARY

Stormwater is one of the last major untapped sources of water in the urban landscape. South East Queensland (SEQ) urban runoff varies between 240 and 750 GL/year, of which about half is required to maintain environmental flow requirements in the lower reaches of the SEQ river systems. The challenge for using stormwater includes its capture, storage, appropriate treatment, and supply to end users at cost effective prices. Major potential end uses include dual reticulation in greenfield urban developments (in lieu of rainwater tanks to achieve the mandated mains water saving of 70 kL/household/year) and irrigation of high value public open spaces such as playing fields.

There is a consensus view amongst freshwater ecologists that the increased frequency and peak discharge of runoff has seriously degraded the ecosystem health of urban creeks. Hence, stormwater harvesting is one method to reduce adverse ecosystem impacts and achieve the runoff objectives (contaminants, frequency, amount, peak discharge) defined in the SEQ Regional Plan (2009) Implementation Guideline #7. However, the science linking hydrological response to creek ecosystem response is poorly understood. Until it can be demonstrated that stormwater harvesting does not adversely affect environmental flows, state regulators are disinclined to promote (or even approve) the practice in the Resource Operating Plan/Resource Allocation Plan (ROP/RAP) environment of water regulation in SEQ.

An inevitable hydrological consequence of urbanisation is an increase in the fraction of impervious areas (roads, roofs, paving etc.) and consequent increases in runoff, frequency of runoff events, and peak discharges at various return intervals. The consequences of this changed hydrology are elevated concentrations of nutrients and contaminants, degraded channel morphology, reduced biota richness, and increased dominance of tolerant species (Walsh *et al.*, 2005). Land uses in an urban catchment which reduce the frequency of runoff events, (and hence runoff %) and the peak discharges are considered to be beneficial to the restoration of stream ecosystem function. It follows that stormwater harvesting practices that can reduce the frequency of small events and take the top off peak discharge rates should be beneficial to the creek ecosystem. However, the other view is that abstraction of water from streams and rivers is likely to cause environmental harm, and until the safe environmental flows (based on the natural flow regime) are defined, extraction for beneficial uses should not be allowed. This stance has been adopted by the water regulator (DERM) as required by the Queensland Water Act (2000) and supported by numerous studies that many of our (inland) river systems are degraded due to over-extraction of water (both in its timing and amount) for human purposes.

Therefore, catchment hydrology modelling is an essential part of this project. Calibrated hydrologic models are widely used for stream flow simulation and to define hydrologic characteristics of streams. A reliable flow simulation depends on availability of reliable stream flow data and a reliable rainfall runoff model. Therefore, considerable effort has been invested in instrumentation of 12 catchments located in SEQ across a land use gradient from nil to significant urbanisation, in order to obtain continuous rainfall and creek flow data. A US EPA Stormwater Management Model (SWMM) has been calibrated and validated for each catchment at an hourly resolution, using two years of continuous hourly rainfall and runoff data. This technical report documents the work involved in doing so from instrumentation to catchment calibration and validation.

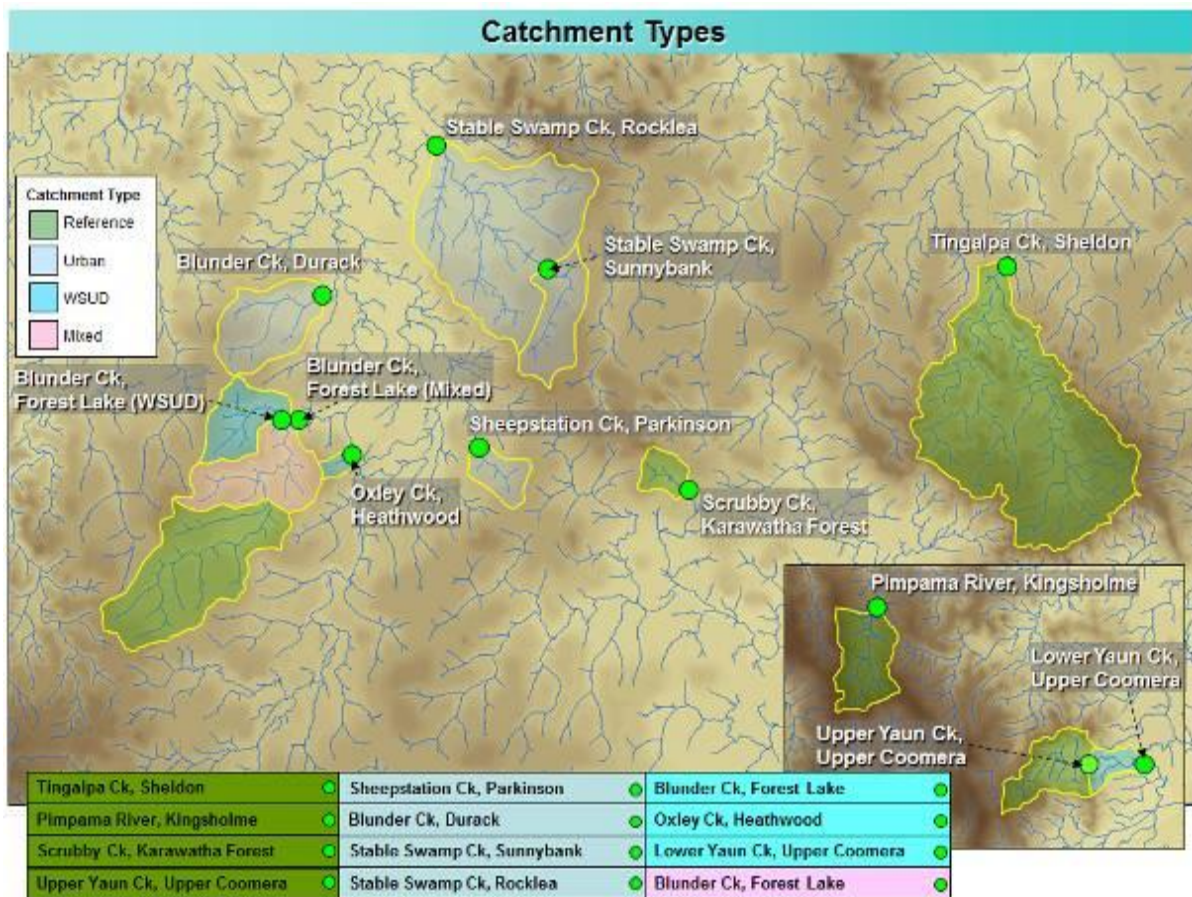
This report consists of a detailed description of catchments, hydrologic instrumentation techniques, rating curve development, estimation of catchment impervious fraction, description of the US EPA Stormwater Management Model, calibration and SWMM parameter estimations, and sensitivity analysis of SWMM parameters. The results of running the SWMM catchment models under baseline (current) land use conditions, and a series of stormwater harvesting and urbanisation scenarios will be reported separately.

# 1. DESCRIPTION OF GAUGED CATCHMENTS

Twelve gauged catchments located in SEQ (Figure 1) are used for hydrologic calibration. These catchments are part of 25 Ecological Health Monitoring Program (EHMP) sites, located in 24 EHMP catchments, monitored by the Healthy Waterways Partnership in SEQ. Figure 2 shows the location of the 12 hydrologically gauged catchments in relation to the 25 EHMP monitoring sites. Table 1 shows their land use and location. These gauged catchments are grouped into three categories based on their land use characteristics:

- Reference or unimpacted catchments (without urbanisation);
- Urban catchments with Water Sensitive Urban Design (WSUD) features such as a wetland or lake; and
- Urban catchments.

Various characteristics of catchment such as area (A), slope (S), total impervious area (TIA) and time of concentration (ToC) were estimated for each catchment. The 25 m resolution Digital Elevation Model (DEM) data set available from the Department of Environment and Resource Management (DERM) was used to estimate area and slope of these catchments. The TIA and ToC estimation procedures are described below.



**Figure 1:** Types and locations of gauged catchments in SEQ, these catchments are grouped into three categories: Reference indicates un-impacted catchments, Urban indicates catchments with significant degree of urban development, WSUD indicates catchments having features such as wetlands. Mixed indicates catchments with a combination of reference, urban and WSUD components.

**Table 1: Description and location of 12 gauged catchments.**

| Creek Name and Location in SEQ          | Area (ha) | Catchment Key Features  | Latitude (degree) | Longitude (degree) |
|---|-----------|---|-------------------|--------------------|
| Tingalpa Creek (R1)<br>Sheldon          | 2785      | <ul style="list-style-type: none"> <li>&gt; Reference<sup>1</sup> catchment</li> <li>&gt; Waterholes (depression) present; creek water are not usually turbid and well shaded</li> <li>&gt; Very little impervious surfaces</li> <li>&gt; Some rural residential properties are observed at upstream</li> <li>&gt; Directly connected impervious area is absent except some road run-off</li> </ul>   | -27.57            | 153.18             |
| Pimpama River (R2)<br>Kingsholme        | 415       | <ul style="list-style-type: none"> <li>&gt; Reference<sup>1</sup> catchment</li> <li>&gt; Waterholes (depression) present; creek water are not usually turbid and well shaded</li> <li>&gt; Very little impervious surfaces</li> <li>&gt; Directly connected impervious area is absent</li> </ul>   | -27.83            | 153.22             |
| Scrubby Creek (R3)<br>Karawatha Forest  | 144       | <ul style="list-style-type: none"> <li>&gt; Reference<sup>1</sup> catchment</li> <li>&gt; Virtually no impervious surfaces</li> <li>&gt; Old metal mine is present at upstream but unlikely to flow in wet conditions</li> <li>&gt; Directly connected impervious area is absent</li> </ul>   | -27.64            | 153.07             |
| Upper Yaun Creek (R4)<br>Coomera        | 362       | <ul style="list-style-type: none"> <li>&gt; Reference<sup>1</sup> catchment</li> <li>&gt; Directly connected impervious area is absent</li> </ul>   | -27.86            | 153.31             |
| Blunder Creek (W1)<br>Carolina Parade   | 2176      | <ul style="list-style-type: none"> <li>&gt; Mixed<sup>2</sup> catchment</li> <li>&gt; Located at downstream of forest lake and large forested catchment area of military reserve</li> <li>&gt; Healthy wide riparian zone is present</li> <li>&gt; Residential land uses are present at upstream</li> <li>&gt; Recently established development works</li> <li>&gt; Limited directly connected impervious area</li> <li>&gt; Recent earthworks (early 2008) have started at south east of sampling site</li> <li>&gt; WSUD features are present such as swales, sediment ponds and wetland</li> </ul> | -27.62            | 152.98             |
| Oxley Creek (W2)<br>Heathwood           | 46        | <ul style="list-style-type: none"> <li>&gt; WSUD<sup>3</sup> catchment</li> <li>&gt; Drains into Oxley Creek</li> <li>&gt; May be influences from road runoff and sewerage pump station overflow</li> <li>&gt; Residential land uses are present at upstream</li> <li>&gt; Directly connected impervious area is absent</li> </ul>  | -27.63            | 152.99             |
| Blunder Creek (W3)<br>Daintree Crescent | 360       | <ul style="list-style-type: none"> <li>&gt; WSUD<sup>3</sup> catchment</li> <li>&gt; Sampling site is located on Blunder Creek, downstream of military reserve area and a small but relatively new industrial development area is located at upstream</li> <li>&gt; Residential land uses at upstream</li> <li>&gt; Channel has been excavated during construction</li> <li>&gt; Creek water are turbid after rain events but clear when settled</li> <li>&gt; New residential development is undergoing</li> </ul>   | -27.62            | 152.97             |
| Lower Yaun Creek (W4)<br>Coomera        | 504       | <ul style="list-style-type: none"> <li>&gt; WSUD<sup>3</sup> catchment</li> <li>&gt; Good riparian zone area is observed</li> <li>&gt; Limited directly connected impervious area</li> <li>&gt; WSUD features are present such as rain gardens, swales, sediment ponds, retention basin and wetland</li> </ul>  | -27.86            | 153.31             |
| Stable Swamp Creek (U1)<br>Sunnybank    | 442       | <ul style="list-style-type: none"> <li>&gt; Urban<sup>4</sup> catchment</li> <li>&gt; Non turbid water flow</li> <li>&gt; Mixed residential and industrial land uses are present at upstream</li> <li>&gt; Directly connected stormwater pipes are present</li> <li>&gt; Open concrete lined channel is constructed at upstream</li> </ul>  | -27.58            | 153.05             |
| Stable Swamp Creek (U2)<br>Rocklea      | 2299      | <ul style="list-style-type: none"> <li>&gt; Urban<sup>4</sup> catchment</li> <li>&gt; Non turbid stream often flowing</li> <li>&gt; Open canopy</li> <li>&gt; Mixed residential and industrial land uses are present upstream</li> <li>&gt; Directly connected stormwater pipes are present</li> </ul>  | -27.55            | 153.02             |
| Blunder Creek (U3)<br>Durack            | 563       | <ul style="list-style-type: none"> <li>&gt; Urban<sup>4</sup> catchment</li> <li>&gt; Large waterhole is present</li> <li>&gt; Non turbid water flow is observed</li> <li>&gt; Residential land uses are present upstream</li> <li>&gt; Directly connected stormwater pipes are present</li> <li>&gt; Open concrete lined channel is constructed upstream of the sampling site</li> </ul>   | -27.59            | 152.98             |
| Sheepstation Creek (U4)<br>Parkinson    | 190       | <ul style="list-style-type: none"> <li>&gt; Urban<sup>4</sup> catchment</li> <li>&gt; Turbid water flow is observed</li> <li>&gt; Residential land uses are present upstream</li> <li>&gt; sedimentation pond upstream</li> <li>&gt; Direct connection to stormwater pipes is present</li> <li>&gt; Constructed pond/wetland system is present upstream</li> </ul>  | -27.63            | 153.04             |

<sup>1</sup> unimpacted or forest catchment; <sup>2</sup> combinations of reference, WSUD and urban land use types; <sup>3</sup> catchment involves water sensitive urban design (WSUD) features (wetland / pond); <sup>4</sup> traditional urban catchments

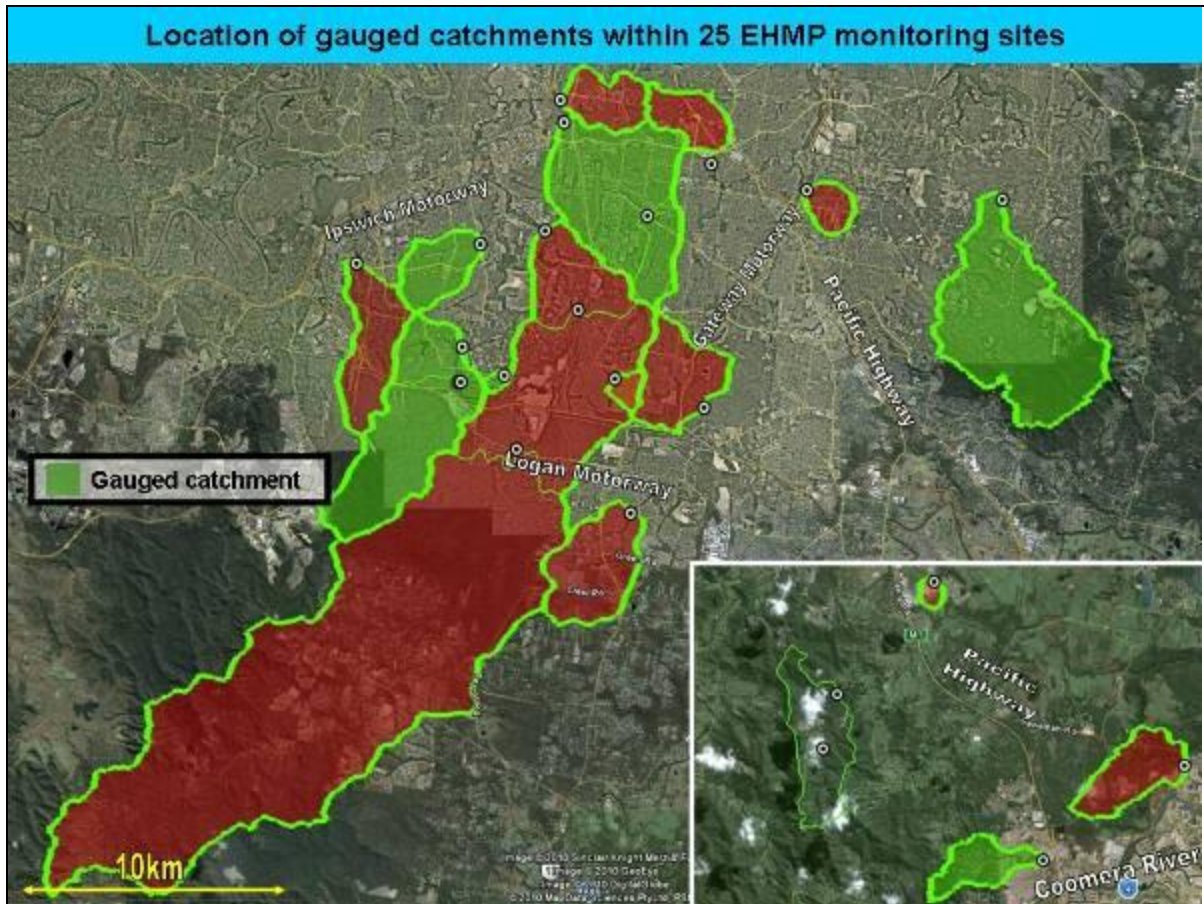


Figure 2: Locations of hydrologically gauged catchments within 25 EHMP monitoring sites in SEQ.

## 2. TOTAL IMPERVIOUS AREA ESTIMATION

In hydrological science, the most important surrogate measure of urbanisation is the fraction of impervious surfaces, which includes pavement, roof, paved parking, driveways and other sealed surfaces. Catchment imperviousness increases surface runoff, sediment concentration, associated pollutant discharge and heating of receiving water bodies, and reduces evapotranspiration and aquifer recharge potential (Han and Burian, 2009). Numerous previous studies have delineated catchment imperviousness as a predictor of stream ecosystem health (Beach, 2003; Walsh *et al.*, 2005). Impervious surfaces are either hydraulically connected to waterways via stormwater pipe inlets or separated by pervious surfaces. Hydraulically connected indicates runoff follows an entirely sealed pathway prior to entry to stormwater pipes or drains. The hydraulically connected portion of total impervious area (TIA) is known as directly connected impervious area (DCIA). Some recent studies have identified a strong empirical relationship between DCIA and ecosystem health indicators (Walsh *et al.*, 2005). Therefore estimation of catchment imperviousness is an essential task.

Several recent studies have attempted to estimate DCIA using a high resolution digital elevation model (DEM), multi-spectral satellite image and digital stormwater drainage pipe network database (Han and Burian, 2009; Kunapo *et al.*, 2009). However, due to lack of availability of required data and estimation difficulties, TIA is widely accepted as an indicator of urbanisation for hydrologic modelling and hydro-ecological studies. Several studies have reported on estimation methods for catchment imperviousness (Lee and Heaney, 2003). All of these methods are based on image analysis techniques. In this study, TIA fractions were estimated using image analyses of orthophotos, and the results were compared with two other methods: the rainfall-runoff relationship method; and manual digitisation of orthophotos. Results from all 3 methods were compared with existing imperviousness data from Brisbane City Council (BCC). However BCC data covers only eight of the 24 EHMP catchments. The methods are described below.

### 2.1 Image Analysis Using the ErDAS IMAGINE and ESRI ArcGIS Software

This automated technique involves conversion of geo-referenced colour aerial photo (tiff format) to native IMAGINE format (.IMG), then creation of mosaics for each catchment area. Development of sample signature sets were then taken for each mosaic with a good representation of surfaces such as different roof colours, road, grass, trees and other key surfaces. An initial supervised classification was run for each mosaic using the respective signature set as training data, with further sampling of signatures and a re-run of the classification to correct false positives. Classified IMAGINE (.IMG) files were converted to ArcGIS GRID format. The GRIDs were re-classified into impervious and pervious classes. Each GRID was clipped to the respective catchment boundary extent. Finally, a comparison was made with digital cadastral data (DCDB) for SEQ to help eliminate large pervious areas (i.e. forest), which contain false-positives in the classified outputs.

During the supervised classification process, performance quality was checked with some additional signature class sampling where spectral confusion occurred, such as for different coloured road surfaces and where roof colours were confused with non-impervious areas such as a green roof and green grass. Total impervious area (TIA) was estimated for each catchment by viewing summary statistics (number of impervious grid cells for reclassified catchment grid) and subtracting number of false positive areas from the digital cadastre comparison.

The major constraints of automated image analysis technique were the shading effects and different colours of roofs. However, while the shading effects cannot easily be corrected, the effects of coloured surface confusion, e.g. green roof and forest, can be reduced with careful selection of signature colours and several iterations of the supervised classification. The method requires advanced skill in GIS

software (ArcGIS and ErDAS IMAGINE). Figure 3 and Figure 4 shows problems in image analysis and TIA estimation respectively.



Figure 3: Two major constraints in image analysis processes, shading and multiple roof colours.

## 2.2 Manual Digitisation of Aerial Photos Using the ArcGIS Software

The method involves digitisation of roof, pavement, paved driveway and other sealed areas, such as swimming pool surrounds, for representative sample areas (8 to 10 sample areas were taken) within the catchment boundary. Representative sample areas were selected based on an aerial view of dwelling density. A weighted average technique was applied to estimate TIA fraction. Mathematically the method can be expressed (Equation 1) as:

$$TIA(\%) = 100 \frac{\sum \left(\frac{I_i}{a_i}\right) A_i}{\sum A_i} \quad (1)$$

Where:

*TIA* is total impervious area in percentage;  $a_i$  is estimated area for representative sample area  $i$  (in  $m^2$ );  $I_i$  is estimated impervious area for representative sample area  $i$ ; and  $A_i$  is part of catchment area (in  $m^2$ ) represented by sample area  $a_i$ . The method is shown in Figure 5, one of numerous samples selected from an orthophoto of a given catchment.

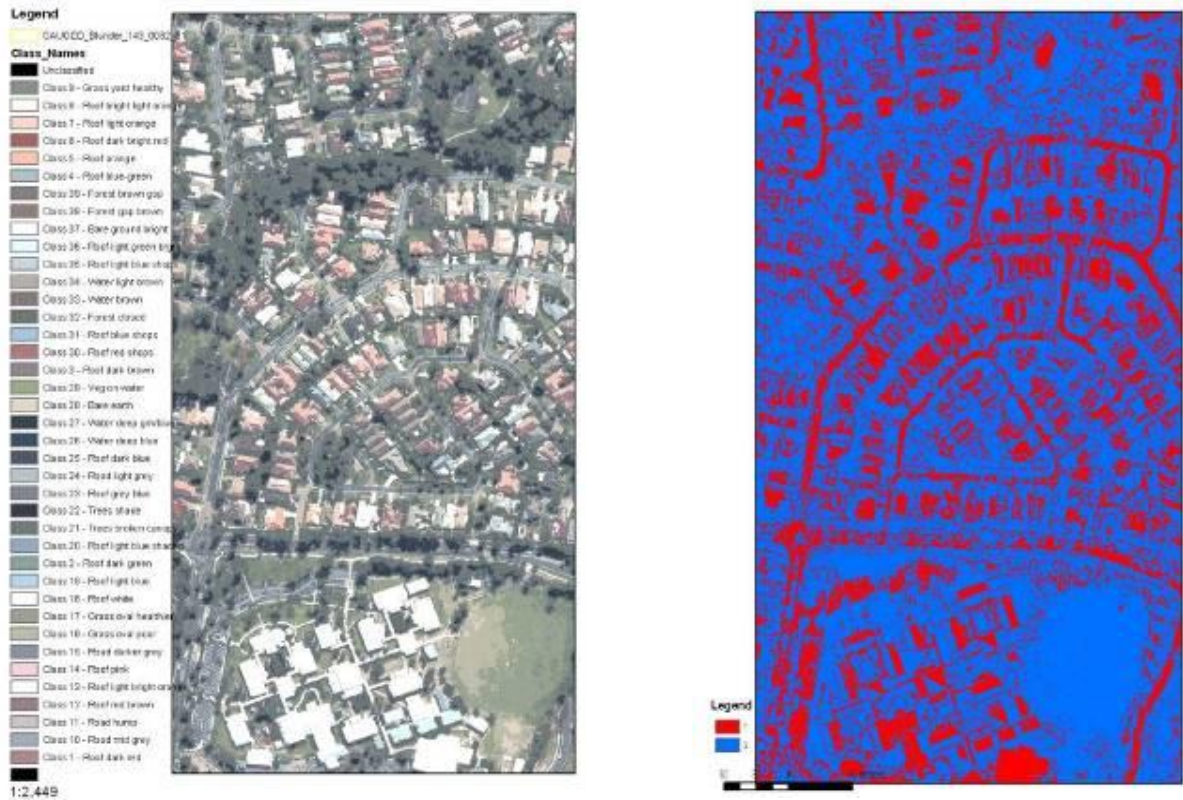


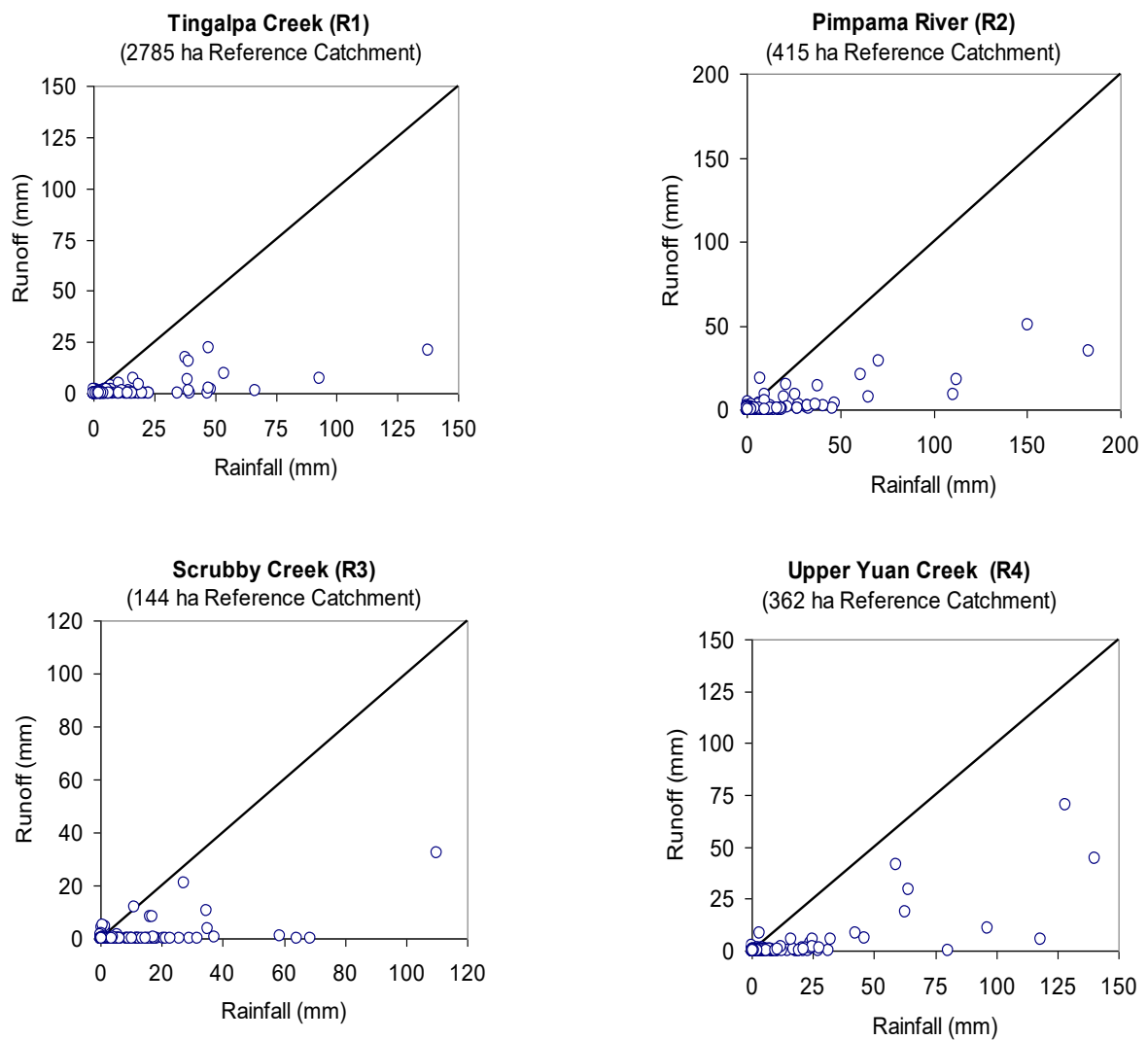
Figure 4: Total impervious area estimation using image analysis of aerial orthophotos. Aerial orthophoto and impervious signature colours are shown in the left hand side and identified impervious areas are shown in the right hand side (“red colour” and “blue colour” are impervious and pervious area respectively).

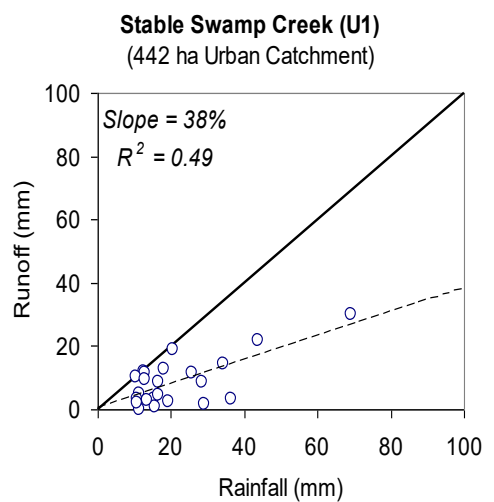
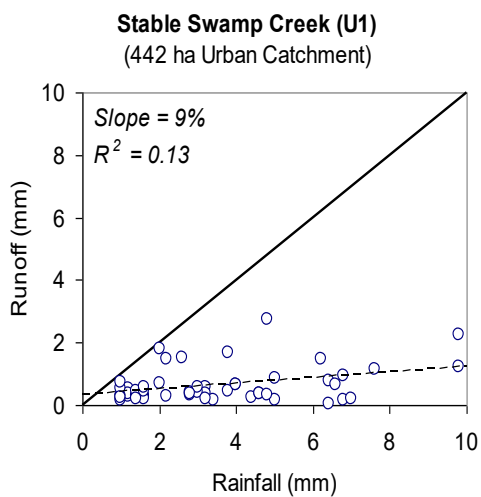
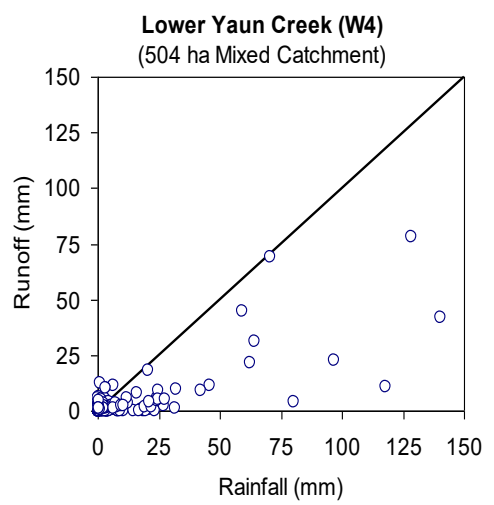
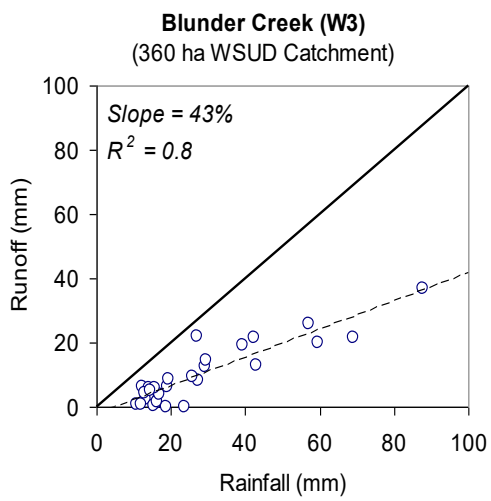
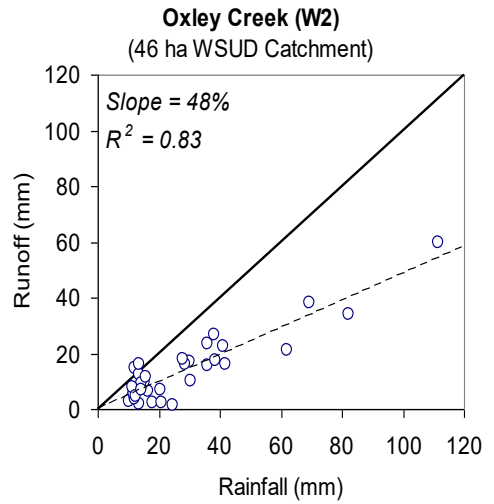
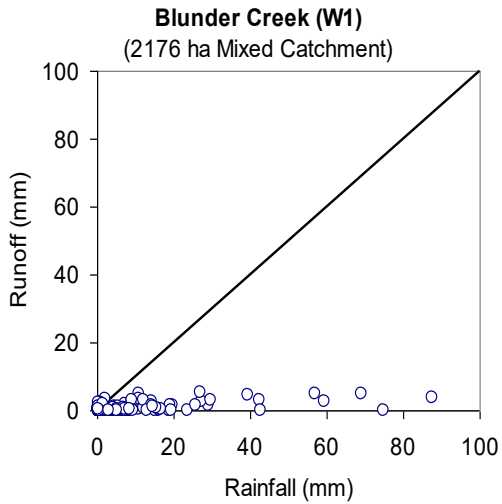


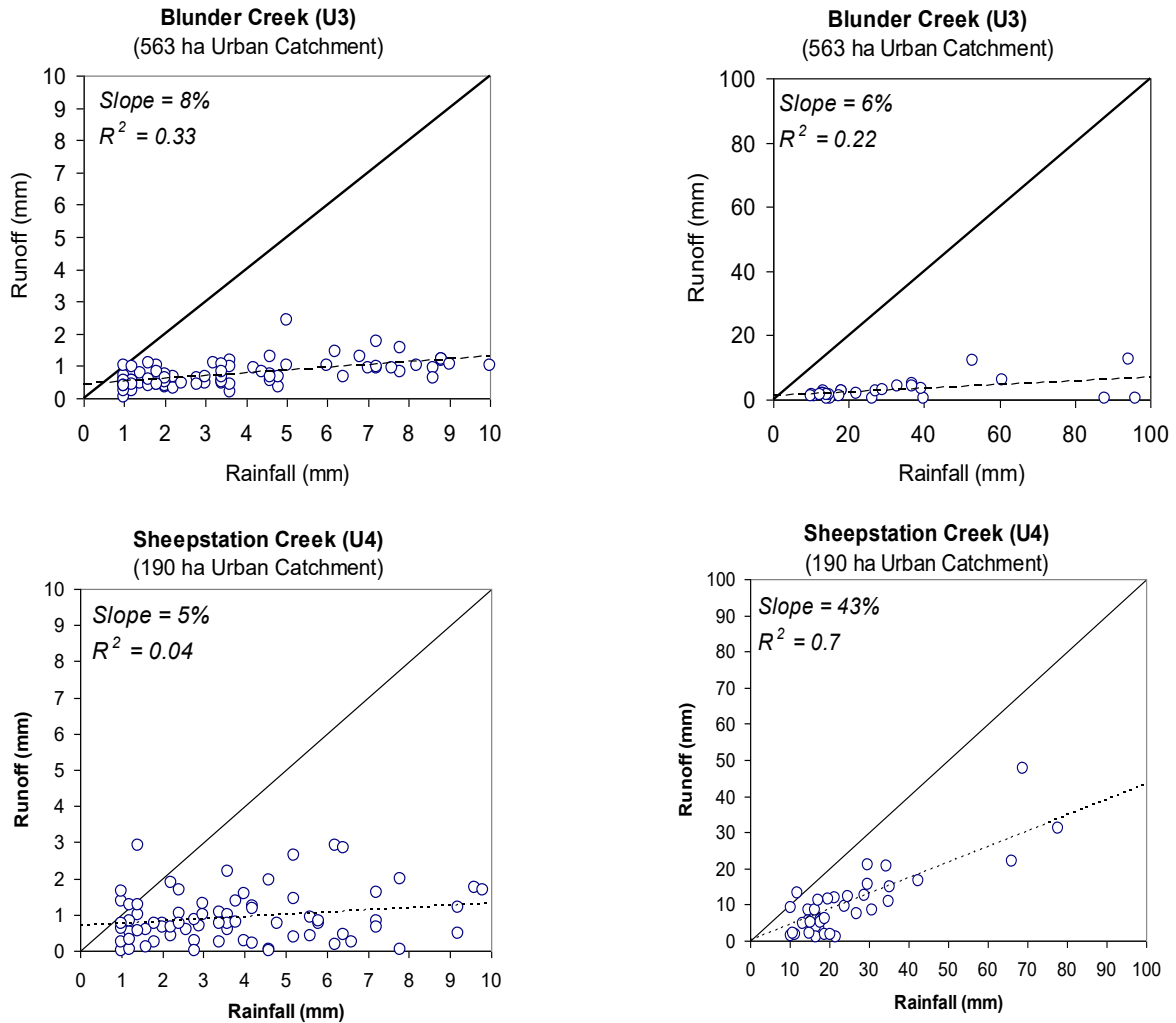
Figure 5: Manual digitisation of impervious area (roof, road, drive area and other paved surfaces such as swimming pool and tool shed) using the ArcGIS software.

## 2.3 Rainfall and Runoff Depth Relationship

The method involves scatter plot and linear regression of rainfall and runoff depth over the catchment. The method was described in Boyd *et al.* (1993). Ideally for an urban catchment, after initial losses of rainfall, there are three segments of linear relationship. Slopes of these segments represent: 1 directly connected impervious area (DCIA) fraction; 2 total impervious area fraction (TIA); and 3 the whole catchment contributing to runoff (1:1 slope). However, easily defined linear relationships are not always observed due to the heterogeneous nature of catchment. None the less, this method is widely used for catchment calibration processes. The major constraint of the rainfall-runoff relationship method is the requirement for a rated gauging station at the catchment outlet. Figure 6 shows the rainfall and runoff scatter plot for the 12 gauged catchments.





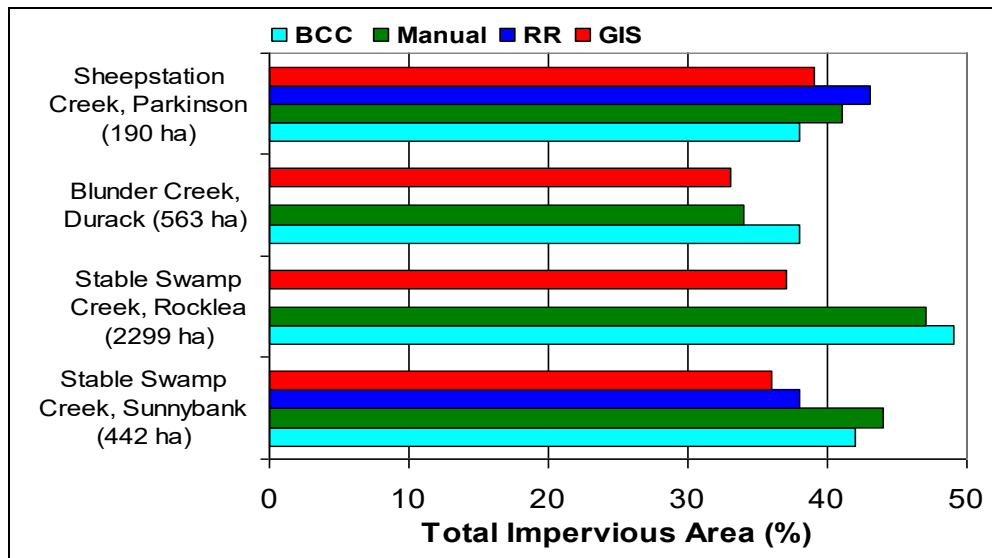


**Figure 6:** Rainfall – runoff depth scatter plot relationships for gauged catchments. For urban catchments (indicated by U), two sets of scatter plots are shown, from 0 mm to 10 mm rainfall depth and 10 mm to 100 mm rainfall depth, in order to identify relationship at small events. The 1:1 line is also shown in each graphic.

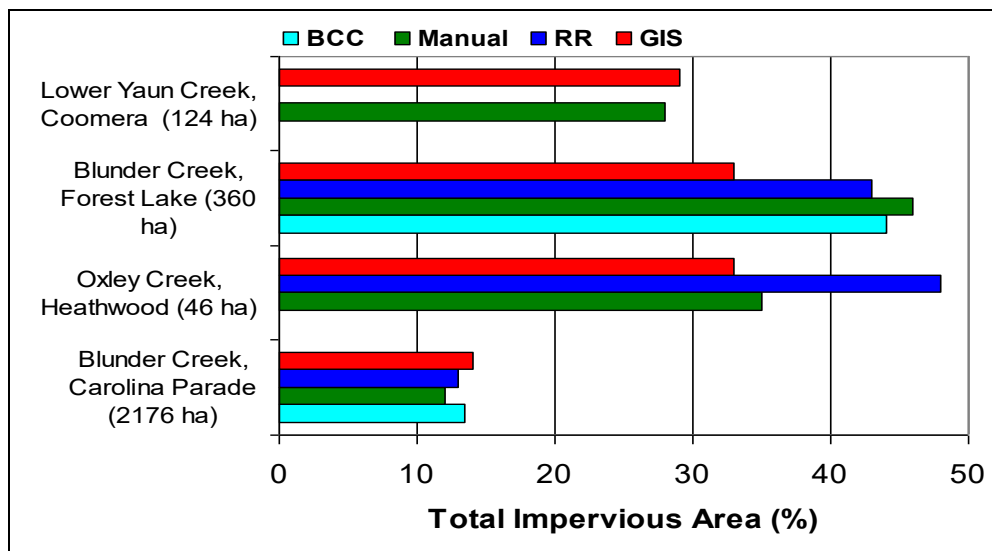
## 2.4 Comparison among Different TIA Estimation Methods

Estimated impervious percentages for Urban and WSUD catchments are given in Figure 7. Results were compared with the Brisbane City Council (BCC) GIS data on impervious area. For three catchments (Oxley Creek at Heathwood, Blunder Creek at Forest Lake and Stable Swamp Creek at Rocklea), standard deviations of TIA (%) lie between 5% and 8%. For the Oxley Creek catchment, the rainfall-runoff method over-estimated impervious area in comparison to other methods. For Stable Swamp Creek and Blunder Creek catchments, the image analysis technique under-estimated results. For the five other catchments, standard deviations of TIA (%) varied from 0.8% to 3.7%, indicating reasonably good estimation by all techniques.

The rainfall-runoff relationship method did not provide a linear relationship between rainfall and runoff for most of catchments (Figure 6) due to heterogeneous catchment characteristics. Whilst the manual digitisation technique (Figure 5) is time consuming, it provided a reasonably good estimation of impervious area. This method requires basic skill on ArcGIS and needs a careful selection of representative sample areas for manual digitisation.



(a)



(b)

**Figure 7: Estimated total impervious area (TIA) for two sets of catchments, (a) urban catchments (b) WSUD catchments. Different methods are expressed as Manual (manual digitization of aerial photo), RR (rainfall-runoff depth relationship) and GIS (automated image analysis technique). BCC indicates Brisbane City Council data. Catchment areas in hectare (ha) are shown for each catchment. For Blunder Creek (Durack), Stable Swamp Creek (Rocklea) and Lower Yuan Creek (Coomera), rainfall-runoff linear relationships were absent. The Lower Yuan Creek is located outside of BCC impervious area data (adapted from Chowdhury et al., 2010).**

Whilst the automated image analysis technique is robust, it underestimated impervious area for few catchments, mainly due to shading effects and the presence of many different roof colours, each having multiple shades due to different sun angles. A careful selection of signature colours and several iterations of a supervised classification may improve the accuracy of results. The method is suitable for any catchment but it requires advanced remote sensing and GIS skills. The rainfall-runoff method was found suitable for urban catchments only. A linear relationship was not observed for some urban catchments with WSUD features. The accuracy of the manual digitisation method depends on selection of representative sample areas. This method gives a reasonably good estimation and it requires only basic GIS skill. However, the method is time consuming. A future improvement by coupling some manual digitising with the automated classification to refine the signature sampling is recommended.

### 3. TIME OF CONCENTRATION

The time of concentration ( $T_c$ ) is generally defined as the time required for a particle of water to travel from the most hydrologically remote point in the catchment to the catchment outlet or point of collection. Time of concentration influences the shape and peak of the runoff hydrograph. Urbanisation (imperviousness) usually decreases time of concentration, thereby increasing the peak discharge. Factors affecting  $T_c$  are:

- Surface roughness: catchment imperviousness generally reduces flow retardance and therefore increases flow velocity.
- Flow patterns: in a non-urban or forest catchment, travel time results from overland flow and thereby increases  $T_c$ , whereas in an urban area, flow follows a lined channel or stormwater pipe thereby reducing  $T_c$ .
- Slope: increased slope reduces  $T_c$  and vice versa.

The travel time of the overland flow path can be estimated using either the Bransby-Williams formula for time of concentration, or by the overland kinematic wave equation (Australian Rainfall and Runoff, 2003). In this study, the former one was used. The Bransby-Williams formula is well suited to situations where no actual relationships for  $T_c$  have been calculated based on observed data, and it does not require an iterative process to reach a solution making it attractive to designers new to these theories, or in areas where little catchment response data exists. It should be noted, however, that where a system is being designed to incorporate detention/retention for downstream flood control,  $T_c$  should be replaced with critical  $T_c$ , i.e. the time of concentration for the critical point of the total downstream catchment (the point at which unacceptable flooding is most likely to occur) (WSUD Guidelines for Tasmania, 2005). The Bransby-Williams formula is given in Equation 2.

$$T_c = \frac{58L}{A^{0.1}S^{0.2}} \quad (2)$$

Where:

$T_c$  is time of concentration in minutes,  $A$  is catchment area in  $\text{km}^2$ ,  $L$  is flow length in km and  $S$  is equal area slope in %, as recommended by Australian Rainfall and Runoff (2003).

An example of  $T_c$  estimation for the Stable Swamp Creek at Rocklea is given below:

Catchment area ( $A$ ) = 22.99  $\text{km}^2$

Estimated flow length ( $L$ ) from DEM data = 8.2 km

Estimated equal area slope ( $S$ ) as derived from Figure 8 = 0.94%

Estimated  $T_c$  from Equation 2 = 5.8 hours

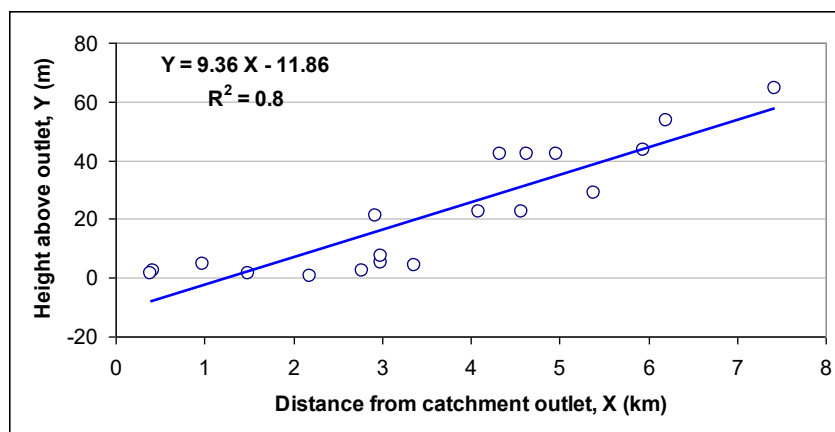


Figure 8: Equal area slope estimation using the (25 m x 25 m) digital elevation model (DEM) data for the Stable Swamp Creek at Rocklea catchment.

## 4. CATCHMENT CHARACTERISTICS

Estimated catchment characteristics for all 12 catchments are given in Table 2, whilst Figure 9 shows their elevation and aerial views.

**Table 2: Characteristics of 12 gauged catchments.**

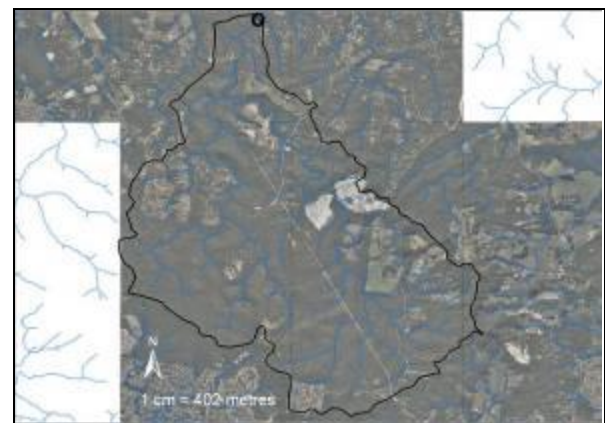
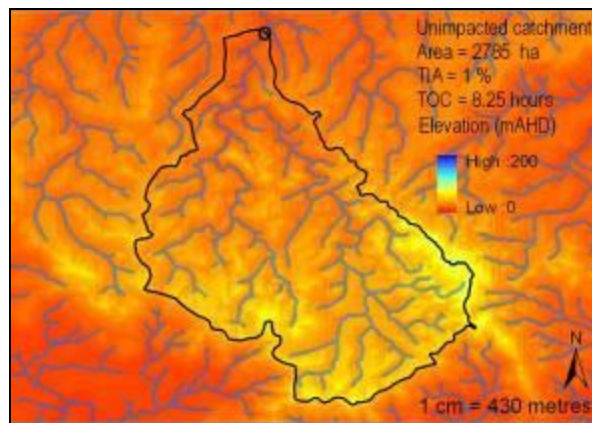
| Creek Name              | Location in SEQ   | Area (ha) | Land Use               | TIA <sup>#</sup> (%) | Slope (%) | ToC <sup>^</sup> (hour) |
|-------------------------|-------------------|-----------|------------------------|----------------------|-----------|-------------------------|
| Tingalpa Creek (R1)     | Sheldon           | 2,785     | Reference <sup>1</sup> | 1                    | 0.9       | 8.25                    |
| Pimpama River (R2)      | Kingsholme        | 415       | Reference <sup>1</sup> | 1                    | 7.0       | 1.70                    |
| Scrubby Creek (R3)      | Karawatha Forest  | 144       | Reference <sup>1</sup> | 0                    | 2.9       | 1.10                    |
| Upper Yaun Creek (R4)   | Coomera           | 362       | Reference <sup>1</sup> | 3                    | 6.8       | 1.90                    |
| Blunder Creek (W1)      | Carolina Parade   | 2,176     | Mixed <sup>2</sup>     | 14                   | 0.4       | 8.85                    |
| Oxley Creek (W2)        | Heathwood         | 46        | WSUD <sup>3</sup>      | 37                   | 3.5       | 0.80                    |
| Blunder Creek (W3)      | Daintree Crescent | 360       | WSUD <sup>3</sup>      | 42                   | 1.1       | 2.15                    |
| Lower Yaun Creek (W4)   | Coomera           | 504       | WSUD <sup>3</sup>      | 10                   | 1.0       | 3.00                    |
| Stable Swamp Creek (U1) | Sunnybank         | 442       | Urban <sup>4</sup>     | 38                   | 1.5       | 2.50                    |
| Stable Swamp Creek (U2) | Rocklea           | 2,299     | Urban <sup>4</sup>     | 43                   | 0.9       | 5.80                    |
| Blunder Creek (U3)      | Durack            | 563       | Urban <sup>4</sup>     | 33                   | 1.6       | 2.80                    |
| Sheepstation Creek (U4) | Parkinson         | 190       | Urban <sup>4</sup>     | 39                   | 1.6       | 1.50                    |

<sup>1</sup> unimpacted or forest catchment

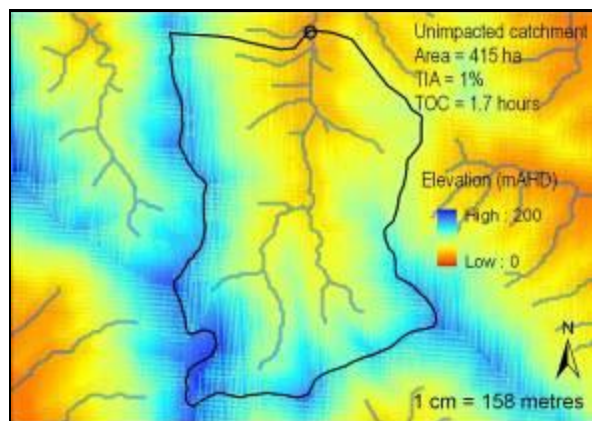
<sup>2</sup> combinations of reference, WSUD and urban land use types

<sup>3</sup> catchment involves water sensitive urban design (WSUD) features (wetland / pond)

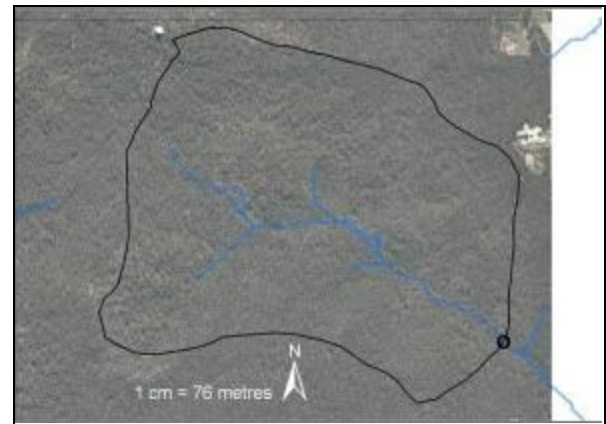
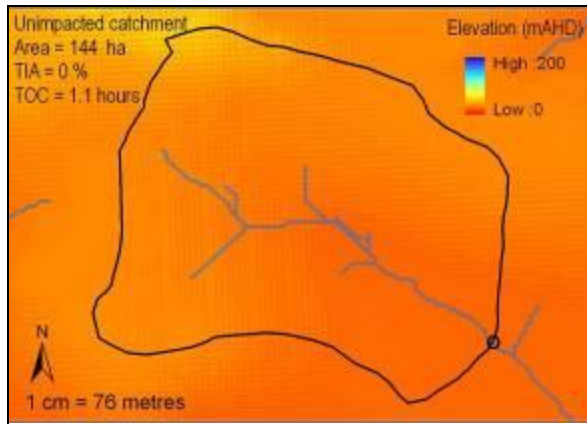
<sup>4</sup> traditional urban catchments, <sup>#</sup> TIA = total impervious area, <sup>^</sup> ToC = time of concentration



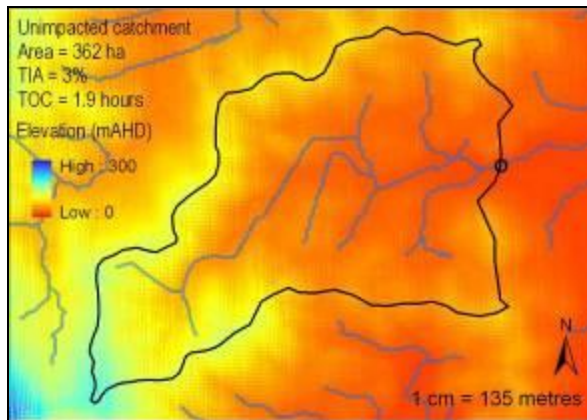
(a) Tingalpa Creek at Sheldon (R1)



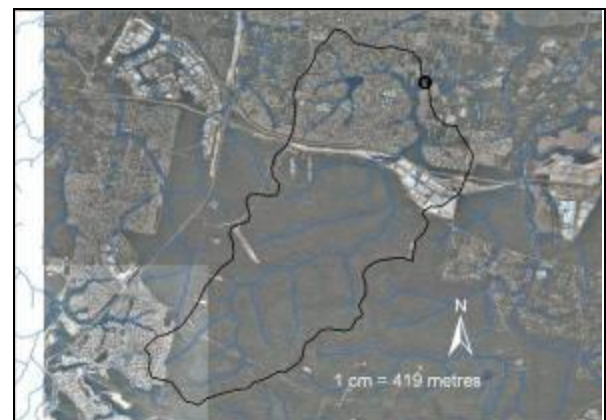
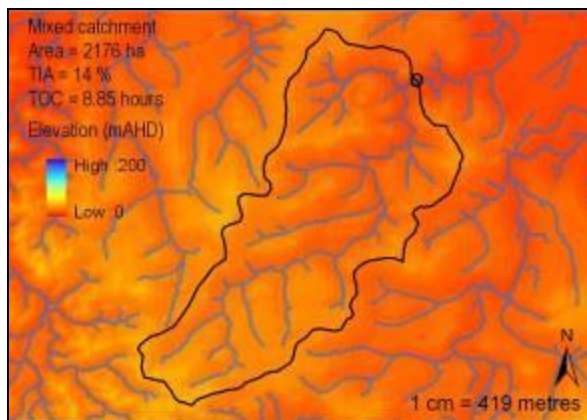
(b) Pimpama River at Kingsholme (R2)



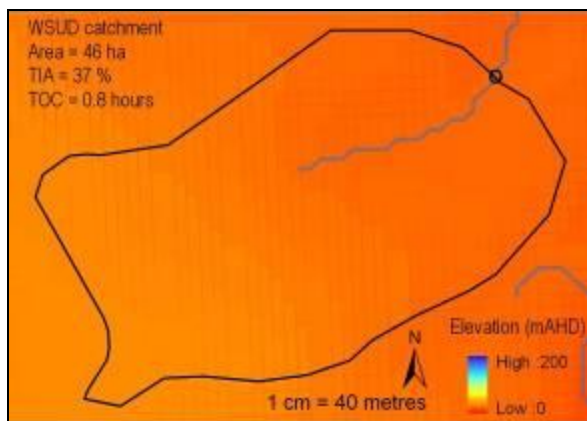
(c) Scrubby Creek at Karawatha Forest (R3)



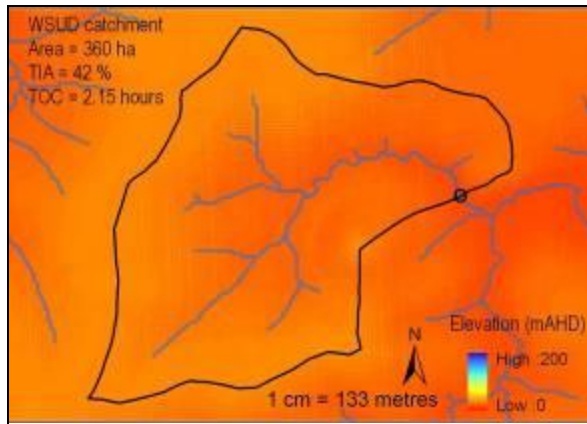
(d) Upper Yuan Creek at Coomera (R4)



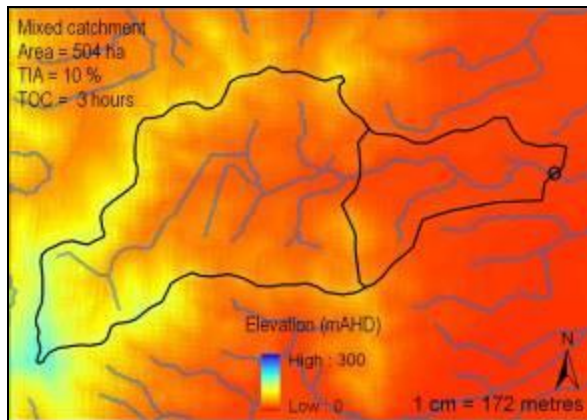
(e) Blunder Creek at Carolina Parade (W1)



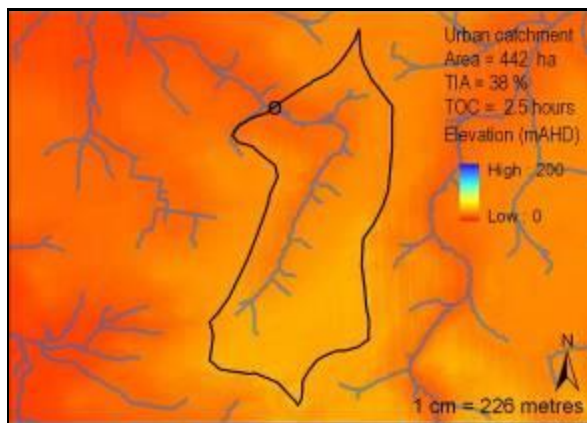
(f) Oxley Creek at Heathwood (W2)



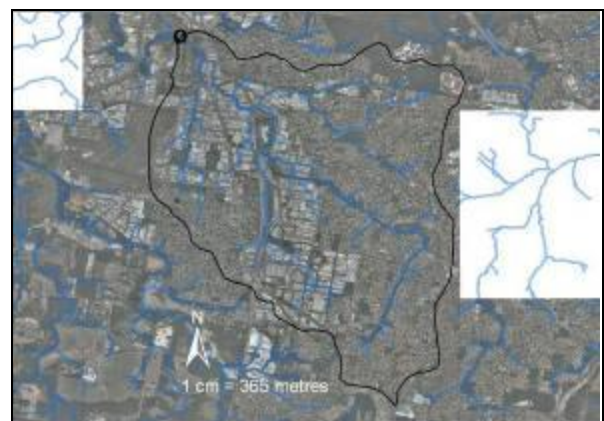
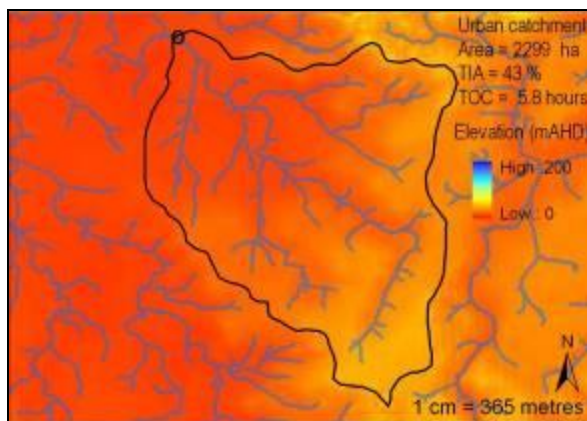
(g) Blunder Creek at Daintree Crescent (W3)



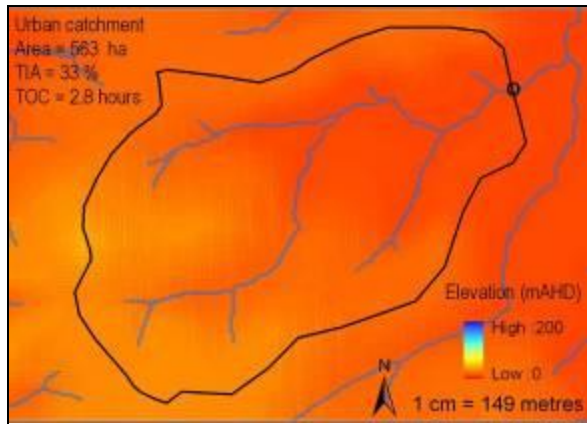
(h) Lower Yuan Creek at Coomera (W4) (in the right hand side aerial photo, 1 indicates upper and 2 indicates lower Yuan Creek)



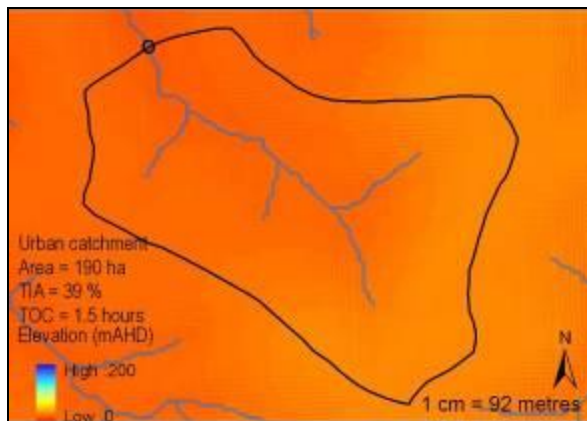
(i) Stable Swamp Creek at Sunnybank (U1) (white space indicates unavailability of orthophotos)



(j) Stable Swamp Creek at Rocklea (U2) (white space indicates unavailability of orthophotos)



(k) Blunder Creek at Durack (U3)



(l) Sheepstation Creek at Parkinson (U4)

**Figure 9:** Delineation of 12 gauged catchments grouped into three categories: (a - d) are reference or unimpacted catchments, (e - h) are urban catchments with WSUD features and (i - l) are urban catchments. In all figures black solid line within the figure indicates catchment boundary, blue line is stream or creek and black circle is gauging station. Left image – elevation from the DEM; right image – aerial view from the orthophoto.

## 5. CATCHMENT INSTRUMENTATION

All 12 catchments have been instrumented with a controlled section, eg. weirs (less affected by erosion and sedimentation), tipping-bucket rain gauge (0.2 mm) and pressure transducer with data logger for measuring continuous six-minute rainfall and water height data respectively. A gauge board was installed at every site for quality control of pressure transducer water height data. Cross sections of all creeks at the gauging section have been surveyed. Flow rate and depth of water at the creek gauging section have been estimated using a Current Meter and an Acoustic Doppler Current Profiler (mounted in a small boat) for different flow conditions (low, medium and high flow). Rating curves (stage *vs* discharge relationship) have been developed and validated for all catchments using the HydStra software. This allowed converting continuous water height data into flow rates. A Sonde was also installed in the catchments (3 Sondes rotated around 12 catchments) for continuous measurement of pH, dissolved oxygen, turbidity and electrical conductivity.

### 5.1 Rain Gauge

A tipping-bucket rain gauge (TBRG) (0.2 mm) has been installed at each catchment to collect six-minute time step continuous rainfall data. Suitable areas were selected for their installation in order to avoid any obstruction from trees and/or building structures. Data were collected regularly in a fortnightly (or monthly) basis. Data quality and TBRG calibration were checked in a regular basis. An installation of TBRG is shown in Figure 10.



Figure 10: Tipping Bucket rain gauge (TBRG) at the Scrubby Creek, Karawatha Forest.

### 5.2 Gauge Board

A gauge board was installed at each gauging station. They were made of steel and marked with black colour in a white background. Gauge board elevations were coincided with the pressure transducer water height elevation. Therefore, gauge board reading of water elevation provides an opportunity for onsite calibration of pressure transducer water elevation data. Gauge boards were installed / attached to some rigid structures (concrete bridge, steel pole etc.) in the stream and in a suitable location so that they could be easily readable. Figures 11 and 12 show installation of gauge boards at two catchments.



**Figure 11:** Gauge board installation at the Pimpama River, Kingsholme.



**Figure 12:** Gauge board installation at the Stable Swamp Creek, Rocklea.

### 5.3 Pressure Transducer and Data Logger

A pressure transducer and data logger was installed at each site in order to collect water level data (Figures 13 to 16). The pressure transducer continuously measured (6-minute) the water height above it, and the data were stored in the Campbell data logger. Data were collected at regular interval (monthly or fortnightly) and were post-processed using the HydStra software system located at the Department of Environment and Resource Management (DERM).

Sedimentation in the creek due to civil construction works and high flood events posed difficulties in data collection in some sites. For example, Scrubby Creek at Karawatha Forest was affected by a high flood event and the data logger was inundated. Therefore, precautions were taken by raising the position of data logger and battery as shown in Figure 15a. Sedimentation and erosion problems at the Blunder Creek site in Forest Lake caused changes in creek cross section area and hence altered flow gauging consistency (Figure 17). The gauged location was changed for this case.

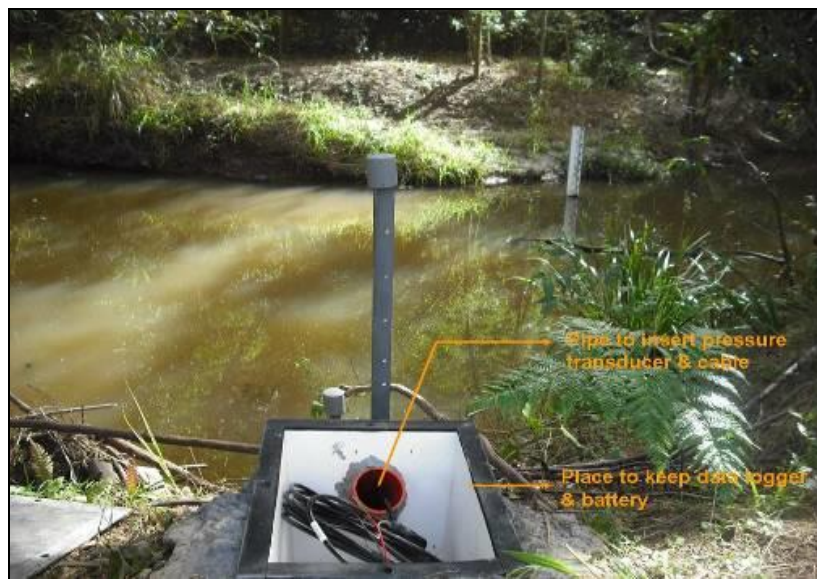


Figure 13: Pressure transducer and data logger installation at Upper Yuan Creek, Coomera (top view).



Figure 14: Pressure transducer and data logger placement at Upper Yuan Creek, Coomera (side view).



(a)



(b)

Figure 15: (a) Raised data logger position in order to avoid flooding inundation at Scrubby Creek, Karawatha Forest. (b) Data logger placement at Blunder Creek, Durack.



Figure 16: Replacement of battery of data logger / pressure transducer at Stable Swamp Creek, Sunnybank. The lid of the environmental enclosure is on the left of photo.



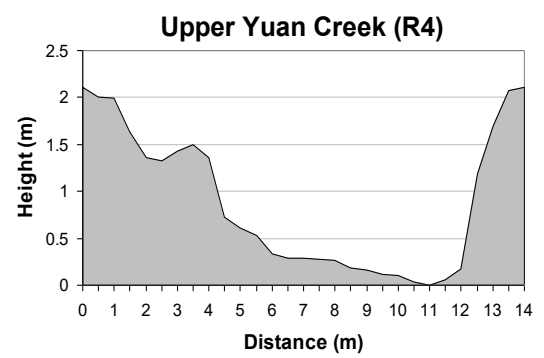
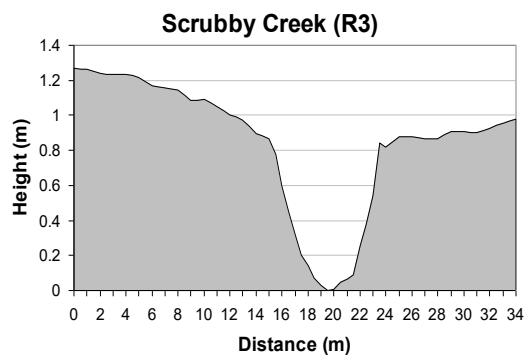
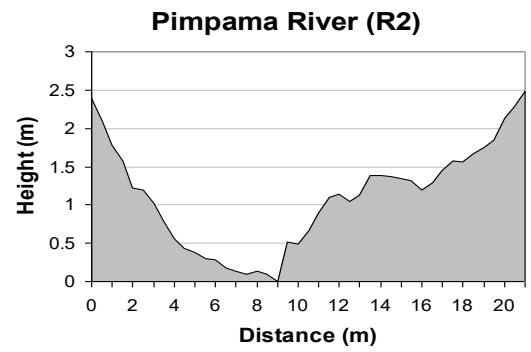
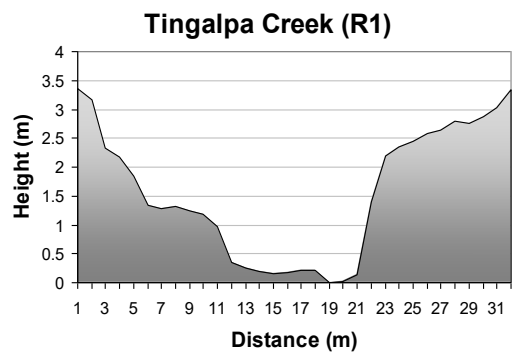
**Figure 17: Sedimentation and erosion problem at Blunder Creek, Forest Lake due to civil construction subdivision works. The gauging station was relocated to suitable location.**

## **5.4 Creek Cross Section**

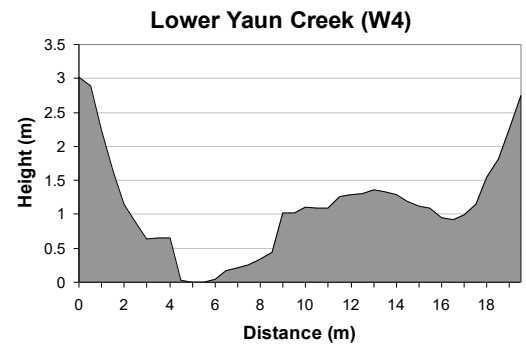
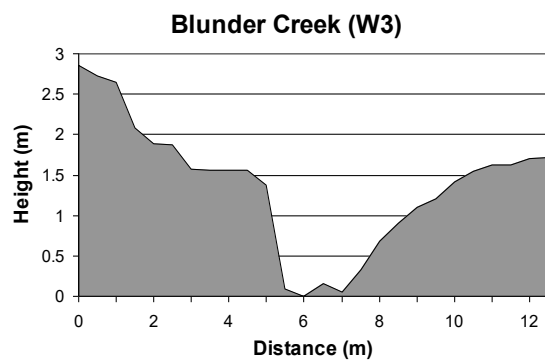
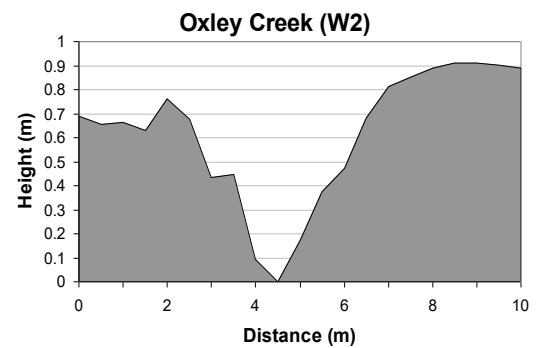
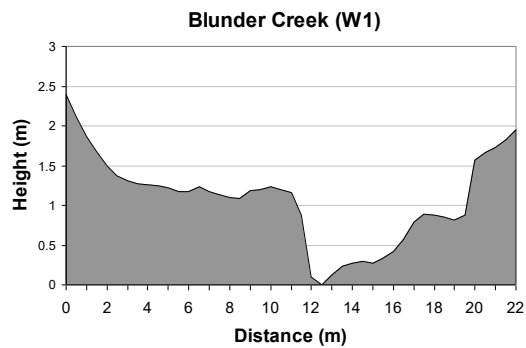
Creek cross section is an essential parameter for rating curve development (water level or stage vs. flow rate discharge relationship) and hydraulic modelling. Efforts have been made to estimate cross sections for all 12 catchments. A Dumpy level surveying instrument was used for this purpose. Figure 18 shows a photograph of cross section measurement, whilst Figure 19 (a-c) show the estimated cross sections for all catchments.



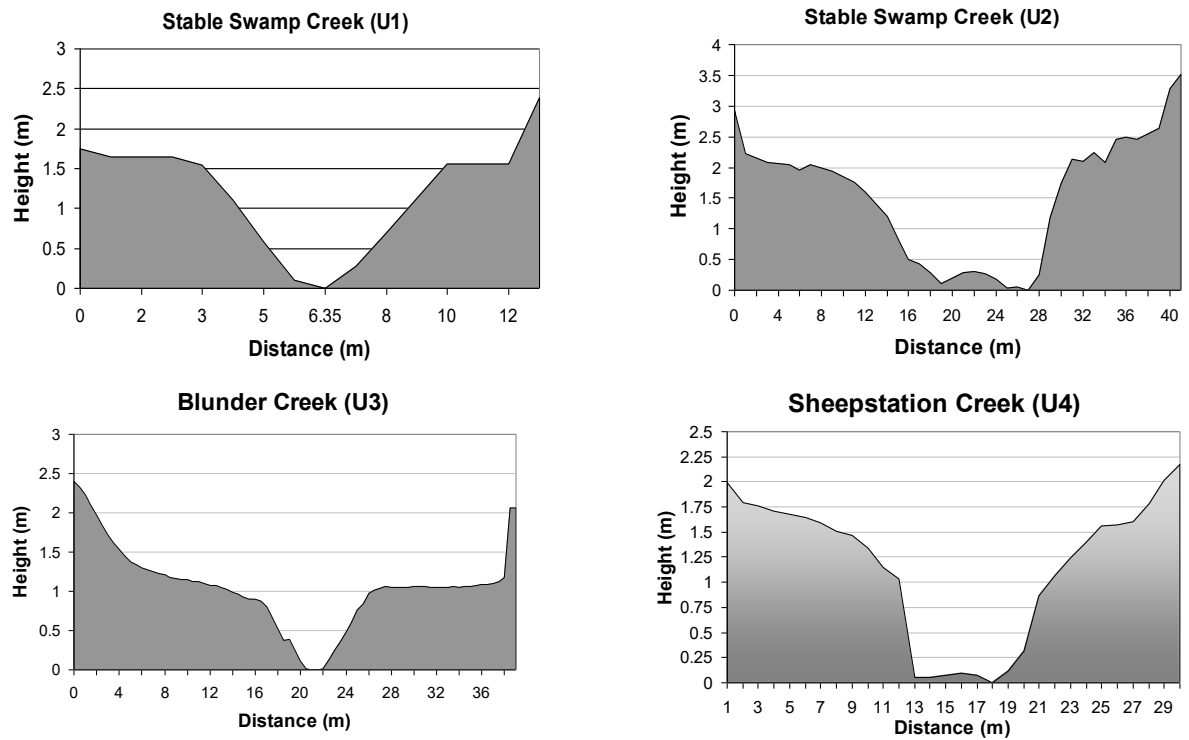
**Figure 18: Surveying the cross section of the gauging location at Scrubby Creek, Karawatha Forest using a Dumpy level.**



(a)



(b)



(c)

Figure 19: (a) Measured creek cross section for reference or unimpacted catchments. (b) Measured creek cross section for WSUD/Mixed catchments. (c) Measured creek cross section for urban catchments.

## 6. RATING CURVE DEVELOPMENT

Rating curves, which describe the relationship between creek discharge and water level (or stage), were developed for all 12 catchments. Development of rating curves was essential in order to convert the continuous water stage data from the pressure transducers into discharge data. The cross section measured at the site enables the determination of the area of the flow at different water levels. This area is then combined with factors such as the slope of the channel and a roughness coefficient of the bed to calculate a theoretical flow. The surface slope of the channel can be measured by marking the edge of the water upstream and downstream of the measured section during high flows. Figure 20 shows the surveying of the height markers which had been placed upstream and downstream of the weir at Sunnybank during a prior high flow event.



**Figure 20: Surveying water surface slope at Stable Swamp Creek, Sunnybank using pegs installed during a prior high flow event.**

Using mean value of water surface slope, Manning's equation was used to estimate flow velocity. Manning's equation is shown in Equations 2 and 3 below:

$$v = \frac{1}{n} R^{2/3} S^{1/2} \quad (2)$$

$$R = \frac{A}{P} \quad (3)$$

Where:

$v$  is mean velocity (m/sec),  $R$  is hydraulic radius (m),  $S$  is slope (m/m),  $A$  is cross sectional area ( $m^2$ ) and  $P$  is wetted perimeter (m) and  $n$  is Manning's roughness coefficient.

The quality of stream flow data conversion from the pressure transducer water stage data depends on the quality of the rating curves. The rating curve is one of major sources of **uncertainty** in hydrologic simulation studies. Rating curves may not generate accurate runoff data because of time depended changes in creek cross sections due to sedimentation and erosion, and also because of systematic error. Therefore validation of rating curves from time to time is recommended. The general equation for a rating curve is shown in Equation 4 (Mosley and McKerchar, 1993):

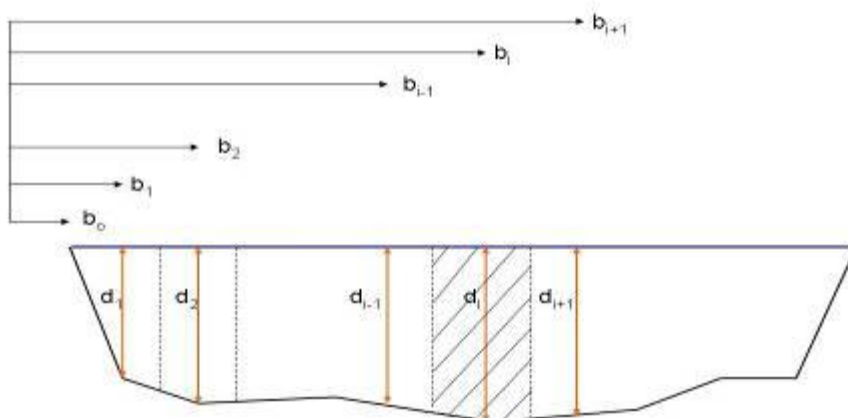
$$Q = C(h + a)^N \quad (4)$$

Where:

$Q$  is discharge ( $m^3/sec$ ),  $h$  is water stage (m),  $a$  is stage (m) at which  $Q = 0$  and  $C$  and  $N$  are fitted constants.

## 6.1 Flow Gauging

Calibration and validation of theoretical rating curves require flow gauging at different flow conditions. At low, medium and high flow conditions, flow velocities were measured using a current meter (for low and medium flow) and an Acoustic Doppler (for high flow). The objective of flow gauging is to measure creek discharge at known water stage heights. The velocity–area method of discharge calculation (Mosley and McKerchar, 1993) was followed in this study. Flow velocities were measured at known intervals perpendicular to flow direction. The method is shown in Figure 21.



**Figure 21:** Velocity-Area method of discharge calculation, where  $d$  is water stage height and  $b$  is horizontal distance from a reference point. Dashed lines indicate midsection and hatched area indicates discharge ( $q_i$ ) corresponds to the depth  $d_i$ .

Discharge ( $q_i$ ) corresponds to depth ( $d_i$ ) is the product of hatched area and measured velocity ( $v_i$ ). This is expressed mathematically using Equation 5:

$$q_i = v_i \left( \frac{b_{i+1} - b_i}{2} + \frac{b_i - b_{i-1}}{2} \right) d_i = v_i \left( \frac{b_{i+1} - b_{i-1}}{2} \right) d_i \quad (5)$$

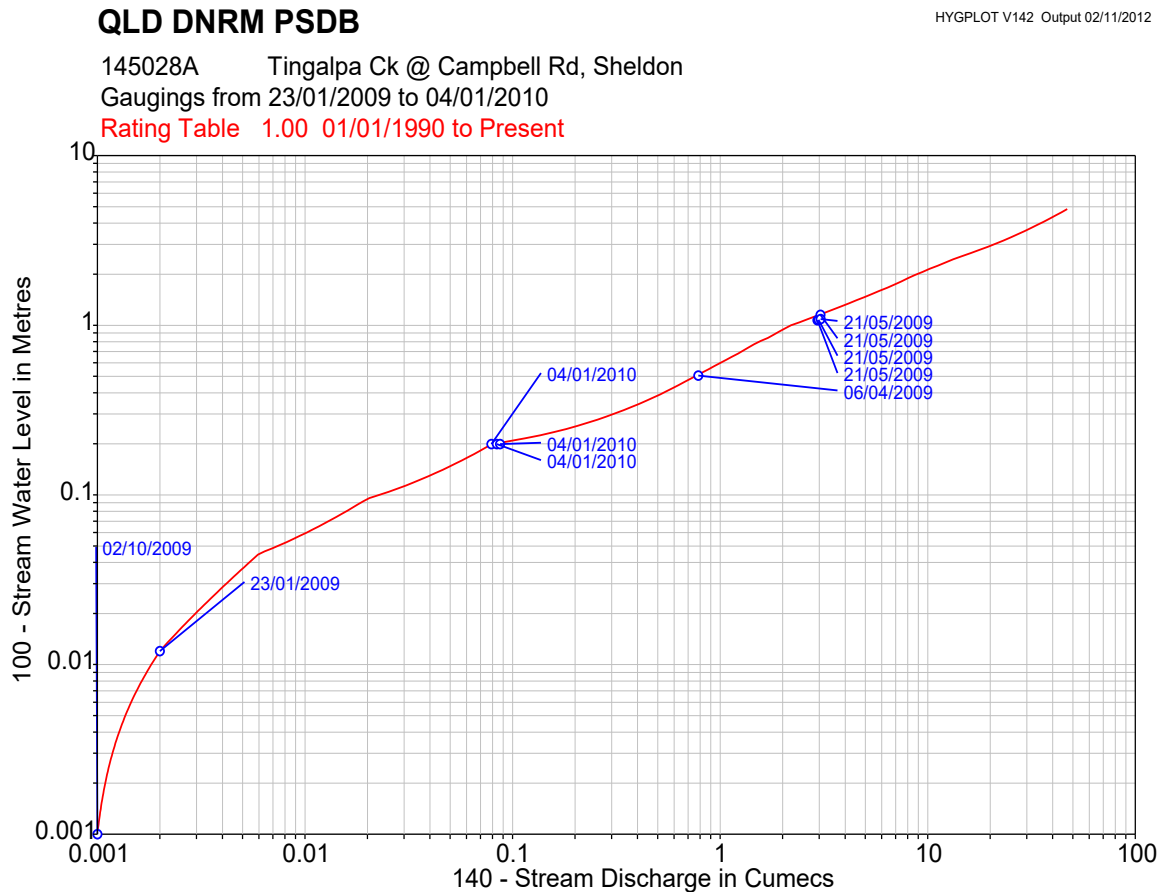
The total discharge is the summation of incremental discharges for all segments. Figure 22 shows photographs of typical velocity measurements undertaken in all 12 catchments.



**Figure 22:** Low and medium flow gauging using a current meter (left) and high flow gauging using an Acoustic Doppler (right).

## 6.2 Rating Curves

Rating curves were developed using the HydStra software installed in the DERM hydrology database system. Theoretical rating curves were calibrated, chiefly by altering Manning's roughness coefficient value to better reflect the measured flows obtained from field gaugings. Figures 23 (a-l) show developed rating curves for all 12 catchments.



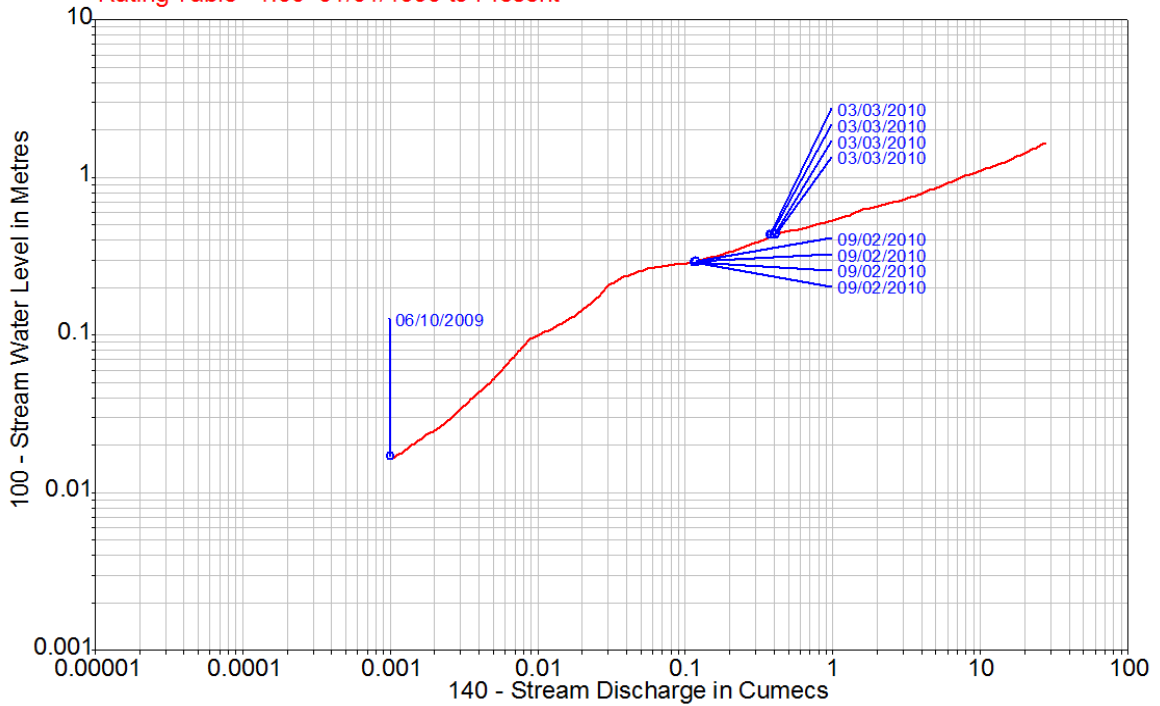
(a) Tingalpa Creek (R1)

**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

146021A Pimpama River Upper @ Kingsholme  
Gaugings from 06/10/2009 to 03/03/2010

Rating Table 1.00 01/01/1990 to Present



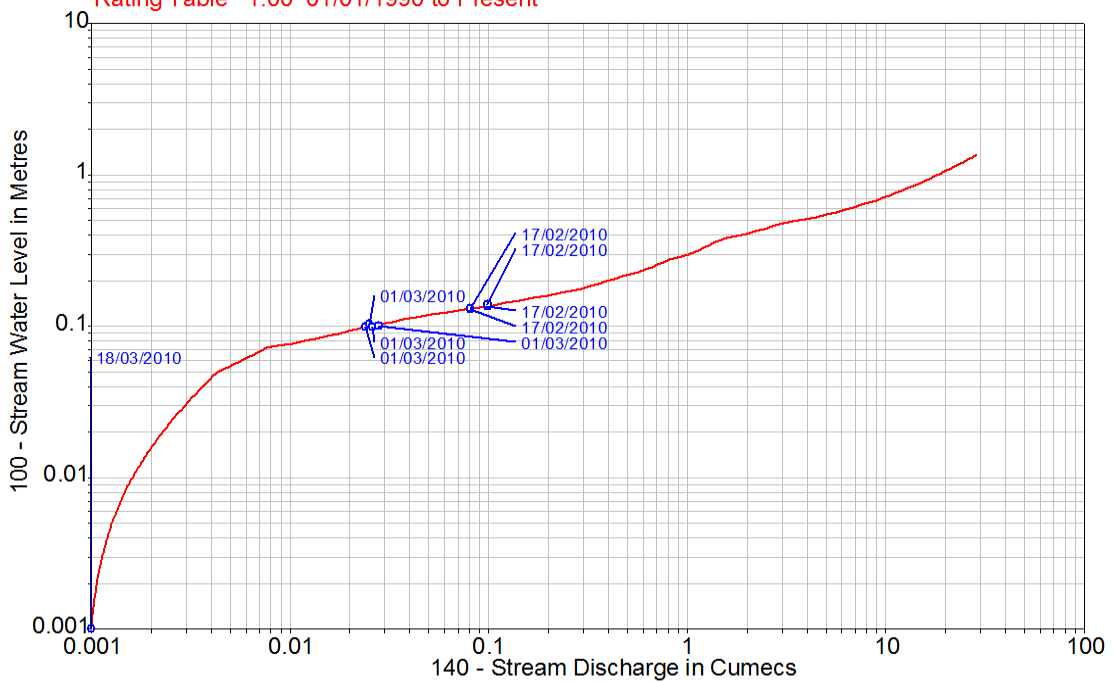
(b) Pimpama River (R2)

**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

145029A Scrubby Ck Trib @ Poplar Ave Karawatha Forest  
Gaugings from 17/02/2010 to 18/03/2010

Rating Table 1.00 01/01/1990 to Present



(c) Scrubby Creek (R3)

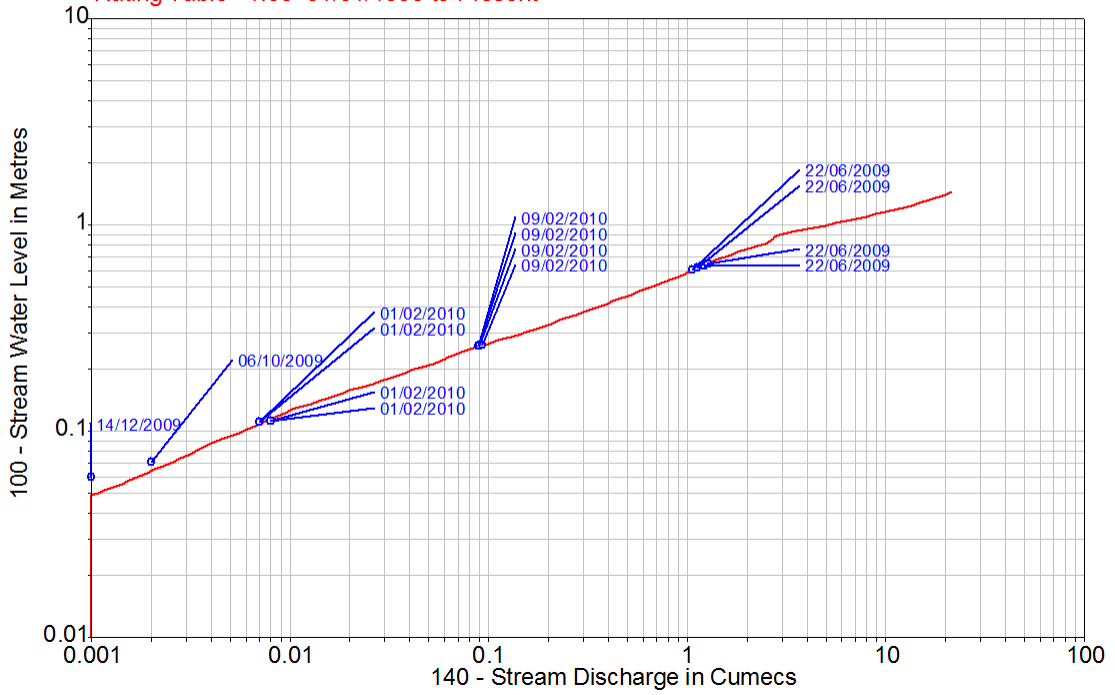
**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

146022A Upper Yaun Ck @ Reserve Rd Coomera

Gaugings from 22/06/2009 to 09/02/2010

Rating Table 1.00 01/01/1990 to Present



(d) Upper Yaun Creek (R4)

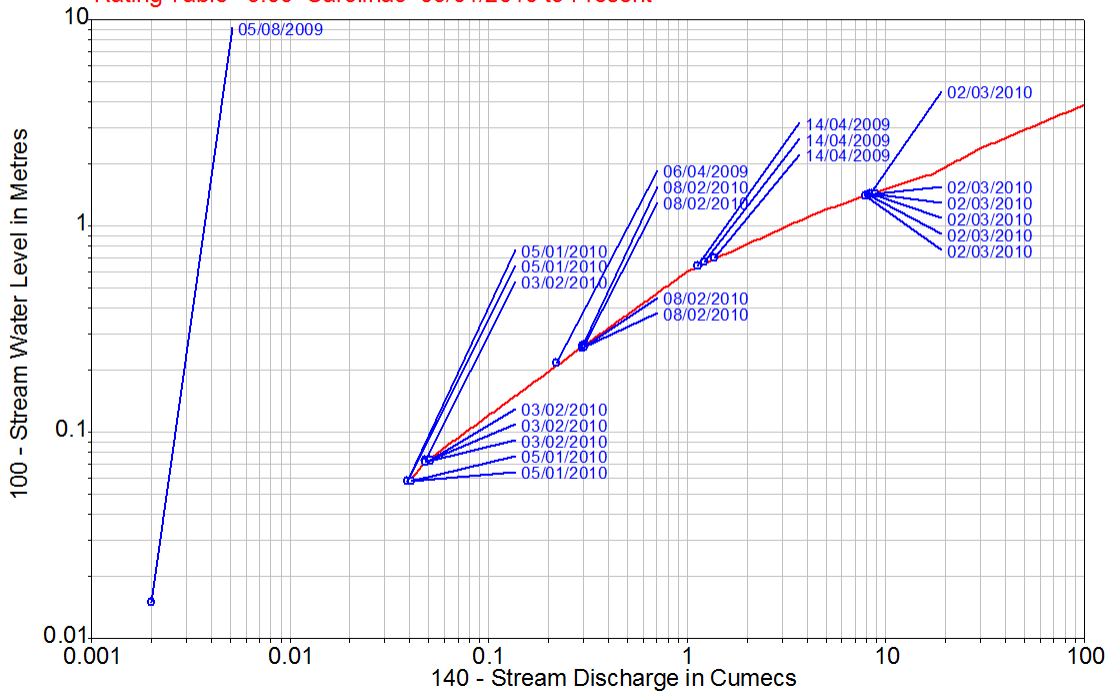
**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

143039A Blunder Ck @ Carolina Pde Forest Lake

Gaugings from 06/04/2009 to 02/03/2010

Rating Table 3.00 Carolina3 03/01/2010 to Present



(e) Blunder Creek (W1)

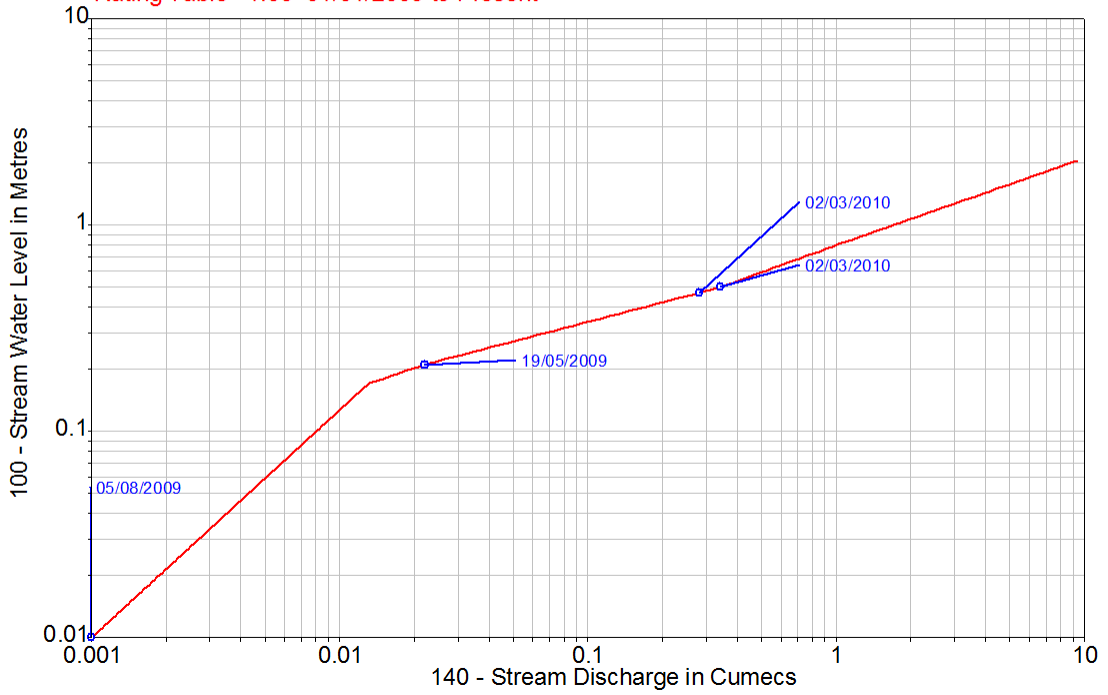
**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

143045A Oxley Ck @ Wadeville St Heathwood

Gaugings from 19/05/2009 to 02/03/2010

Rating Table 1.00 01/01/2009 to Present



(f) Oxley Creek (W2)

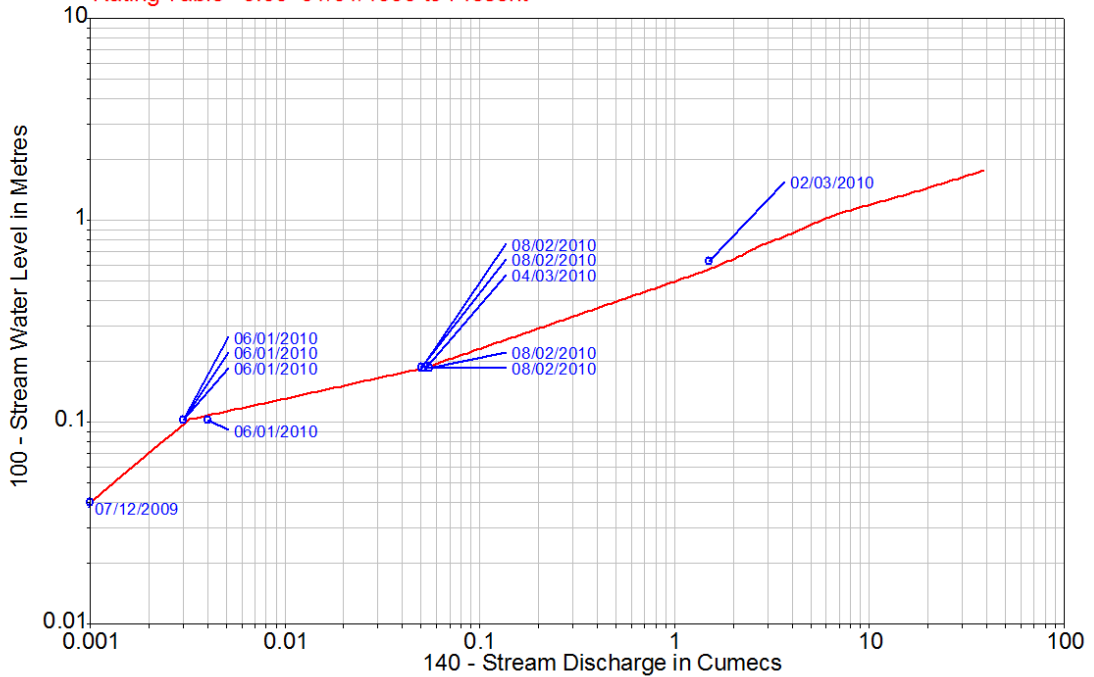
**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

143044A Blunder Ck @ Daintree Close Forest Lake

Gaugings from 07/12/2009 to 04/03/2010

Rating Table 3.00 01/01/1990 to Present



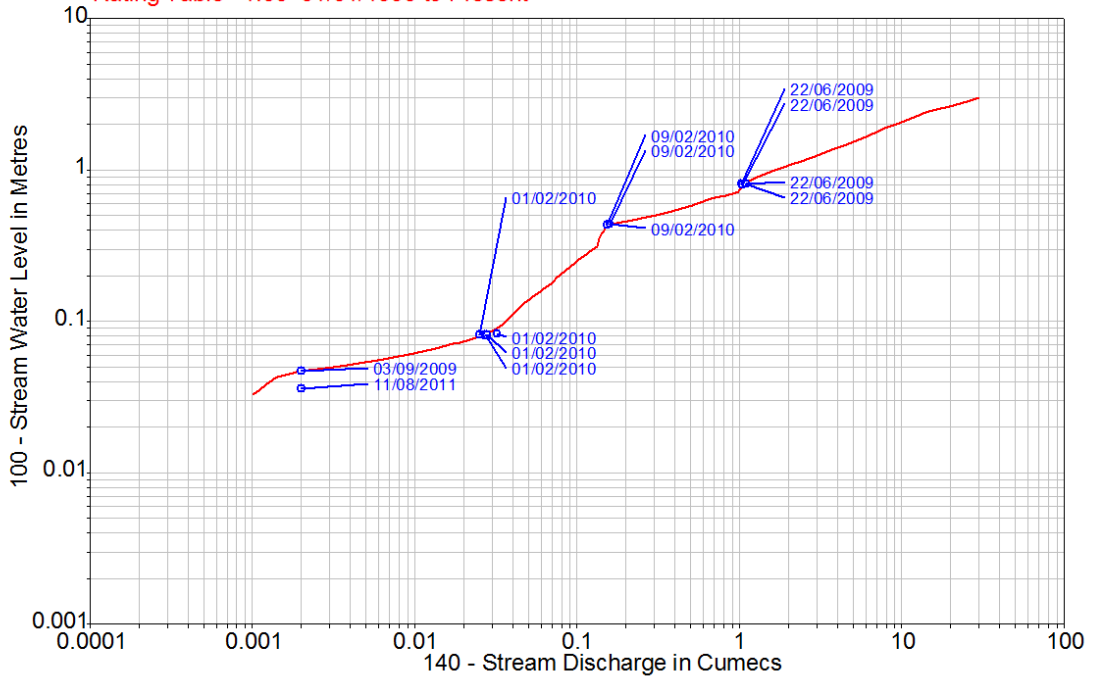
(g) Blunder Creek (W3)

**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

146023A Lower Yaun Ck @ Abraham Rd Coomera  
Gaugings from 22/06/2009 to 11/08/2011

Rating Table 1.00 01/01/1990 to Present



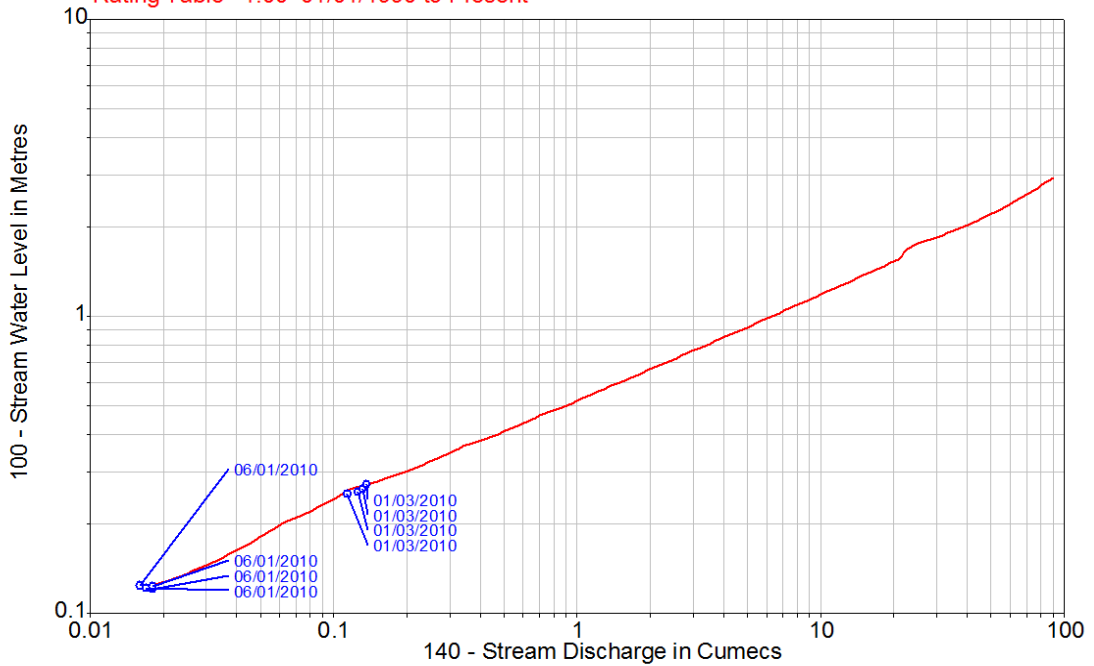
**(h) Lower Yaun Creek (W4)**

**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

143042A Stable Swamp Ck Upper @ Sunnybank  
Gaugings from 06/01/2010 to 01/03/2010

Rating Table 1.00 01/01/1990 to Present

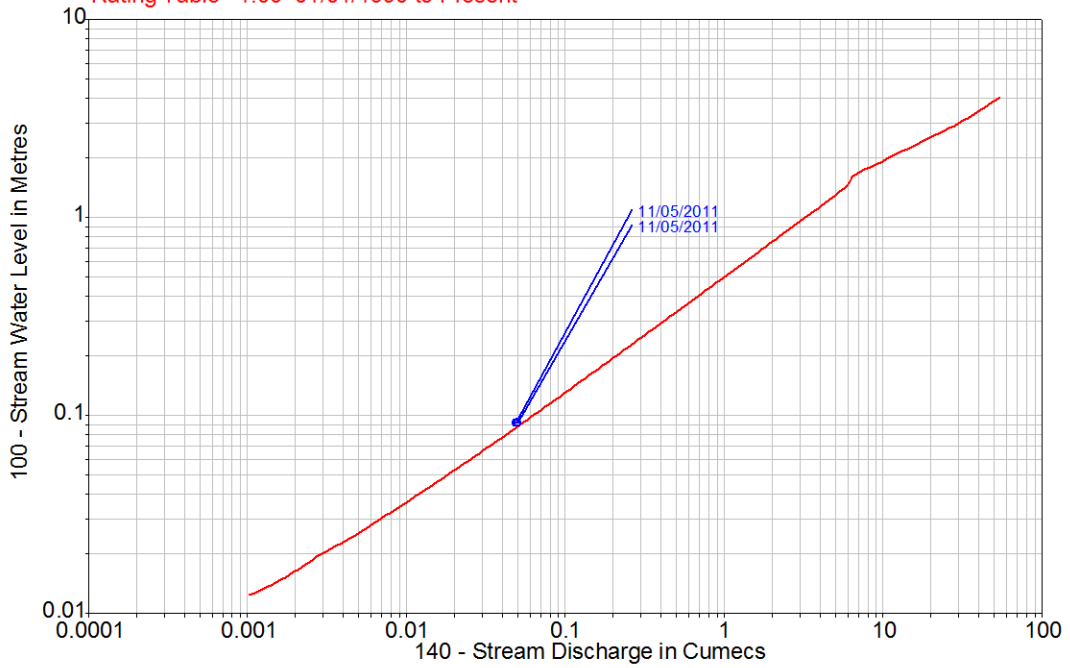


**(i) Stable Swamp Creek (U1)**

**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

143043A Stable Swamp Ck Lower @ Rocklea  
Gaugings from 11/05/2011 to 11/05/2011  
Rating Table 1.00 01/01/1990 to Present

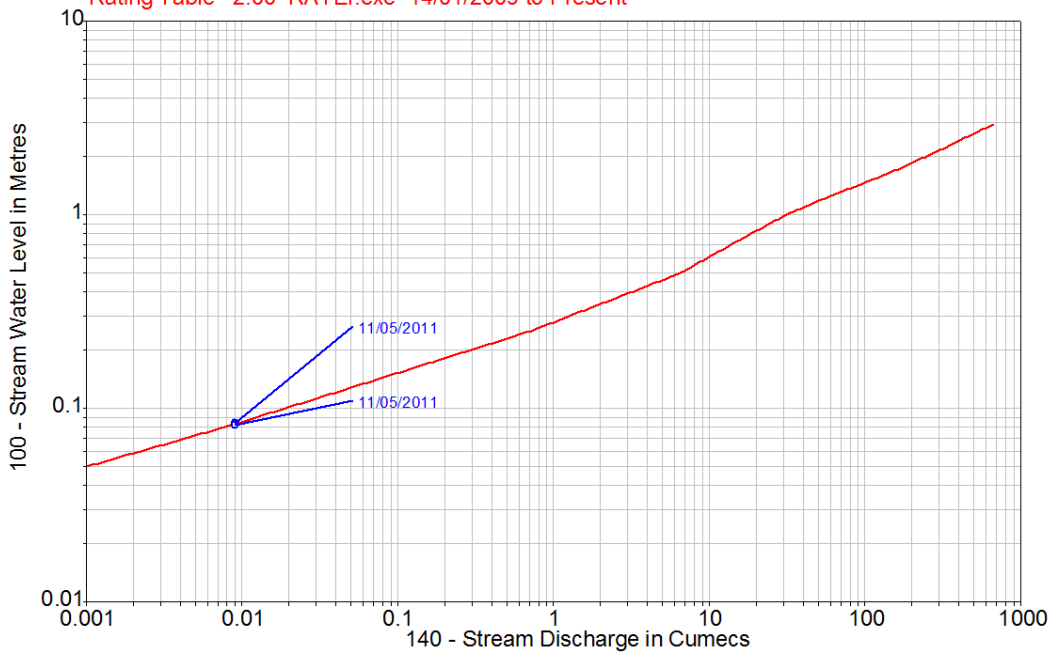


(j) Stable Swamp Creek (U2)\*

**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

143041A Blunder Ck West @ Durack  
Gaugings from 11/05/2011 to 11/05/2011  
Rating Table 2.00 RATEI.exe 14/01/2009 to Present



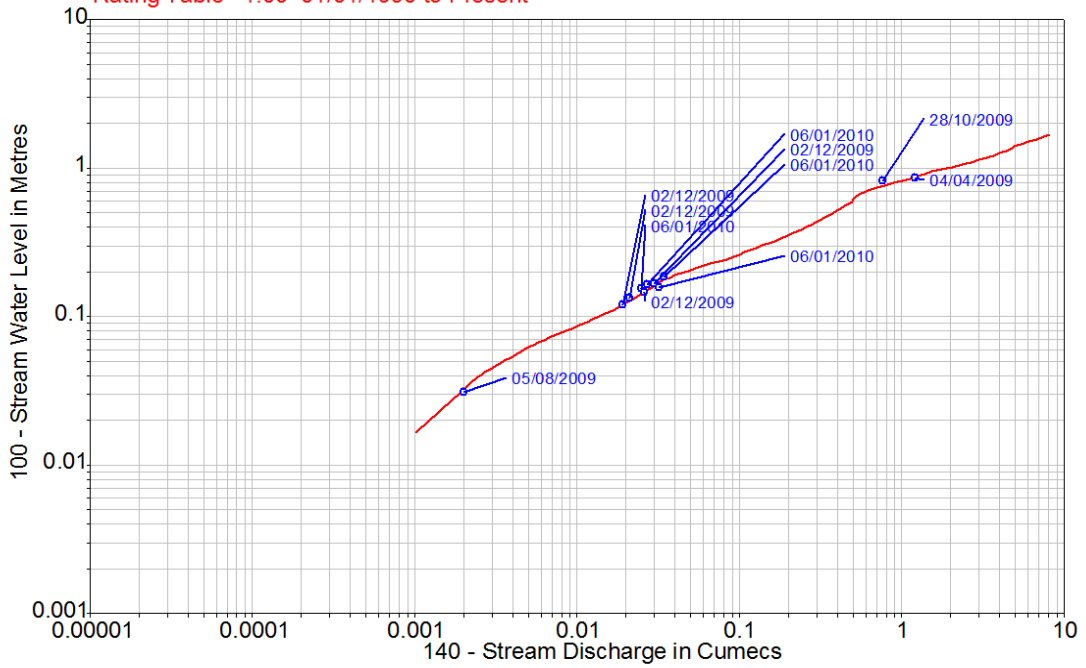
(k) Blunder Creek (U3)\*

**QLD DNRM PSDB**

HYGPLOT V142 Output 02/11/2012

143040A Sheepstation Ck @ Nottingham Rd Parkinson  
Gaugings from 04/04/2009 to 06/01/2010

Rating Table 1.00 01/01/1990 to Present



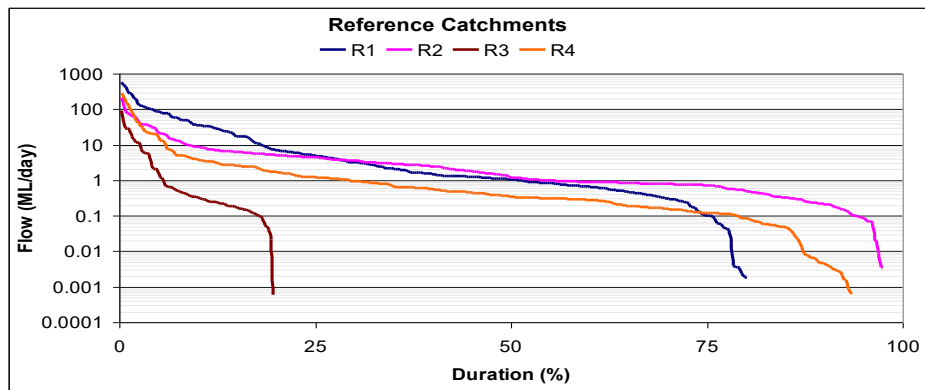
**(l) Sheepstation Creek (U4)**

**Figure 23: Developed rating curves at the outlet of 12 gauged catchments (\* Concrete channel, theoretical rating curve is used).**

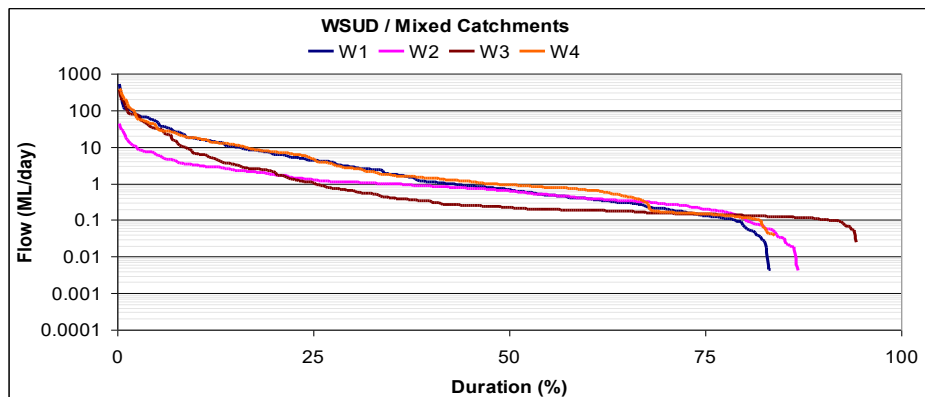
## 7. OBSERVED FLOW CHARACTERISTICS

Using February/March 2009 to April/May 2010 observed flow data, flow-duration curves (FDCs) for all catchments have been generated in order to characterise their flow-duration behaviour. Figure 24 shows the flow-duration curves for the four reference catchments, and Table 3 lists some of the hydrological statistics. Amongst the four reference catchments, Scrubby Creek (R3) exhibits strongly ephemeral characteristics in that no flow occurred for more than 75% of time.

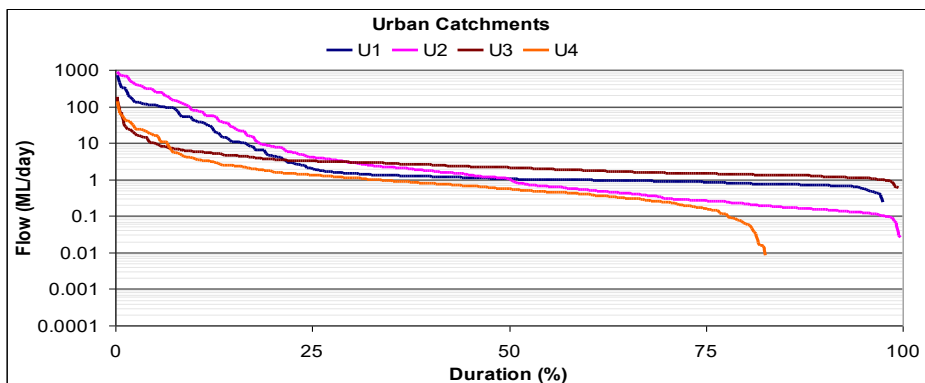
The reader should note that further flow data has been gathered since the FDCs in Figure 24 were generated. Consequently the flow characteristics should not be taken as being representative of the long term hydrological behaviour of each creek. This long term behaviour will be described using 30-year duration, hourly time-step SWMM simulation results in a separate report.



R1 = Tingalpa Creek, R2 = Pimpama River, R3 = Scrubby Creek and R4 = Upper Yaun Creek



W1 = Blunder Creek, W2 = Oxley Creek, W3 = Blunder Creek and W4 = Lower Yaun Creek



U1 = Stable Swamp Creek, U2 = Stable Swamp Creek, U3 = Blunder Creek and U4 = Sheepstation Creek

**Figure 24: Observed flow-duration curves for all 12 catchments based on March/April 2009 to April/May 2010 flow data, grouped into three categories: reference, WSUD and urban catchments.**

**Table 3: Observed flow characteristics of creeks.**

| Flow Characteristics                          | Reference Catchments |      |       |      |
|---|----------------------|------|-------|------|
|   | R1                   | R2   | R3    | R4   |
| Mean daily runoff (ML/day/km <sup>2</sup> )*  | 0.58                 | 1.34 | 0.64  | 1.30 |
| Median daily runoff (ML/day/km <sup>2</sup> ) | 0.04                 | 0.29 | 0.00  | 0.09 |
| CV of daily flow                              | 3.50                 | 3.01 | 6.68  | 5.13 |
| Skewness of daily flow                        | 6.41                 | 7.78 | 10.91 | 8.56 |
| Rise rate (ML/day/day)                        | 26.9                 | 5.27 | 11.59 | 7.13 |
| CV of rise rate                               | 3.12                 | 4.23 | 2.43  | 4.58 |
| Fall rate (ML/day/day)                        | 7.87                 | 2.54 | 3.93  | 4.68 |
| CV of fall rate                               | 4.23                 | 4.74 | 3.83  | 5.44 |
| Base Flow Index (BFI)                         | 0.14                 | 0.33 | 0.03  | 0.10 |

\* ML/day/km<sup>2</sup> is equivalent to mm/day.  
*Tingalpa Creek (R1), Pimpama River (R2), Scrubby Creek (R3), Upper Yaun Creek (R4)*

| Flow Characteristics                          | WSUD/Mixed Catchments |      |       |       |
|---|-----------------------|------|-------|-------|
|   | W1                    | W2   | W3    | W4    |
| Mean daily runoff (ML/day/km <sup>2</sup> )   | 0.40                  | 3.29 | 1.68  | 6.25  |
| Median daily runoff (ML/day/km <sup>2</sup> ) | 0.03                  | 1.36 | 0.06  | 0.65  |
| CV of daily flow                              | 3.94                  | 2.40 | 4.55  | 3.78  |
| Skewness of daily flow                        | 10.70                 | 7.10 | 8.88  | 7.87  |
| Rise rate (ML/day/day)                        | 13.68                 | 1.57 | 10.71 | 13.44 |
| CV of rise rate                               | 3.88                  | 2.80 | 3.43  | 3.56  |
| Fall rate (ML/day/day)                        | 7.95                  | 1.05 | 6.41  | 7.18  |
| CV of fall rate                               | 4.98                  | 3.69 | 4.60  | 4.74  |
| Base Flow Index (BFI)                         | 0.12                  | 0.31 | 0.07  | 0.18  |

Blunder Creek (W1), Oxley Creek (W2), Blunder Creek (W3), Lower Yaun Creek (W4)

| Flow Characteristics                          | Urban Catchments |       |       |      |
|---|------------------|-------|-------|------|
|   | U1               | U2    | U3    | U4   |
| Mean daily runoff (ML/day/km <sup>2</sup> )   | 3.81             | 1.55  | 0.71  | 1.50 |
| Median daily runoff (ML/day/km <sup>2</sup> ) | 0.23             | 0.04  | 0.37  | 0.29 |
| CV of daily flow                              | 3.55             | 3.23  | 2.86  | 3.60 |
| Skewness of daily flow                        | 7.17             | 4.50  | 12.62 | 8.24 |
| Rise rate (ML/day/day)                        | 24.23            | 50.96 | 3.27  | 5.20 |
| CV of rise rate                               | 3.23             | 2.50  | 4.25  | 2.62 |
| Fall rate (ML/day/day)                        | 12.86            | 27.27 | 2.58  | 2.55 |
| CV of fall rate                               | 4.82             | 3.10  | 5.21  | 4.12 |
| Base Flow Index (BFI)                         | 0.16             | 0.06  | 0.46  | 0.14 |

Stable Swamp Creek (U1), Stable Swamp Creek (U2), Blunder Creek (U3), Sheepstation Creek (U4)

## 8. STORMWATER MANAGEMENT MODEL (SWMM)

In this section, we provide an overview of the theory and methodology adopted for the development of the Stormwater Management Model (SWMM) for each of the catchments in this study.

### 8.1 Surface Runoff Component

Two of the most widely used routing methods in hydrology are non-linear reservoir routing and kinematic-wave routing. Hydrologic models are developed based on hypothesised relationships between catchment storage and overflow, where the sub-catchments are considered as conceptual reservoirs (Xiong and Melching, 2005). Hydraulic models are developed on the basis of approximations of the real rainfall-runoff processes. The kinematic-wave routing in hydraulic models is the solution of the simplest form of the full dynamic equations of motion for one dimensional flow (Saint Venant's equation) (Xiong and Melching, 2005). SWMM (Huber and Dickinson, 1988) and Dynamic Watershed Simulation Model (Borah *et al.*, 2002) are examples of hydrologic and hydraulic models respectively (Xiong and Melching, 2005).

SWMM uses a non-linear reservoir routing method for surface runoff routing over pervious and impervious surfaces. It accounts for infiltration using either the Horton or Green-Ampt equation, evaporation, depression storage (abstractions). It estimates surface runoff using simple routing through pipes or channels (Walters and Geurink, 2001).

#### 8.1.1 Reservoir Routing

Reservoir routing is also known as a storage–discharge model, where storage in a catchment is approximated by a reservoir, and is a function of inflow and outflow to and from the catchment. The reservoir routing method concentrates on flood water storage and considers as negligible the effects of resistance to flow (Raudkivi, 1979). The continuity equation is shown as Equation 6:

$$I - O = \frac{dS}{dt} \quad (6)$$

where:

$I$  is inflow to catchment at time  $t$ ,  $O$  is outflow from the catchment at time  $t$  and  $S$  is storage at time  $t$ .

Two forms of reservoir routing are: linear reservoir routing, where outflow is a linear function of stored water in the reservoir; and non-linear reservoir routing, where stored water in the reservoir is a non-linear function of inflow and outflow. Mathematically, these are shown in Equations 7 and 8:

$$S = KO \quad (7)$$

$$S = f(I, O) \quad (8)$$

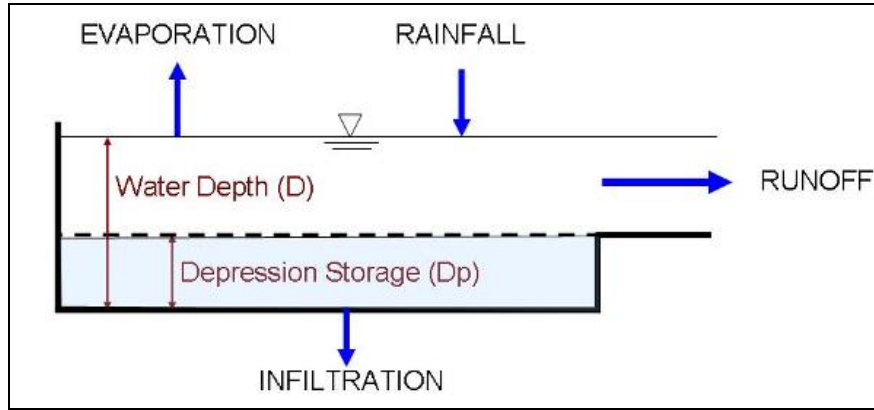
Equation (7) represents linear reservoir routing,  $K$  is a proportionality constant, and Equation (8) represents non-linear routing.

The mass balance equation for non-linear reservoir routing in SWMM (Figure 25) can be expressed using Equation 9 as:

$$\frac{d\forall}{dt} = A \frac{dD}{dt} = Ai_e - Q \quad (9)$$

where:

$\forall$  is volume of water in a sub-catchment;  $A$  is sub-catchment area;  $D$  is water depth in the sub-catchment;  $t$  is time;  $i_e$  is rainfall excess which is equal to rainfall intensity minus infiltration rate, and  $Q$  is surface runoff or overland flow.



**Figure 25: System concept of the non-linear reservoir routing in SWMM, where every sub-catchment is considered as a system of reservoir with a constant depression storage depth ( $D_p$ ). System input is precipitation (rainfall) and system outputs are evaporation, infiltration and surface runoff.**

Flow from a sub-catchment with length ( $L$ ) and characteristics width ( $W$ ) can be simulated using the Manning's equation (Equation 10):

$$Q = W \frac{1}{n} S^{1/2} (D - D_p)^{5/3} \quad (10)$$

where:

$Q$  is surface flow ( $\text{m}^3/\text{s}$ ) per unit length ( $L$ ),  $W$  is sub-catchment width (m),  $n$  is Manning's roughness coefficient,  $S$  is sub-catchment slope (m/m),  $D_p$  is depth of depression storage (m).

The SWMM model used a spatially lumped continuity equation coupled with Manning's equation in order to simulate continuous flow (Huber, 2003). The algorithm is given below:

From Equations 6 and 10:

$$i_e A - W \frac{1}{n} (D - D_p)^{5/3} S^{1/2} = A \frac{dD}{dt} \quad (11)$$

$$i_e = i - f \quad (12)$$

where:

$i_e$  is rainfall excess intensity (m/hour),  $i$  is rainfall intensity (m/hour) at time  $t$ ,  $f$  is infiltration rate (m/hour) at time  $t$ ,  $W$  is the conceptual or characteristic width of sub-catchment (m) calculated as the ratio of catchment area to average maximum flow path length, and  $A$  is sub-catchment area ( $\text{m}^2$ ).

Dividing Equation 11 by the sub-catchment area gives:

$$i_e - \frac{W}{A} \frac{1}{n} (D - D_p)^{5/3} S^{1/2} = \frac{dD}{dt} \quad (13)$$

$$i_e + \Psi (D - D_p)^{5/3} = \frac{dD}{dt} \quad (14)$$

$$\Psi = -\frac{WS^{1/2}}{An} \quad (15)$$

where:

$\psi$  is a constant which spatially lumps all parameters of Manning's equation for the sub-catchment.

Equation 14 is a nonlinear function with dependent variable  $D$  and  $i_e$  is an arbitrary function of time,  $t$ . Therefore numerical solution of Equation 14 using a simple finite difference scheme is (Huber, 2003):

$$\frac{(D_2 - D_1)}{\Delta t} = i_e + \Psi \left\{ \frac{(D_1 + D_2)}{2} - D_P \right\}^{5/3} \quad (16)$$

$$\Delta D = D_2 - D_1 \quad (17)$$

$$(D - D_P)^{5/3} = \left\{ \frac{(D_1 + D_2)}{2} - D_P \right\}^{5/3} = \frac{(D_1 - D_P)^{5/3} + (D_2 - D_P)^{5/3}}{2} \quad (18)$$

where:

subscripts 1 and 2 indicate start and end of time step respectively,  $\Delta t$  is length of time step,  $i_e$  is average rainfall excess over the time step  $\Delta t$ . Equation 16 can be solved using the Newton-Raphson iteration method (Huber, 2003; Chapra and Canale, 2002).

### 8.1.2 Kinematic Wave Routing

The kinematic wave routing method is widely used in hydraulic routing of overland and channel flow (Xiong and Melching, 2005). The method differs from the reservoir routing method because stream storage is not a function of stream stage or discharge only (Raudkivi, 1979). The method is based on laws of conservation of mass (continuity equation) and momentum (equations of motion). The continuity equation as given by Raudkivi (1979) in Equation 19:

$$\frac{dA_c}{dt} + \frac{dQ}{dx} = q \quad (19)$$

where:

$A_c$  is cross section area of stream perpendicular to the  $x$  direction and  $q$  is lateral inflow per unit length of catchment.

The driving forces for open channel flow are gravity force, friction forces due to surface wind and boundary drag and internal pressure gradient. In the kinematic wave theory, internal pressure gradient force is neglected (Xiong and Melching, 2005). For steady uniform flow condition, Raudkivi (1979) expressed the equation of momentum as (Equation 20):

$$S_f = S_0 \quad (20)$$

where:

$S_f$  is friction slope and  $S_0$  is bed slope of the channel. The Manning's equation can be written as Equation 21:

$$Q = \frac{1}{n} A_c R^{2/3} S_0^{1/2} \quad (21)$$

where:

$R$  is hydraulic radius which is a ratio of flow cross sectional area to flow wetted perimeter.

Xiong and Melching (2005) showed that discharge ( $Q$ ) can be expressed as function of cross-sectional area ( $A_c$ ) using Equations 22 to 25:

$$Q = \alpha A_c^m \quad (22)$$

$$\alpha = \frac{S_0^{1/2}}{a^{2/3} n} \quad (23)$$

$$m = \frac{(5 - 2b)}{3} \quad (24)$$

$$P = a A_c^b \quad (25)$$

where:

$\alpha$  and  $m$  are constants determined from sub-catchment geometry, slope and roughness coefficient;  $P$  is wetted perimeter; and  $a$  and  $b$  are constants. For overland flow,  $a = 1$  and  $b = 0$ .

## 8.2 Water Loss Component

Three types of water losses are considered in SWMM: **evaporation**, **depression storage** and **infiltration**. SWMM does not compute evaporation losses, rather this is an input parameter from the user as a daily time series or monthly average value. Evaporation losses are subtracted from rainfall values before computation of surface flow (Huber, 2003). Depression storage ( $Dp$ , in Figure 25) is the initial abstraction of rainwater and it may evaporate and infiltrate. It is a constant value which differs for pervious and impervious surfaces. Impervious surfaces consists less depression storage than pervious surfaces. It is also used to account for interception losses from vegetation (Huber, 2003). SWMM computes infiltration losses and is described in the next section.

### 8.2.1 Infiltration

Either Horton's equation or the Green-Ampt method is used in SWMM to simulate infiltration losses. Both methods require three parameters: initial infiltration capacity, ultimate infiltration capacity and decay constant. The Horton's equation (Equation 26) for exponential decay of infiltration capacity (illustrated in Figure 26) is:

$$f = f_c + (f_0 - f_c)e^{-Kt} \quad (26)$$

where:

$f$  is infiltration rate at time  $t$  when surface water is not limiting,  $f_0$  is initial infiltration capacity,  $f_c$  is ultimate infiltration capacity and  $K$  is a decay rate ( $\text{time}^{-1}$ ). Unit of infiltration rate is mm/hour or m/hour.

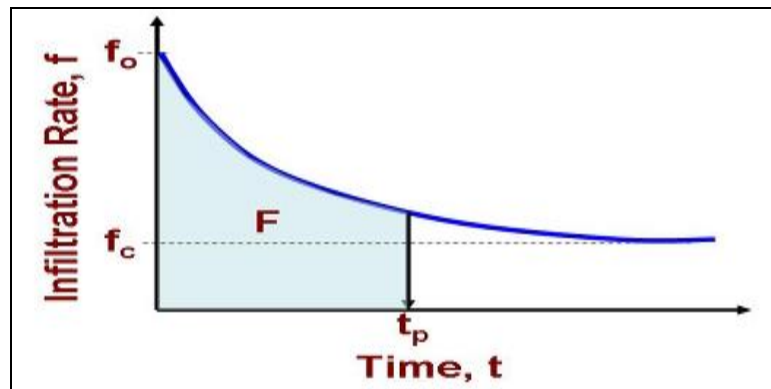


Figure 26: Horton's exponential decay of infiltration capacity. Infiltration capacity reduced as a function of cumulative infiltration,  $F$  (the shaded area under curve up to time,  $t_p$ ).

In SWMM, Horton's infiltration capacity decays as a function of cumulative infiltration,  $F$  (Huber and Dickenson, 1988) (Equation 27).

$$F = f\Delta t = \Delta t f_c + K(f_0 - f_c)(1 - e^{-\frac{\Delta t}{K}}) \quad (27)$$

The Green-Ampt method of infiltration capacity estimation described in Huber (2003) is shown in Equation 28:

$$f = Ks(1 - \frac{M_d \Psi_f}{F}) \quad (28)$$

where:

$Ks$  is saturated hydraulic conductivity,  $\Psi_f$  is average soil suction along the wetting front (negative value),  $F$  is cumulative infiltration and  $M_d$  is initial moisture deficit which is different between upper soil water storage limit (or Field Capacity) and initial moisture content.

### 8.3 Groundwater Flow Component

The SWMM groundwater component simulates two zones: unsaturated upper zone and saturated lower zone. Figure 27 represents the groundwater modelling component of SWMM. Flow from **unsaturated zone to saturated zone** is performed by an empirical equation (Equation 29). Infiltration and evapotranspiration are the only inflow ( $f_i$ ) and loss ( $f_{EU}$ ) from the unsaturated zone respectively (Figure 27). **Outflows from lower saturated zone** consists of deep percolation ( $f_L$ ), saturated zone evapotranspiration ( $f_{EL}$ ) and **groundwater flow to stream ( $f_G$ )**. The user-defined power function of groundwater flow is a function of groundwater table stage ( $H_{GW}$ ) and water depth in stream ( $H_{SW}$ ) (Huber and Dickenson, 1988; Walters and Geurink, 2001). The power function is given in Equation 29:

$$Q_{GW} = A_1(H_{GW} - H_B)^{B_1} - A_2(H_{SW} - H_B)^{B_2} \quad (29)$$

where:

$Q_{GW}$  is groundwater flow,  $A_1$  is groundwater influence coefficient,  $A_2$  is stream water influence coefficient,  $H_{GW}$  is average groundwater table elevation,  $H_B$  stream bottom elevation,  $H_{SW}$  is water elevation in stream,  $B_1$  is groundwater influence flow exponent and  $B_2$  is stream water influence flow exponent.

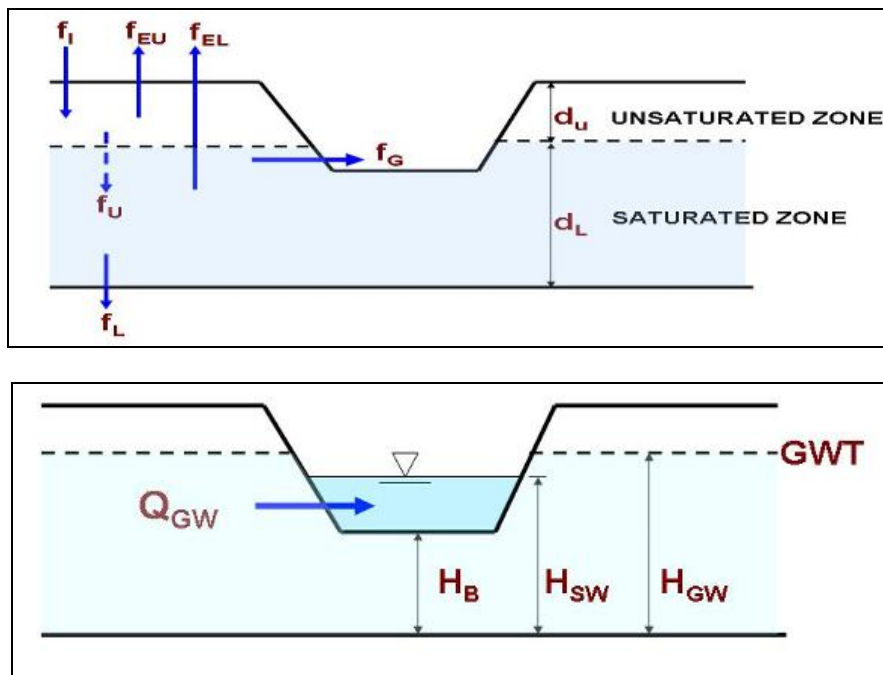


Figure 27: SWMM groundwater flow simulations: (top) system concept of SWMM groundwater flow; (bottom) user-defined power function to generate groundwater flow.

## 9. CATCHMENT CALIBRATION AND VALIDATION

The calibration of catchment models requires the determination of the set of model parameter values which maximise the goodness of fit between model outputs and the real response of the catchment for a given rainfall (input). This is accomplished by adjustments of control parameters in order to minimise prediction errors between observed and model generated flow data (Choi and Ball, 2002). Control parameters can be divided into two categories based on their estimation techniques.

**Measured Parameters:** Physically measured parameters such as stream cross section, catchment area, impervious fraction, rainfall intensity etc. These parameters are assumed error free and are not adjusted in the calibration process.

**Adjusted Parameters:** These parameters are not physically estimated, but rather are adjusted during the model calibration process in order to minimise prediction errors between observed and model computed flow data.

Two alternative techniques of parameter estimation are described in Choi and Ball (2002). The first technique is the modification of parameter values until both observed and computed hydrographs are well matched. The second technique is selection of parameter values on the basis of catchment hydrogeological characteristics. For example, selection of soil hydrologic properties (hydraulic conductivity and field capacity) from soil texture information. The first method is also called *trial and error* method. Several previous studies have used optimisation search technique to determine control parameters' value (Kuczera, 1983; Liong and Ibrahim, 1994). The *trial and error* approach is only applicable when monitoring data on rainfall and stream flow are available. This calibration process is shown in Figure 28. The reader should note that the actual computational process details will vary substantially depending upon the technique used, e.g., in some cases (as with the technique employed in this study) the output to recorded data loop is automated within an optimisation process.

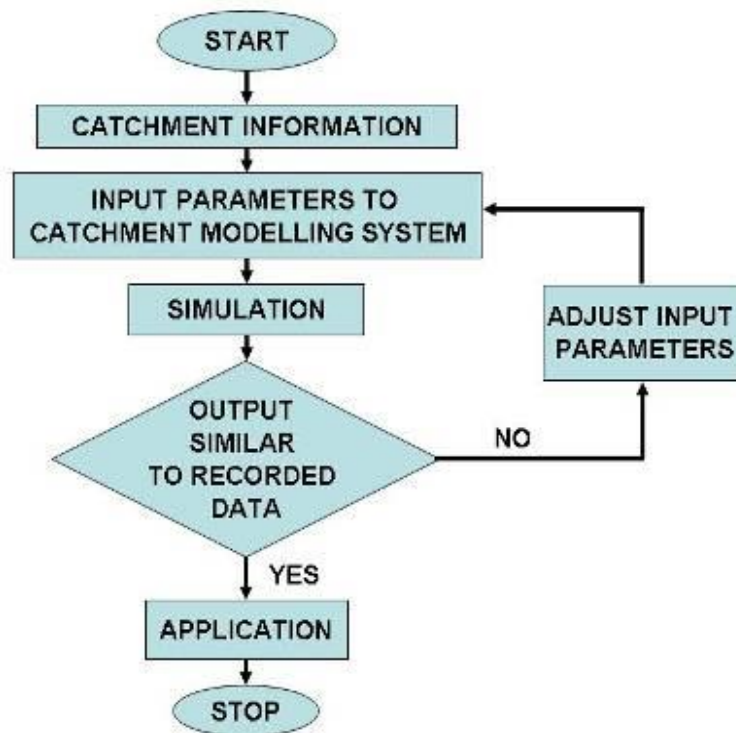


Figure 28: Schematic of the SWMM model calibration flow diagram (*trial and error* method).

## 9.1 Methodology

Observed streamflows from the SEQ catchments were used to calibrate and validate the SWMM. The calibration was used to adjust model parameter values so that the modelled flows agree with observed flow data to user specified criteria. These criteria can either be subjective (e.g., visual matching of flow hydrographs) or objective (e.g., comparing **Nash Sutcliffe efficiency (NSE)** (Nash and Sutcliffe, 1970)). Manual or automatic calibration methods or a combination of these can be used.

The ‘split sample testing’ approach is used in hydrologic modelling for calibration and validation to prepare the model for scenario prediction. In this approach, a part of observed data is used for calibration for parameter estimation and the other part is used for model validation to test the model’s capability for satisfactory prediction.

### 9.1.1 Model Calibration

Ten catchments in SEQ with varying degree of urbanisation were calibrated against the hourly streamflow data from 2009 to 2012. In the calibration, the model parameter was optimised using the shuffled complex evolution automated optimiser (Duan *et al.*, 1992) to maximise the objective function given by the NSE for hourly flow data.

NSE is a common measure of goodness of fit in water resource modelling and is calculated using Equation 30:

$$NSE = 1 - \frac{\sum(Q_o - Q_m)^2}{\sum(Q_o - \bar{Q}_o)^2} \quad (30)$$

where:

$Q_o$  is the observed flow,  $\bar{Q}_o$  is the mean of the observed flow and  $Q_m$  is the modelled flow.

The NSE is an estimate of the variance in model error between simulated and observed data. Values can vary from  $-\infty$  to 1, with 1 indicating a perfect fit, and a value of zero indicating that the model is no better than assuming an average flow over the period. A negative NSE value implies a bad prediction which is hard to interpret. Whilst undue influence of high flows can be an issue with NSE, it is considered a reliable statistic for assessing the goodness of fit of hydrological models and is recommended for a variety of model types (ASCE, 1993; McCuen *et al.*, 2006).

The use of hourly rainfall streamflow data was adopted to capture the rapid rise and fall of flows in urban catchments during a storm event. The time of concentration, a measure of travel time for water particle from the farthest point in the catchment to its outlet, of all catchments is more than one hour (see Table 1). Thus the SWMM modelling using a time step less than an hour was deemed unnecessary.

### 9.1.2 Automatic Optimisation

The shuffled complex evolution (SCE) algorithm used to optimise of the model parameters is a general purpose global optimisation program and is available as a MATLAB routine at <http://www.mathworks.com/matlabcentral/fileexchange/7671>. We coupled the SCE routine with the SWMM executable in MATLAB to develop a tool for the parameter optimisation.

Seven parameters of SWMM found to be most sensitive (Javaheri, 1998) were chosen for the optimisation. Those parameters were:

1. Overland flow width
2. Manning's  $n$  for pervious surface
3. Pervious depression store
4. Porosity
5. Field capacity
6. Hydraulic conductivity
7. Lower groundwater loss rate.

The first six parameters were changed in unison for all subcatchments but the lower groundwater loss rate was varied for each aquifer within a catchment (see Equation 29 and Figure 26). The optimisation to maximise the NSE using hourly observed and modelled flow was done by varying the above parameter values within predetermined upper and lower bounds.

### 9.1.3 Assessment of Model Performance and Model Robustness

Model performance refers to the ability of the models to reproduce observed hydrological patterns and can therefore only be tested retrospectively. Model performance was assessed using the NSE of both hourly and daily streamflows. A set of objective criteria were used to determine model performance. These included the model's ability to reproduce the observed runoff series with:

- (a) **hourly** NSE values greater than 0.5 in at least 90% of subcatchments; and
- (b) **daily** NSE values greater than 0.6 in at least 90% of subcatchments.

The model was assessed for its ability to represent the observed conditions within the calibration data period. Hourly and daily NSEs greater than 0.5 and 0.6 for the majority of catchments gives confidence in the calibrated parameter values used in the determinations of runoff for these time steps.

### 9.1.4 Validation

The data not used in calibration were used for validation. The purpose was to assess the model's potential performance for simulating catchment response to future input rainfall. Ideally, validation NSE should be as good as the calibration NSE. However, in reality, the validation NSEs are usually lower due to the shorter time series of data employed.

### 9.1.5 Input Data

The hourly rainfall data were obtained from the network of tipping bucket (0.2 mm) rain gauges installed for the project. The stream flow data were also obtained from the streamflow gauging stations. Although data from 2009 were available, providing about two years of rainfall and streamflow data for calibration/validation, data for the year 2009 and early 2010 suffered from frequent gaps and quality problems. Furthermore, 2009 was drier compared to 2010 and 2011. Therefore data mostly from 2010 and 2011 was used in calibration to expose the model to a range of flow conditions to determine a more robust parameter set.

## 9.2 Catchment Results

Table 4 shows the start and end dates for calibration and validation, and the daily and hourly NSE values for all 10 catchments. The hourly and daily calibration NSEs for nine of ten catchments are more than 0.5 and 0.6 respectively. This fulfils the criteria set for the good model calibration as described in Section 9.1.3.

## 9.2.1 Tingalpa Creek at Sheldon

One year of hourly data is used to calibrate the Tingalpa catchment with hourly and daily calibration NSEs of 0.49 and 0.64 respectively. The corresponding validation NSEs are 0.51 and 0.50. Except for one large event, the hourly observed and modelled streamflow during the calibration periods match reasonably well (Figure 29).

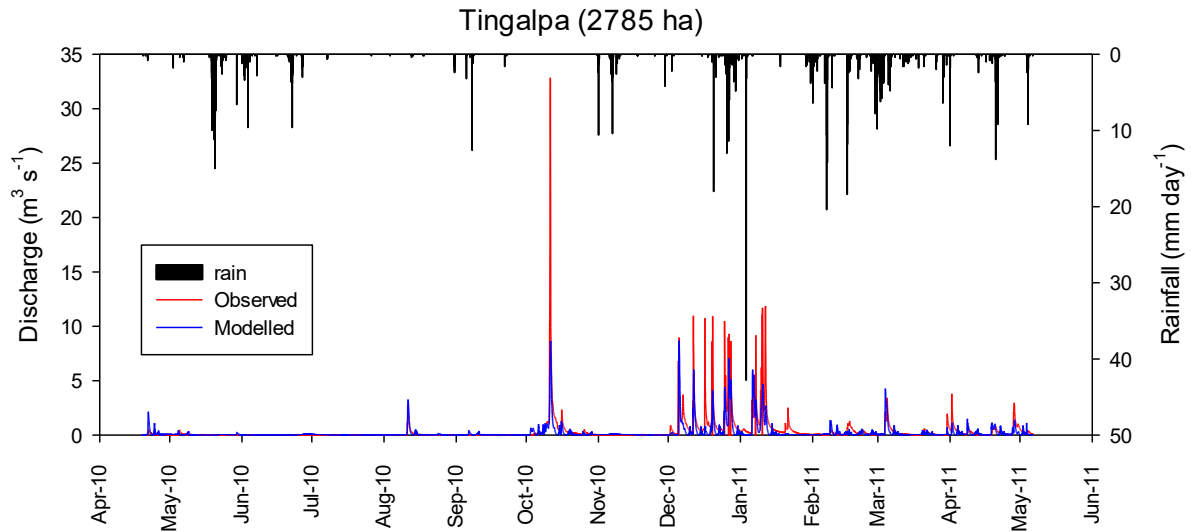


Figure 29: Observed and modelled hourly flows in Tingalpa catchment.

## 9.2.2 Upper Yaun Creek at Coomera

For the Upper Yaun Creek hourly observed and modelled streamflows events match quite well during the calibration (Figure 30) resulting in hourly and daily NSEs of 0.78 and 0.81 respectively. The hourly validation NSE is the lowest (0.33) of all the catchments, however the daily flow NSE is quite good (0.75). This could be due to the hourly time step for the observed not fully synchronised with the rainfall data.

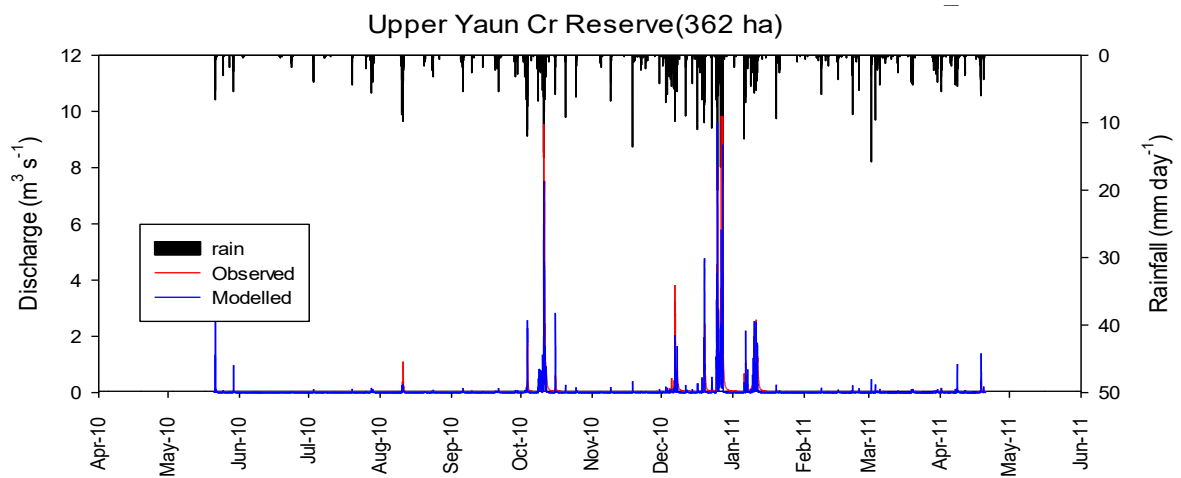


Figure 30: Observed and modelled hourly flows in Upper Yaun Creek catchment.

### 9.2.3 Scrubby Creek at Karawatha Forest

One year of hourly data is used to calibrate the Scrubby Creek catchment at Karawatha Forest with hourly NSE of 0.55. The hourly validation NSE is 0.59, giving reasonable confidence in the predictive ability of the model for future scenarios. Figure 31 shows that the model has not been able to capture the full extent of observed flow at the hourly time scale. However, as indicated by the daily calibration and validation NSEs (0.75 and 0.85 respectively), the matching of these flows at daily time scale is much better.



Figure 31: Observed and modelled hourly flows in Scrubby Creek catchment.

### 9.2.4 Blunder Creek (Daintree Crescent) at Forest Lake

The calibration for the Blunder Creek at Forest Lake runs from March 2010 to May 2011, with hourly calibration NSE of 0.55. The hourly validation NSE is 0.74. The daily calibration and validation NSEs are still better (Table 1) implying satisfactory modelling results at this time scale. Figure 32 shows the observed and modelled flow for the Blunder Creek for the calibration period.

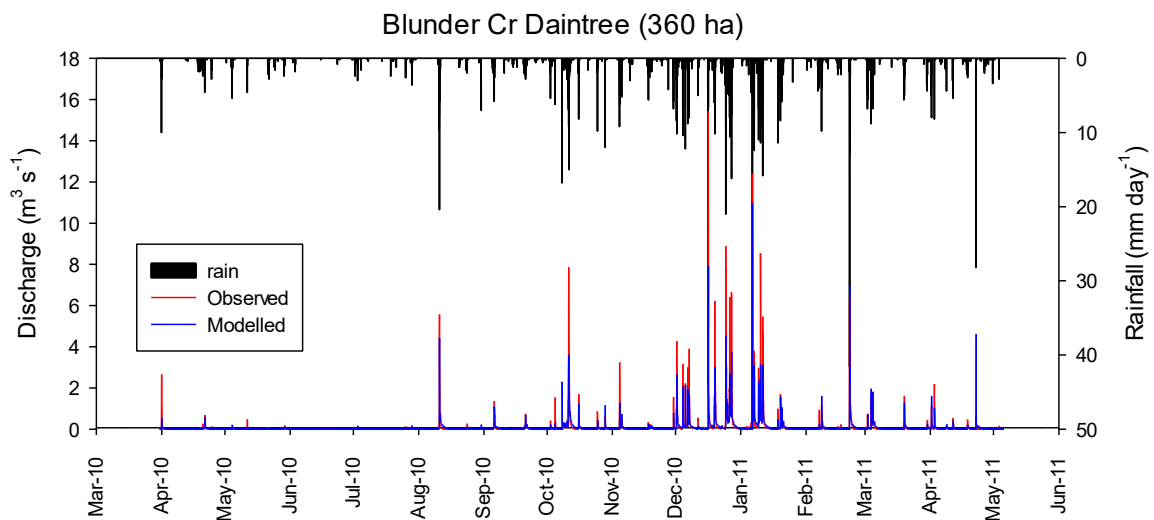


Figure 32: Observed and modelled hourly flows in Blunder Creek catchment at Forest Lake.

## 9.2.5 Stable Swamp Creek at Sunnybank

Seven months of hourly data is used in calibration for the Stable Swamp Creek (Figure 33) due to a lack of longer rainfall and runoff data without missing periods and suspect quality. The hourly calibration and validation NSEs are 0.60 and 0.81. Although these are good values, they have come from relatively smaller data set compared to that for the other catchments.

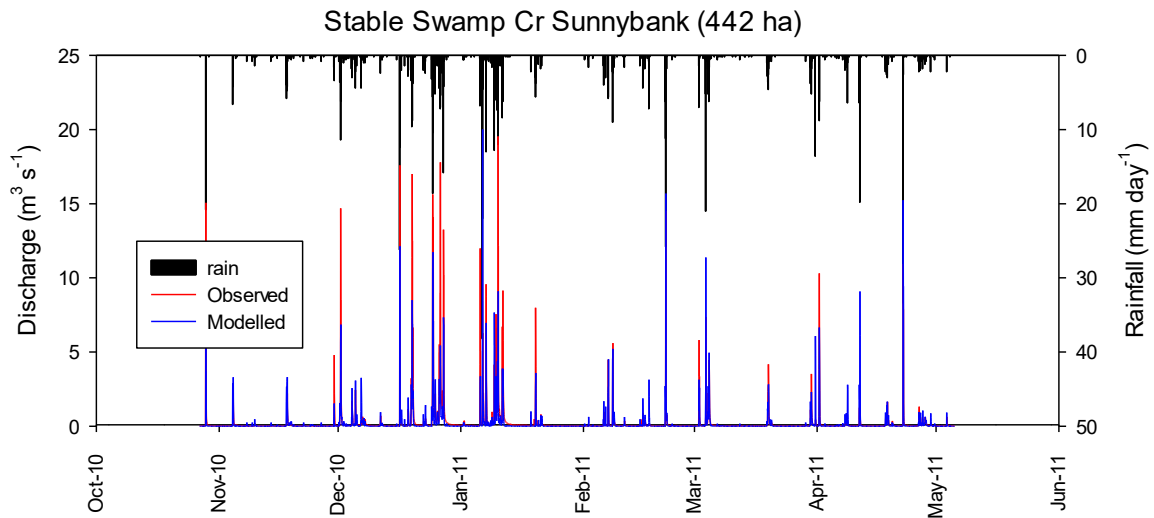


Figure 33: Observed and modelled hourly flows in Stable Swamp Creek.

## 9.2.6 Oxley Creek at Heathwood

Oxley creek is the smallest of the study catchment resulting in smaller observed flow (Figure 34). It was calibrated using a comparatively longer period of data with good hourly calibration and validation NSEs (0.59 and 0.66 respectively). This gives confidence in the calibrated model's ability for prediction.

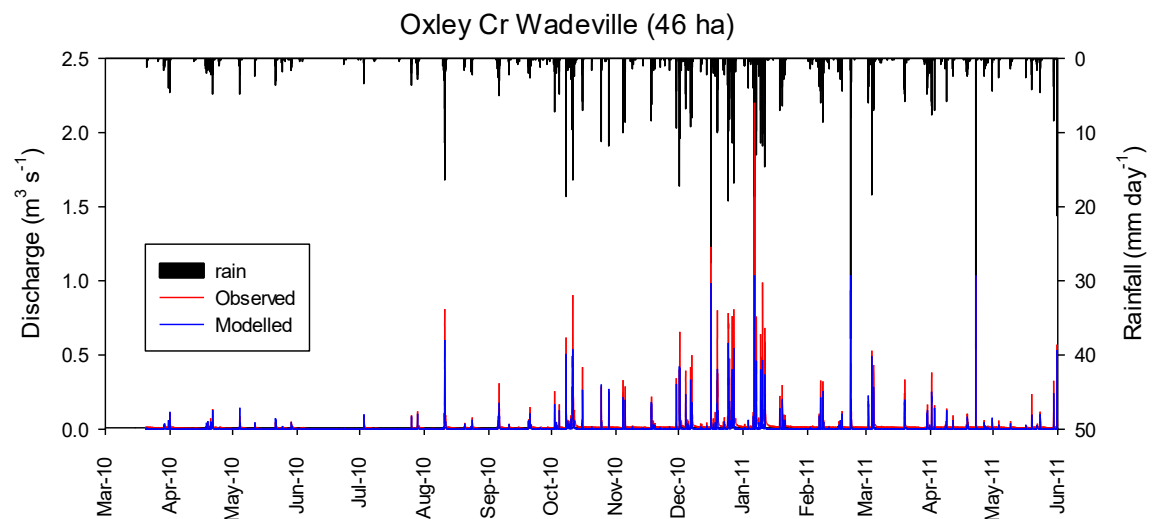


Figure 34: Observed and modelled hourly flows in Oxley Creek.

## 9.2.7 Pimpama River at Kingsholme

The hourly flow hydrographs for the Pimpama River shows (Figure 35) missing response for rainfall during October 2009. The hourly calibration is quite good at 0.6, while the validation NSE is lower. This is due to a lack of higher intensity rainfall during the validation period which failed to initiate quick runoff response in the model. The daily calibration and validation NSEs are better suggesting that the model is able to capture daily flows better than the hourly flows.

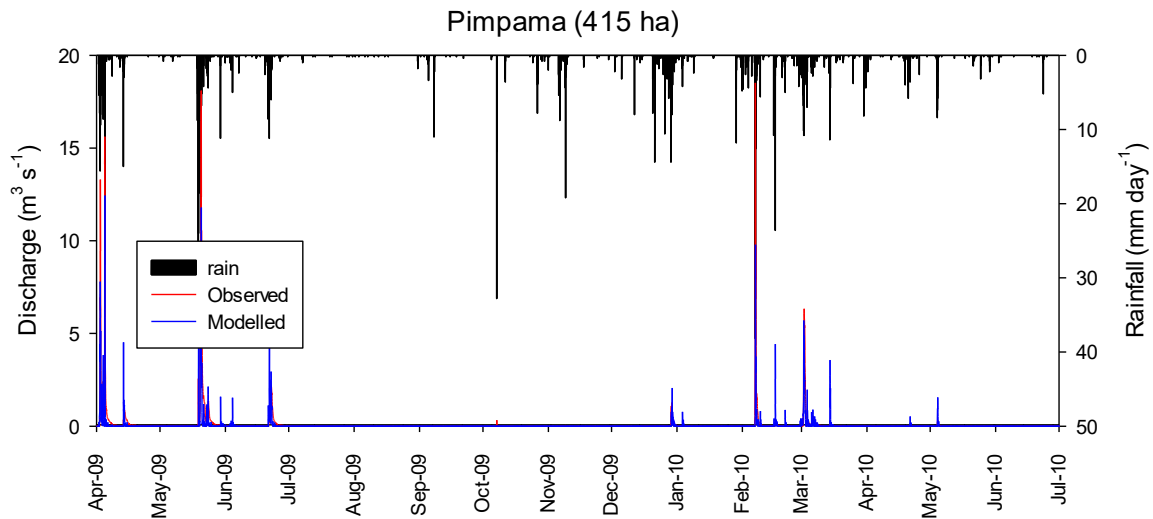


Figure 35: Observed and modelled hourly flows in Pimpama River.

## 9.2.8 Blunder Creek at Carolina Parade

The flow hydrographs for Blunder Creek catchment at Carolina Parade shows the model is simulating the flow events well (Figure 36). The hourly calibration NSE is quite good (0.68), while the hourly validation is also reasonable (0.52). The modelled runoffs at daily time scale are still better as indicated by the higher daily NSEs (Table 4).

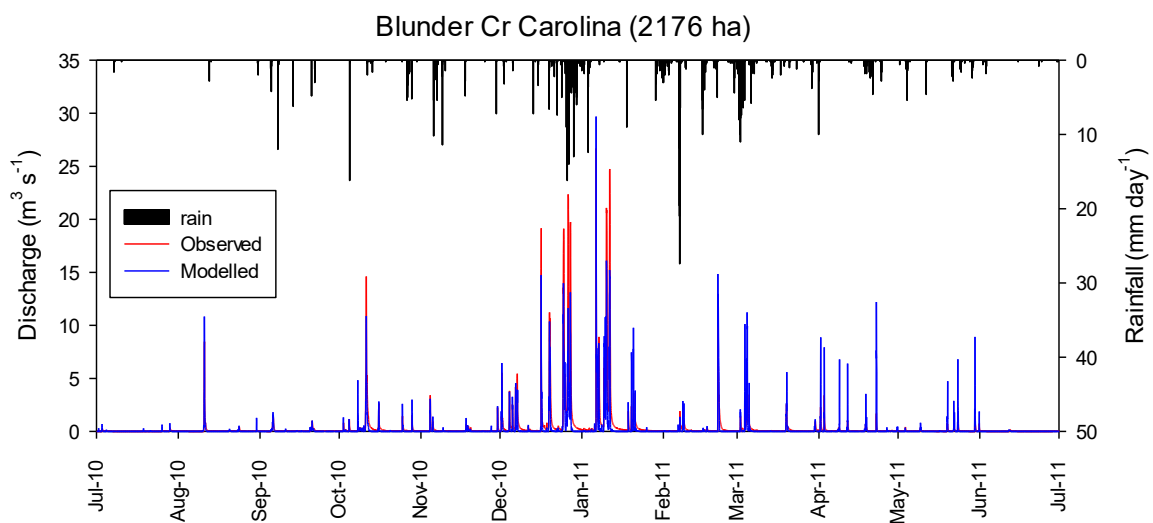


Figure 36: Observed and modelled hourly flows in Blunder Creek catchment Carolina Parade.

### 9.2.9 Sheepstation Creek at Parkinson

Figure 37 shows that the model was able to pick the flow event reasonably well for this catchment. The hourly calibration NSE is good (0.63), with slightly low validation NSE of 0.47. The daily calibration and validation NSEs show mixed results.

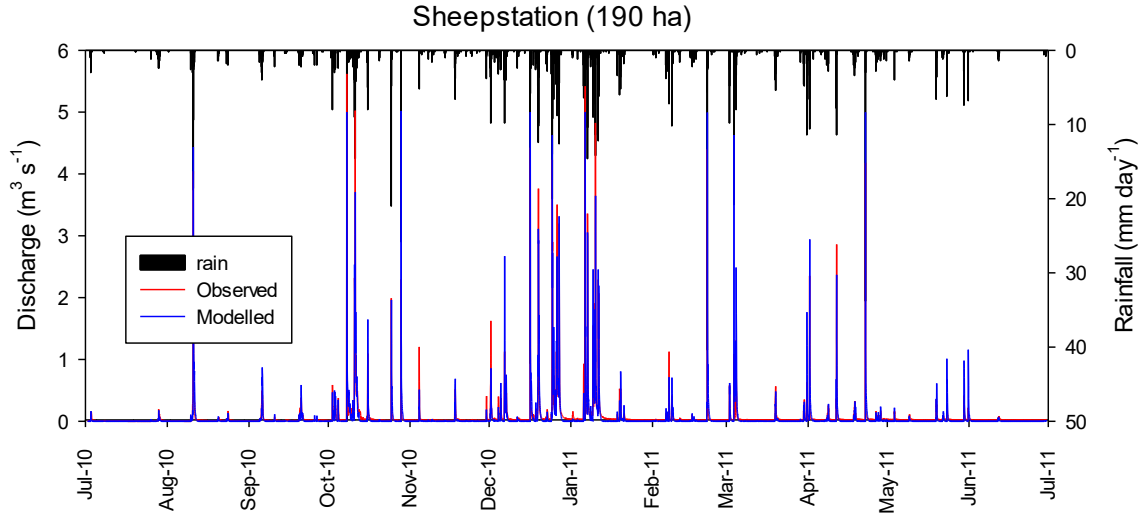


Figure 37: Observed and modelled hourly flows in Sheepstation Creek catchment.

### 9.2.10 Blunder Creek at Durack

Blunder Creek at Durack has reasonably good hourly and daily calibration NSEs (0.52 and 0.71 respectively). The model has picked up the timing of storm events well (Figure 38). The hourly validation is less than the corresponding calibration NSE however the daily validation NSE is quite good (Table 4).

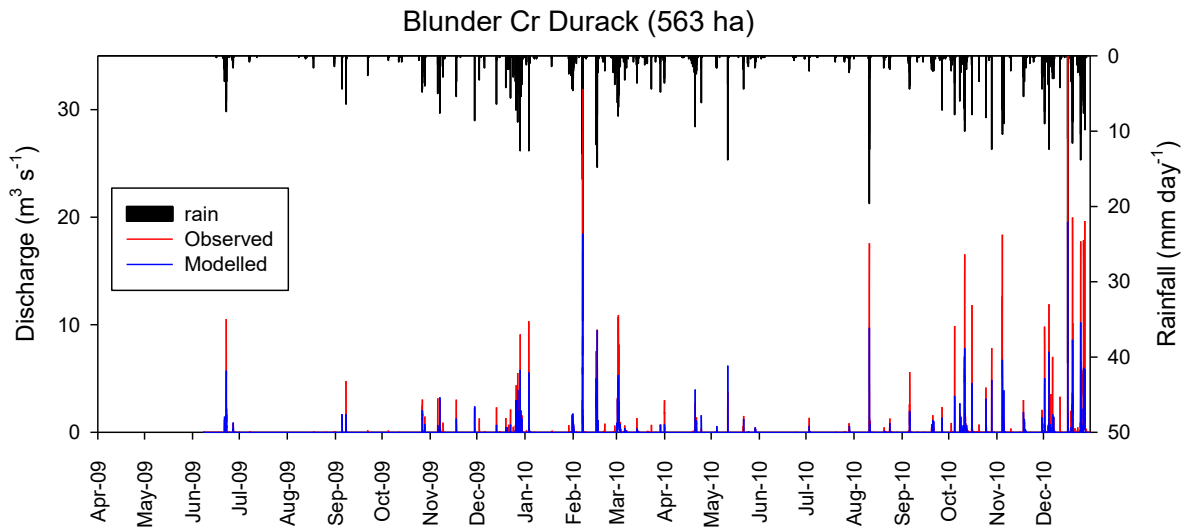


Figure 38: Observed and modelled hourly flows in Blunder Creek catchment Durrack.

### 9.3 Overview of Calibration and Validation Results

Table 4 below provides an overview of the calibration and validation results for all the catchments, describing the data periods used, the separate calibration and validation NSE scores.

**Table 4: Calibration and validation results for 10 catchments in SEQ. NSE is the Nash Sutcliff Efficiency value, a measure of the goodness of fit.**

| Creek / River              | Location         | Area (ha) | Calibrat'n Start | Calibrat'n End | Validation Start | Validation End | Hourly Calibrat'n NSE | Hourly Validation NSE | Daily Calibrat'n NSE | Daily Validat'n NSE |
|----------------------------|------------------|-----------|------------------|----------------|------------------|----------------|-----------------------|-----------------------|----------------------|---------------------|
| Tingalpa Ck                | Sheldon          | 2,785     | Apr-2010         | May-2011       | Mar-2009         | Sep-2009       | 0.49                  | 0.51                  | 0.64                 | 0.50                |
| Stable Swamp Ck            | Sunnybank        | 442       | Oct-2010         | May-2011       | April-2009       | Sep-2009       | 0.60                  | 0.81                  | 0.73                 | 0.87                |
| Upper Yaun Ck (Reserve Rd) | Upper Coomera    | 362       | May-2010         | April-2011     | Aug-2009         | Jan-2010       | 0.78                  | 0.33                  | 0.81                 | 0.75                |
| Scrubby Ck                 | Karawatha Forest | 144       | Apr-2010         | Apr2011        | Jun-2009         | Dec-2009       | 0.55                  | 0.59                  | 0.75                 | 0.85                |
| Blunder Ck (Daintree Ck)   | Forest Lake      | 360       | Mar-2010         | May-2011       | May-2009         | Oct-2009       | 0.55                  | 0.74                  | 0.77                 | 0.83                |
| Pimpama R                  | Kingsholme       | 415       | Apr-2009         | Jun-2010       | July-2010        | Dec-2011       | 0.60                  | 0.44                  | 0.72                 | 0.75                |
| Blunder Ck                 | Carolina Pde     | 2,176     | Jul-2010         | Jun-2011       | July-2011        | Dec-2011       | 0.68                  | 0.52                  | 0.75                 | 0.72                |
| Oxley Ck (Wadeville St)    | Heathwood        | 46        | Mar-2010         | Oct-2011       | Mar-2011         | Dec-2011       | 0.59                  | 0.66                  | 0.54                 | 0.59                |
| Sheepstation Ck            | Parkinson        | 190       | Jul-2010         | Jun-2011       | July-2011        | Dec-2011       | 0.63                  | 0.47                  | 0.85                 | 0.31                |
| Blunder Ck                 | Durack           | 563       | Jun-2009         | Dec-2010       | Jan-2011         | Dec-2011       | 0.52                  | 0.42                  | 0.71                 | 0.78                |

## 10. SUMMARY AND NEXT STEPS

Having selected a set of 12 creek catchments in SEQ to represent a range of urbanisation extents from no impervious area through to significant IA, and with (prototype) water sensitive urban design features in the built environment in some of the catchments, a GIS based method for IA determination from aerial photographs was developed. This method was used to characterise each catchment in terms of percentage of total IA (TIA), which enabled the construction and parameterisation of a set of SWMM catchment models. In parallel with this activity, the flow of each of the creeks was gauged and rating curves developed. Flow data was gathered along with rainfall data for over two years for each catchment to allow each SWMM model to be calibrated and then validated against a separate length of flow data.

Despite the time series of available flow data being relatively short by hydrological standards, most models were both calibrated and validated with an NSE of  $> 0.5$ . In a few cases, the calibration NSE was  $> 0.5$ , whilst the validation was slightly under 0.5. The calibration technique used selected the optimal set of parameter values to maximise NSE, so the goodness of fit cannot be improved further without more flow data.

Having developed this set of sufficiently well calibrated and validated SWMM catchment models, the task is now to use those models with extended (20- to 30-year) rainfall time series to generate 20- to 30-year flow time series. Having a set of long term (simulated) flow time series for each catchment will enable the flow regime and metrics to be characterised with confidence, and the impact of different stormwater management actions on each catchment to be evaluated. This work is reported on separately.

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