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Hydrological data monitoring for urban stormwater drainage systems

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Abstract

Good quality hydrologic data are required to develop and calibrate simulation models, which are often used to plan, design and upgrade urban stormwater drainage systems. These good quality data can be obtained from a successful data collection program. This paper describes the issues that should be considered in conducting such a successful and cost-effective hydrologic data monitoring program. The issues addressed include considerations given in the selection of suitable monitoring sites, the selection of appropriate measuring equipment and the calibration and installation of the measuring equipment. Furthermore, the techniques that were used to test the accuracy and consistency of the measured data are also outlined. In addition to these issues, the effects of rainfall measuring resolution of pluviometers and data logging interval of flowmeters on the accuracy of rainfall and stormwater runoff data, and computer modelling results were investigated. These investigations revealed that tipping bucket resolutions up to 0.5 mm would give reasonably accurate results in urban stormwater modelling. A two-minute data logging interval was found to be suitable for flow data monitoring. The results of the investigations also suggest that a combination of low cost simple flow measurements and limited high cost sophisticated measurements can be used to reduce the data acquisition cost without compromising the accuracy of flow hydrographs measured in stormwater conduits.

Keywords: Hydrologic data; Data acquisition; Mathematical model; Monitoring; Urban drainage

1. Introduction

Simulation models, which consider complex hydrologic and hydraulic processes of urban catchments are often used to plan, design and upgrade urban stormwater drainage systems. The model parameters of these urban stormwater drainage simulation models are often estimated based on the recommendations and guidelines given in user manuals and in the literature. However, accurate and reliable model results can be achieved through calibration of model parameters using good quality hydrologic data. Such good quality hydrologic data can be obtained through a well-designed and implemented data collection program, which is often an important component of any urban stormwater drainage investigation. However, the cost of field data collection often constitutes a significant proportion of the total cost of an urban stormwater drainage investigation. Therefore, careful attention should be paid to the selection of suitable monitoring sites and appropriate measuring equipment, and the proper instrumentation, operation and maintenance of such measuring equipment.

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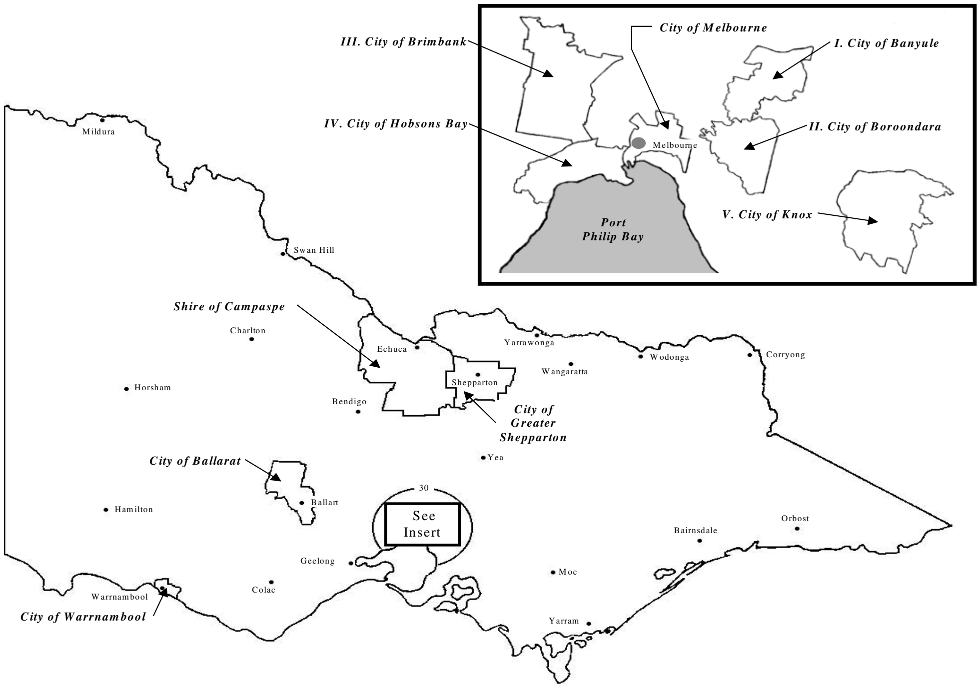


Fig. 1. Locations of collaborating city/shire councils in Victoria, Australia.

This paper describes the issues considered in a major hydrologic data acquisition program. These issues include the selection of suitable study catchments and measuring equipment, as well as the calibration and installation of the selected equipment. The selection of appropriate measurement resolution for pluviometers and data logging interval for flowmeters is also presented. To reduce the monitoring cost, the possibility of using inexpensive flow depth monitors and a small number of sophisticated flowmeters is investigated. The paper also analyses the effect of time resolution of rainfall and runoff measurements on urban stormwater simulation model results.

2. The urban stormwater drainage monitoring project

Good quality hydrologic data are not presently available for most urban catchments in Victoria, Australia. Consequently, the School of the Built Environment of Victoria University of Technology, in collaboration with ten widely dispersed municipal councils in Victoria, undertook a major research project in 1996, to acquire high quality hydrologic data from 26 urban catchments. The locations of the collaborating councils are shown in Fig. 1.

The 26 catchments were continuously monitored for rainfall and stormwater runoff for three years. For each catchment, stormwater runoff was monitored at the catchment outlet and at one or two upstream locations. The catchments were selected to ensure that different catchment characteristics and hydraulic systems were represented. Also, some specific catchments identified by the collaborating councils as critical with respect to susceptibility to present and future flooding were monitored. The sizes of the catchments ranged from 8 to 3000 ha. The characteristics of monitored catchments include different land use characteristics (e.g. residential, commercial, industrial and some rural areas) and physical characteristics (e.g. slope of terrain, drainage pipe sizes and different soil types). The physical properties and land use characteristics of study catchments are summarised in Table 1. All catchments have pipe drainage systems except those in the City of Ballarat (i.e. BALL1,

Table 1
Properties of study catchments (R: residential; C: commercial; I: industrial, U: undeveloped)

Catchment	Area (ha)	Maximum pipe size (mm) or maximum channel base width (m)	Land use	Council
BALL1	580.0	Channel (2)	R, C and U	Ballarat
BALL2	560.0	Channel (2.5)	R and C	
BALL3	3000.0	Channel (11.5)	R, C and U	
BANY1	29.3	1200	C and R	Banyule
BANY2	44.5	1350	R	
BANY3	42.5	850	R	
BORO1	15.8	1050	R	Boroondara
BORO2	17.2	670	R	
BRIM1	7.7	760	R	Brimbank
BRIM2	38.5	900	R	
BRIM3	19.9	1200	I	
ECHU1	183.2	1050	C and R	Campaspe
ECHU2	184.7	1050	R, C and U	
ECHU3	75.5	825	R	
HOBS1	9.7	900	R	Hobsons Bay
HOBS2	13.8	600	R and I	
KNOX1	22.0	760	R	Knox
KNOX2	30.2	670	R	
KNOX3	41.3	1050	R	
MEL1	22.8	760	C and R	Melbourne
MEL2	59.7	1300	C	
MEL3	24.0	1200	C and R	
SHEP1	152.2	1050	C, R and I	Shepparton
SHEP2	33.8	1200	C	
SHEP3	164.9	1050	R	
WAR	105.0	1650	R and C	Warrnambool

BALL2 and BALL3 in Table 1), which have open channels for drainage. The City of Ballarat catchments also have a larger rural area (or undeveloped area), making them larger than the other catchments (Table 1).

2.1. Selection of measuring equipment

The type of measuring equipment should be selected to suit the data requirements of the investigation. In this study, complete rainfall hyetographs and runoff hydrographs were required to calibrate and test urban stormwater drainage simulation models. Therefore, pluviometers and flowmeters with data loggers were selected for the data acquisition program for continuous rainfall and runoff measurements.

2.1.1. Rainfall measuring equipment

Tipping bucket pluviometers are widely used to monitor the temporal pattern and the magnitude of storm events. Since this type of pluviometers records the time at which rainfall occurs (i.e. the time of tip), it gives a good representation of the temporal rainfall distribution. Furthermore, battery power and memory space are efficiently utilised, since no recordings are taken during dry weather periods. Therefore, the automatic electronic tipping bucket pluviometer (Monitor Sensors, 1991) was selected in this project to measure rainfall. The selected pluviometer has a tipping resolution of 0.2 mm (i.e. one tip of the bucket is equivalent to 0.2 mm of rainfall). A comparison of the accuracy of other tipping resolutions is discussed in Section 2.4.

2.1.2. Flow measuring equipment

The selection of the most appropriate type of flowmeter was based on the following factors:

1. suitability of the flowmeter for continuous monitoring of velocity and depth of flow;
2. suitability for installation and operation in drainage pipes under wet and submerged conditions;
3. accuracy of measurements;
4. ease of installation, operation and maintenance;
5. cost of the equipment.

Although there are a number of different types of flowmeters available on the market, the majority of them are designed for laboratory use with clean water. Of the flowmeters that can be used for field applications, the common type is non-intrusive flowmeters that measure discharge without any contact with the liquid. These non-intrusive flowmeters are not suitable for this project, since many of the stormwater drainage systems are underground pipe systems for which these flowmeters cannot be installed. Some of the sufficiently robust and accurate intrusive type flowmeters are very expensive and/or not suitable for measuring small flows because they are large and can create excessive interference for the magnitude of flows expected in most urban stormwater drainage conduits. Thus, an ultrasonic doppler type flowmeter, STARFLOW (Unidata Australia, 1996), which is an intrusive type flowmeter was selected to measure the stormwater runoff. STARFLOW measures flow depth and velocity separately. This flowmeter can measure flow depths up to 5 m and velocities ranging between 0 and 4.5 m/s. The ultrasonic flowmeter has been used for a number of other monitoring projects in Australia (e.g. Allison and Chiew, 1995; Williams and Daniell, 1997).

2.2. Laboratory/field testing and calibration of equipment

All measuring equipments (i.e. pluviometers and flowmeters) should be tested and calibrated to ensure that they work properly and produce accurate rainfall and runoff measurements.

2.2.1. Calibration of pluviometers

The pluviometers were calibrated in the laboratory prior to installation and in the field periodically (approximately once in every 18 months) after installation. As recommended by Monitor Sensors (1991), the tipping bucket settings of pluviometers were adjusted to give the correct number of tips, when a known quantity of water was added to the pluviometer during pluviometer calibration.

2.2.2. Calibration of flowmeters

The flowmeters are installed at the invert of drainage pipes or at the centre of stormwater channels to measure flow depth and velocity. The flowmeter transmits a continuous ultrasonic signal at a 30° angle to the horizontal. The change of frequency (or the doppler shift) of the signals reflected back by particles (or scatterers) moving with the flow is detected by the electronic components of the flowmeter. The velocity of particles is related to the corresponding doppler shifts. Since the flowmeter measures the signals returning from particles along a beam, these signals are resolved to produce a depth-averaged velocity in the section of the stormwater conduit that receives ultrasonic signal.

The depth-averaged flow velocity is not necessarily the mean flow velocity in the pipe or channel, because the velocity at the centre, which receives most of the ultrasonic signals, is generally higher than that close to the boundary (Chow, 1958; Henderson, 1966). Consequently, correction factors should be applied to the stormwater flow based on the measured velocity, especially for large pipes (diameter >750 mm) and wide channels. These correction factors can be obtained by calibration of the flowmeters in channels with different sizes and shapes, under different flow conditions.

Flowmeters were calibrated prior to installation in two rectangular laboratory flumes, 8 m long, 100 mm wide and 15 m long, 500 mm wide. The calibrations were done for different flow conditions (i.e. laminar and turbulent) with flow velocities up to about 2 m/s and flow depths up to 250 mm. Since flowmeters can be installed in the field with their velocity sensors facing either upstream or downstream direction of flow, calibration was done for both settings in the laboratory flumes. The results of laboratory calibrations indicated that the discharges obtained with flowmeters were within ±10% of the actual discharge. The results were similar for both cases with the velocity sensors facing upstream or downstream.

Field calibration of flowmeters was undertaken in rectangular (1.25 m × 0.9 m) and trapezoidal (bed width of 1.27 m and side slopes of 1 on 1.5) irrigation canals. These canals were not part of the monitored catchments and used only for field calibrations. The discharges in the canals were computed with flowmeter measurements at the centre of the canals. Those discharge values were compared with the values calculated using direct depth measurements and the measurements of local velocities at a number of locations across the canal section. The local velocities were measured with a pre-calibrated ultrasonic doppler spot velocity gauge.

Field calibrations in the rectangular channel indicated that the discharge obtained with the flow depth and velocity measurements at the centre of the channel was up to 30% higher than the actual discharge. However, for the trapezoidal canal with a wider base than the width of the rectangular channel, the error in the discharge obtained with velocity measurements at the centre was within 10% of the actual discharge. The larger error for the rectangular channel is due to low velocity zones around the corners of a rectangular channel.

In situ field calibrations were also carried out at a flow monitoring site, during a storm event. The diameter of the pipe at the site was 670 mm. When compared with pipe sizes in Table 1, this pipe is one of the smallest. However, Table 1 shows only the details of the outlet pipes of the catchments. In general, for each catchment in Table 1, there were two other measurement points, which had pipe diameters normally in the range 375–450 mm. Therefore, most pipe diameters at flow measurement points had diameters smaller than 670 mm. This particular in situ site was selected due to the following reasons:

1. the site was not far from the University and therefore, it was easy to reach the site during a storm event;
2. the site consists of a continuous pipe through the manhole with access for flow measurements from the opening on the top of the pipe. Flow is continuous at the manhole. This manhole is different to the standard manholes, where pipe is discontinuous at the manhole;
3. larger pipes are generally laid at greater depths and thus difficult to use the spot velocity gauge for flow velocity measurements. The selected pipe was at a reasonable depth and hence was suitable to work with the spot velocity gauge;
4. operator safety was also considered as an issue in selecting the site in terms of accessibility, depth of pipe from the road, flow measurements from the road, etc.

Stormwater discharge was obtained using local velocities measured at three points across the cross section of flow, using an ultrasonic doppler spot velocity gauge. This calibration was done during a steady, relatively long duration (i.e. about 30 min) storm, so that the flow inside the pipe was steady during measurements. Calibration was done for flow depths of 100 and 112 mm. The results of in situ calibration revealed that the errors in discharges obtained with the flowmeter on the invert of the pipe (i.e. flow depth and depth-averaged velocity measurements at the mid-section of the flow) were within 5% of the actual discharge. It can be expected that the error in discharge measurements in the pipes described in Table 1 (even with larger pipe diameters compared to that of the in situ calibration) to be within 10%, since it has shown that the error in the field trapezoidal channel with the base width of 1.27 m was within 10%. The lower velocity areas in a circular channel are less compared to trapezoidal (and especially rectangular) channels, giving lesser error margins.

Based on the calibration of flowmeters discussed above (i.e. laboratory, field and in situ calibrations), the errors in flow rates obtained from flow measurements of this study were expected to be within 10% of the actual flow rates. In all these calibrations, it was found that the flow measurements at the centre of the pipe produced flow rates that were higher than the actual flow rates. An error margin of this magnitude (i.e. 10%) is within the hydrographical accuracy of such measurements. However, for wide stormwater drainage channels of the City of Ballarat catchments, the error in the computed flow based on velocity and depth measurements using the ultrasonic flowmeter at the centre of the channel was expected to be higher (i.e. greater than 10% error). This is because the base widths of channels vary between 2 and 11.5 m at the monitoring stations, which are significantly larger compared to the width of the irrigation canal considered in the field calibrations. Therefore, rating curves (i.e. relationships between flow depth and discharge) were developed for these drainage channels. The discharges for rating curves were obtained through measurements of local flow velocities at number of points across the cross section of the channel. The depth at the centre of the channels was measured in the monitoring program using the ultrasonic flowmeters and this depth was converted to the discharge using the rating curves.

2.3. Installation of measuring equipment and data retrieval

2.3.1. Installation of measuring equipment

The measuring equipment should be properly installed at carefully selected sites to obtain good quality data. Since the areal distribution of rainfall varies over urban catchments that exceed a few square kilometres in size, a number of pluviometers may be required to measure the rainfall. However, there are no guidelines available on the required pluviometer network density for modelling urban areas. One pluviometer plus an additional pluviometer for every 4 km^2 of relatively flat catchments have been suggested in Water Authorities Association/Water Research Centre (1987), for realistic simulation of rainfall in mathematical models. Certainly, the economics and the suitability of the location of the pluviometer sites dictate the pluviometer network density. For research projects, such as the one described in this paper, dense networks are likely, but in practice, it is unlikely that dense networks are used due to economic reasons. This is certainly the case in Melbourne metropolitan area in Victoria (most of the study catchments are in this area), where the pluviometer density is coarser than 1 in 4 km^2. However, it should be noted that these pluviometers were installed for use in flood studies and flood warning in much larger catchments.

As shown in Table 1, the majority of selected catchments in this study were much smaller than 4 km^2 (i.e. ranging from 0.08 to 1.85 km^2) except the three catchments in Ballarat (areas from 5.6 to 30 km^2). Therefore, one pluviometer was installed at a location close to the centre of each small catchment. Four pluviometers were used to cover three relatively large catchments in Ballarat. Ideally, the pluviometers should be installed at ground level to reduce wind turbulence effects. However, they can be subjected to vandalism, when they are placed in open spaces at ground level. Therefore, the pluviometers were installed on roofs of short buildings where there is no obstruction from surrounding structures or tall trees, and relatively safe and secure against vandalism.

The flowmeters were installed at the outlets of catchments and on average at two upstream locations in each catchment. When selecting the locations for installation of flowmeters, the following factors were taken into account:

1. whenever possible, flowmeters were installed in stormwater pipes at a distance of, at least, $2D$ (where D is the diameter of pipe) from a manhole to minimise non-uniform flow conditions and interference caused by the manhole and flows converging at the manhole;
2. flowmeters were installed in straight sections of the pipe, to avoid skewed flow patterns at the flowmeter;
3. sites with reasonably flush manhole and pipe inverts were selected to avoid the excessive turbulence at the flowmeter;
4. sites prone to silting were not selected because the flow depth and velocity measurements could be severely affected by silt;
5. pipes of very flat gradients, where flow velocities can be extremely low, were avoided because the doppler signal of the flowmeter could be insensitive resulting in inaccurate velocity measurements;
6. special attention was paid to install the flowmeters at sufficient distance away from hydraulic features that affect the flow pattern, such as backdrops and drop shafts. These features could create gradually varied flow conditions that are undesirable at the monitoring sites;
7. pipe sizes less than 375 mm were not selected because it was difficult to install flowmeters inside such small pipes. Furthermore, there could be unacceptable disturbance when flow passes over and around the flowmeter.

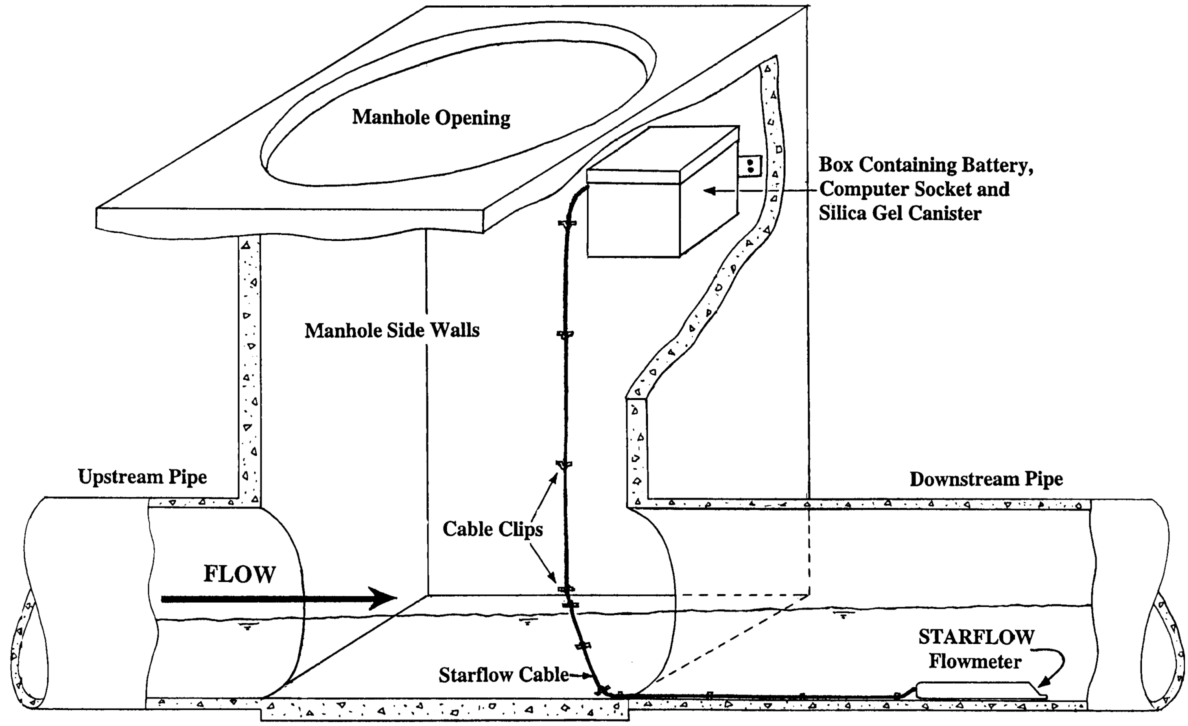


Fig. 2. Installation of a flowmeter in a stormwater pipe.

As stated earlier, most drainage systems considered in this project consisted of a network of underground pipes, except in few places where open channels were used. Therefore, the flowmeter installations in these cases were in confined spaces inside underground conveyance systems. An example of flowmeter installation is shown in Fig. 2. The flowmeter was fixed to the invert of the pipe with anchor screws or with a stainless steel clamping ring, and the communication cable of the flowmeter was secured and run along the pipe and manhole side-walls into a weather proof box. This box contained a 12 V DC battery to power the flowmeter, a computer socket connection for configuration and retrieval of data from the flowmeter, and a tube full of silica gel to absorb any moisture in the vent tube of the depth sensor. This box was located close to the top cover of the manhole so that it could be opened from outside and the data could be retrieved without entering underground pipes. When the stormwater flow in open channels have to be monitored, flowmeters were installed inside culverts or under bridges to reduce the susceptibility of the flowmeters to vandalism.

As indicated in Section 2.2.2, the testing carried out in laboratory flumes showed that the measured discharges were similar for both upstream and downstream facing sensor settings. When the velocity sensors of flowmeters face upstream in stormwater conduits, they are prone to damage by heavy objects and sediments in stormwater flow. Therefore, the flowmeters were installed in stormwater conduits with their velocity sensors facing downstream, as shown in Fig. 2.

2.3.2. *Data retrieval from the field*

Rainfall and stormwater runoff data of storm events are stored in the memory of data loggers built into pluviometers and flowmeters, respectively. These data were retrieved, loggers emptied (or re-set) and batteries changed at appropriate intervals to avoid losing data due to insufficient logger capacity and battery power.

The data retrieval effort for pluviometers does not

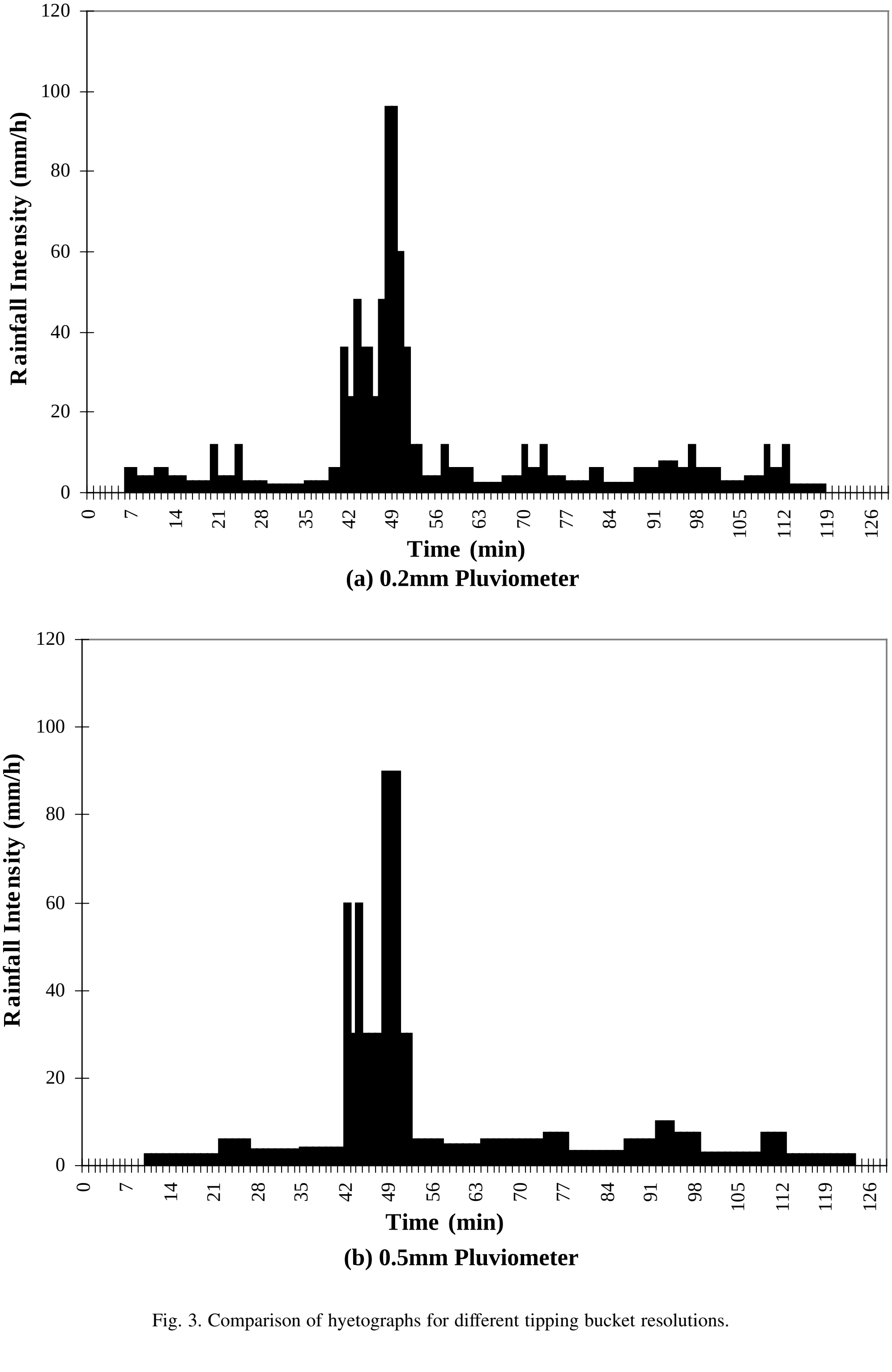


Fig. 3. Comparison of hyetographs for different tipping bucket resolutions.

Table 2
Summary of hydrograph attributes for different logging intervals (% change is computed with respect to one-minute logging value)

	Logging interval (min)	Flow depth (mm)		Velocity (m/s)		Runoff (m^3/s)		Time to peak runoff (min)	
		Peak	% change	Peak	% change	Peak	% change	Peak	% change
Event 1	1	334		2.147		0.458		31	
	2	333	−0.3	2.099	−2.2	0.458	0	31	0
	4	309	−7.2	2.075	−3.4	0.411	−10.3	31	0
	6	280	−16.2	2.028	−5.5	0.300	−34.5	35	12.9
Event 2	1	263		1.831		0.297		21	
	2	259	−1.5	1.821	−0.5	0.294	−1.0	21	0
	4	237	−9.9	1.758	−4.0	0.270	−9.1	23	9.5
	6	236	−10.3	1.719	−6.1	0.264	−11.1	23	9.5
Event 3	1	427		2.127		0.602		94	
	2	413	−3.3	2.040	−4.1	0.583	−3.2	94	0
	4	358	−16.2	1.991	−6.4	0.462	−23.3	94	0
	6	313	−26.7	1.970	−7.4	0.415	−31.1	100	6.4

largely depend upon the tipping resolution. Since the tips occur only during storm events, pluviometer battery power is greatly conserved. The power required to detect a tip and record in the logger is extremely small. A fully charged battery is sufficient for about six months under normal weather conditions. However, in order to reduce the risk of data loss due to battery failure and equipment malfunction, rainfall data stored in pluviometer loggers were downloaded into a notebook computer at two-month intervals.

The duration for which the data can be stored in the logger of the flowmeter depends on the memory capacity of the logger and the data logging interval. In this study, a two-minute logging interval was adopted to obtain a good representation of runoff hydrographs. The selection of the appropriate logging interval for flowmeters is discussed in Section 2.4. With a two-minute logging interval, the stormwater flow data could be stored in the logger up to about five weeks. Hence, the flow data were retrieved and the flowmeter loggers emptied at four-week intervals.

During each data retrieval visit, pluviometers and flowmeters were cleaned of any debris and their important components were checked for damage. Also, a report or a site check sheet was filled out during every site visit, so that a quality assurance record on each instrument was maintained. All collected data were kept in a database with backup copies stored on compact discs.

2.4. Data logging interval

Many of the commercially available tipping bucket type pluviometers have resolutions of 0.2 mm or greater. The effect of the tipping resolution on the measured rainfall hyetograph was investigated by operating two pluviometers with resolutions of 0.2 and 0.5 mm at the same location and comparing the data obtained from them. The rainfall hyetographs of a selected storm event obtained with two pluviometers are shown in Fig. 3. The 0.2 mm pluviometer is expected to give more realistic representation of the temporal pattern of storm events, since it gives more tips at shorter time intervals than the 0.5 mm pluviometer. As indicated in Fig. 3, the 0.5 mm pluviometer smoothed out the hyetograph during low intensity rainfall periods. However, this ‘smoothing out’ effect in high intensity rainfall period of the storm event is not significant. For the storm event shown in Fig. 3, both 0.2 and 0.5 mm pluviometers gave the same peak rainfall intensity (i.e. 90 mm/h) and similar rainfall totals (i.e. 17.8 and 18.0 mm for 0.2 and 0.5 mm pluviometers, respectively). The effect of the tipping resolution of pluviometers on urban stormwater simulation model output is discussed in Section 2.7.

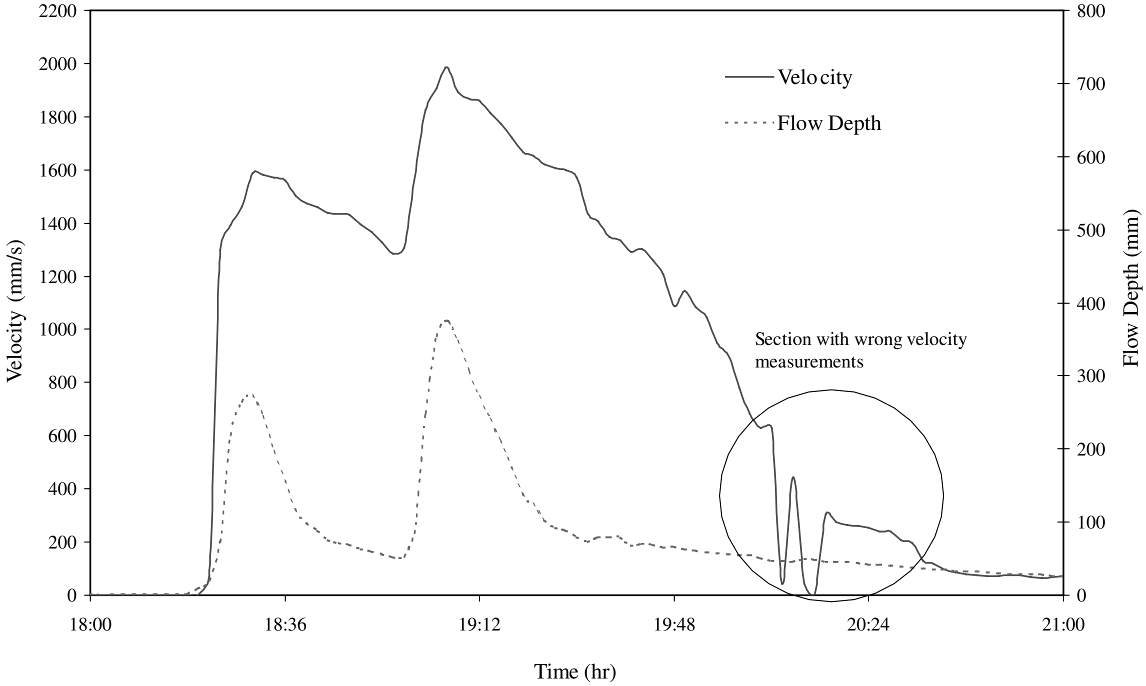
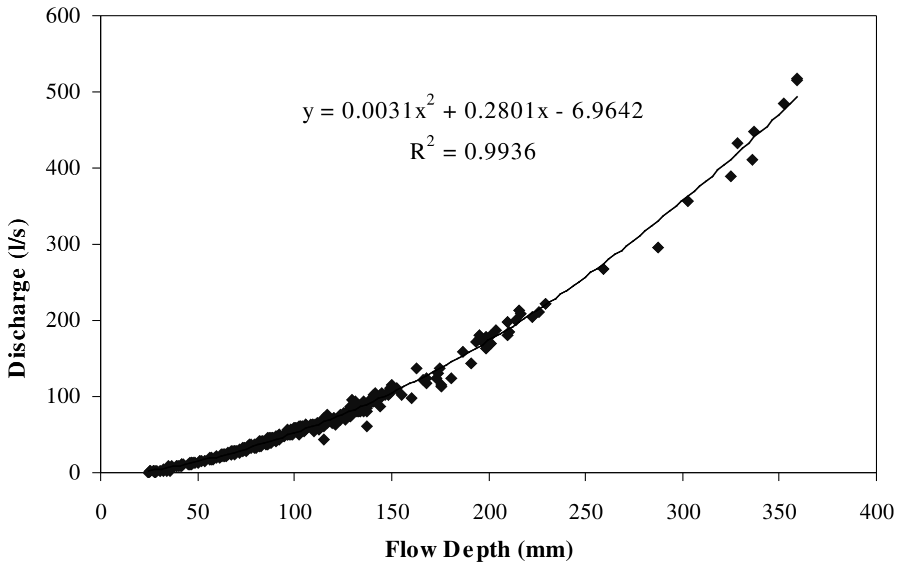


Fig. 4. Time series plot of measured flow depth and velocity data of a storm event.

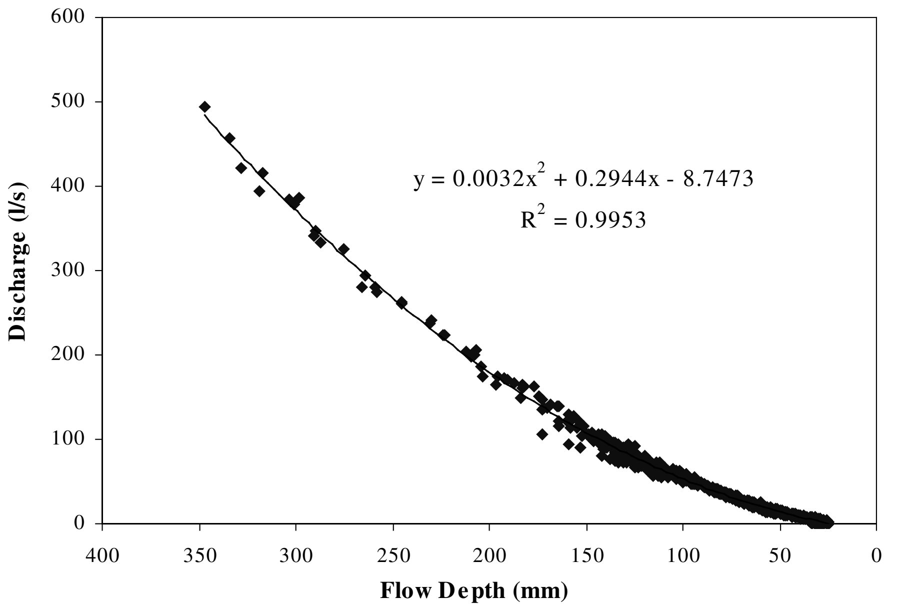
Good representation of runoff hydrographs can be obtained from flowmeters when small logging intervals are used. However, for such logging intervals, the memory of the flowmeter logger is expected to be used up in a shorter time, and the energy of the batteries is expected to drain faster. Thus, the data retrieval from the field and battery replacement for the flowmeters must be undertaken more frequently for shorter logging intervals. For example, the memory of the flowmeter logger gets full in about two and a half weeks with one-minute logging interval compared to about five weeks for two-minute logging. Consequently, the operational costs of the data acquisition program were reduced by adopting larger data logging intervals for flowmeters. For example, the cost of data retrieval was reduced by about 50% by using a two-minute logging interval instead of a one-minute logging interval.

For flowmeters, different logging intervals were tested to select the most appropriate logging interval. In the monitoring program, some flowmeters were operated with one-minute logging interval and 30-seconds scanning interval. In this case, flow depth and velocity were measured at every 30 s and the average values of those readings for each minute were logged in the flowmeter. A flowmeter of a catchment, which was operated with one-minute logging interval and 30-second scanning interval, was considered for studying the most appropriate logging interval. The data corresponding to two, four and six-minute logging intervals were computed from the logged one-minute data. For three measured storm events with different magnitudes and intensities, the peak flow depth, peak velocity, peak runoff and time to peak runoff corresponding to different logging intervals are given in Table 2.

The summary of hydrograph attributes in Table 2 indicates that the peak runoff, flow depth, velocity and time to peak runoff corresponding to one and two-minute logging intervals are similar. However, for four- and six-minute logging intervals, peak runoff, flow depth and velocity were significantly reduced, but the time to peak was increased compared to those of the one-minute logging interval. Therefore,



(a) Rising Limb of Hydrographs



(b) Falling Limb of Hydrographs

Fig. 5. Rating curves for rising and falling limbs of hydrographs.

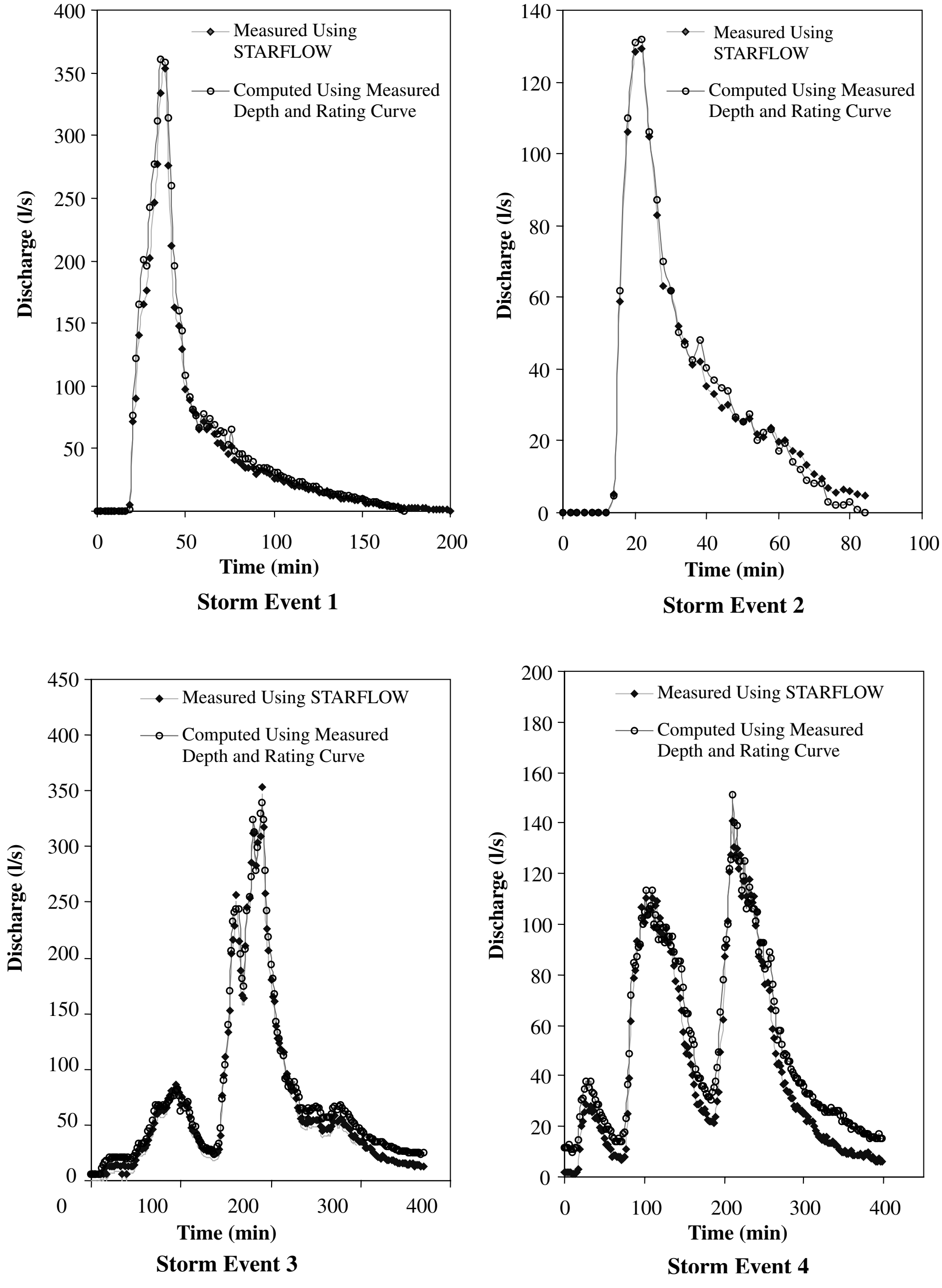


Fig. 6. Comparison of hydrographs from STARFLOW measurements and from depths and rating curves.

the two-minute logging interval was found to be the most appropriate data logging interval to obtain good quality stormwater flow hydrographs while minimising project costs.

2.5. Preliminary screening and checking of data

After the data were downloaded from pluviometers and flowmeters, they were manually checked for apparent malfunctioning of instruments, and errors and inconsistencies in the raw data. For example, starting and finishing times of downloaded files were compared to check whether the starting time of one downloaded file agreed with the finishing time of the previous one. Rainfall data collected in some cases were checked against independent rainfall data obtained from nearby (within about 5 km) measuring stations operated by other agencies such as Melbourne Water and the Bureau of Meteorology, for selected storm events. The rainfall data collected matched well when the distance between pluviometers used in this project and of other agencies was less than about 2 km. Even when they were more than 2 km apart, there were some consistent correlations between the rainfall data from the two sources.

The rainfall data for storm events of different magnitudes and the corresponding runoff data were checked for consistency in terms of matching rainfall and runoff volumes, preserving continuity and conforming temporal trends. If the flow data were consistent, the flow velocities for the same flow depth should be similar. The process of data checking was discussed in detail in Maheepala et al. (1999).

As indicated in Maheepala et al. (1999), occasionally some gaps and/or errors in velocity readings were found in the raw data that were retrieved from the flowmeters. In some instances, erratic velocity values were recorded, while flow depth varied as shown within the circle in Fig. 4. These problems usually occur due to temporary malfunctioning of velocity sensors because of trapped rubbish and debris around the sensors of the flowmeter, during low velocity recession flow periods. The statistical relationships (or rating curves) between flow depth and discharge (or flow depth and velocity relationships) were used to fill the gaps in observed data series and to correct the erroneous velocity readings. The details of derivation of such rating curves are discussed in Section 2.6.

2.6. Data generation from simple measurements

Measuring equipment such as STARFLOW ultrasonic doppler flowmeters and Monitor Sensors electronic pluviometers used in this project are more sophisticated and expensive than simple flow depth sensors and manual raingauges. For example, the price of a flow depth sensor and logger arrangement is about 65% of the price of STARFLOW flowmeter (which has both depth and velocity sensors, and a data logger). Furthermore, the installation, operation and maintenance costs of sophisticated measuring equipment are generally greater than those of simpler ones because special care and attention are often required for the operations with sophisticated equipment. Therefore, the possibility of using a smaller number of expensive and more accurate measuring equipment together with less expensive devices to estimate accurate rainfall and runoff data was investigated. The adequacy of measuring water depths and estimating runoff from these depth measurements and rating curves was investigated and discussed first. Then, the possibility of using a raingauge (which measures only the rainfall depth) and nearby pluviometer to disaggregate the rainfall total into the appropriate hyetograph was investigated.

For a selected measuring site, flow measurements of several storm events obtained with a STARFLOW flowmeter were used to develop rating curves (i.e. statistical relationships between flow depth and discharge). These rating curves were derived separately for the rising and falling limbs of hydrographs, since the hydraulic conditions in the pipe are often different for the rising and falling limbs. Fig. 5 shows such rating curves for a monitoring site, which describe discharge and flow depth for the rising and falling limbs, as second order polynomial relationships. These rating curves were derived from the data of eight storm events in two data downloads, which represent eight weeks data.

As indicated in Fig. 5, there is a high correlation between discharge and flow depth for both rising and falling limbs (i.e. correlation coefficients are 0.994 and 0.995 for rising and falling limbs, respectively). For some independent storm events that were not used in developing the above rating curves, hydrographs were derived using measured flow depths and the above rating curves. The comparison of hydrographs obtained from STARFLOW depth and velocity measurements, and from measured STARFLOW depths and rating curves is shown in Fig. 6.

The good agreement shown between the hydrographs in Fig. 6 suggests that the rating curves derived as above can be successfully applied to estimate runoff from flow depth measurements obtained from a simple depth sensor and data logger arrangement. One sophisticated

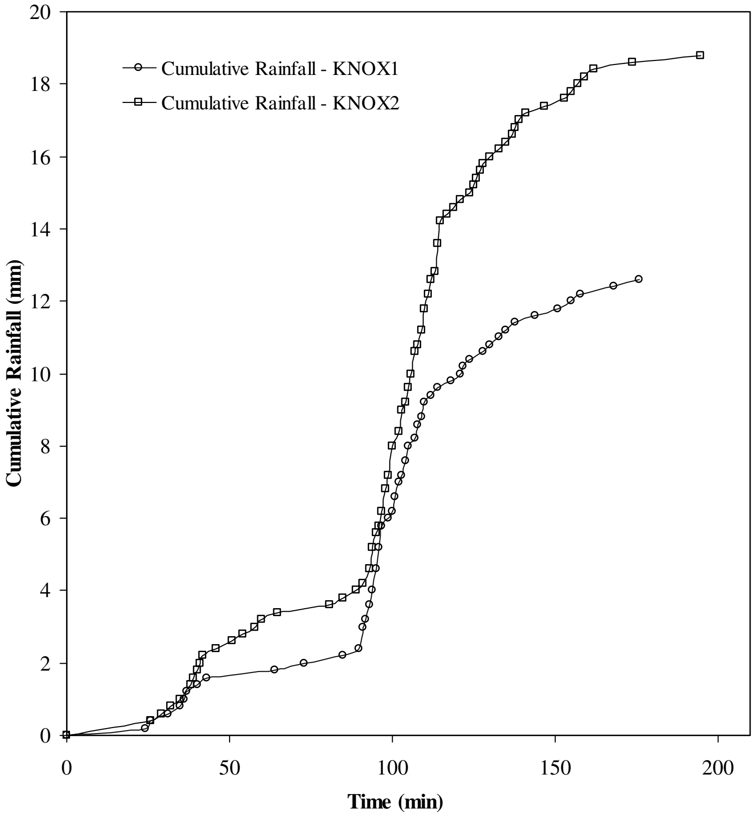


Fig. 7. Comparison of concurrent rainfall at nearby drainage catchments.

flowmeter such as STARFLOW can be operated at number of sites, for a short period at each site to obtain sufficient data required to develop the rating curves. For example, in a three year monitoring program involving flow measurements at three sites, one sophisticated and expensive flowmeter (e.g. one STARFLOW flowmeter worth of $1500AUD) can be operated at three sites, one year at each site. In that year, two other less expensive flowmeters (e.g. two depth sensor and data logger arrangements worth of $1800AUD in total) can be used in the remaining sites. This procedure will save more than 25% (i.e. $3300AUD spent instead of $4500AUD) of the capital cost for instrumenting three sites. Furthermore, there will be some savings from operational and maintenance costs because more sophisticated flowmeters require special care and attention compared to simple flowmeters.

As indicated in Section 2.3.1, more than one pluviometer will be required in large catchments for accurate estimation of rainfall over the entire catchment. A study was conducted to investigate the rainfall variability in nearby catchments and to study whether the rainfall depth of a storm can be used with a nearby pluviometer data to obtain the storm hyetograph. Rainfall data (i.e. hyetograph data) of storm events, which occurred within the same time period, in two nearby catchments were compared (Fig. 7). Although the distance between pluviometer site 1 and 2 is only 3 km, Fig. 7 clearly indicates that there are significant differences in the magnitudes (i.e. 12.6 mm for site 1 and 18.8 mm for site 2) and the temporal patterns of storm events recorded at the two sites. This shows that it is not feasible to use a raingauge and a nearby pluviometer to disaggregate rainfall data into a hyetograph, even if the distance between the raingauge and pluviometer is about 3 km. Fig. 7 also clearly justifies the need for several pluviometers for large catchments.

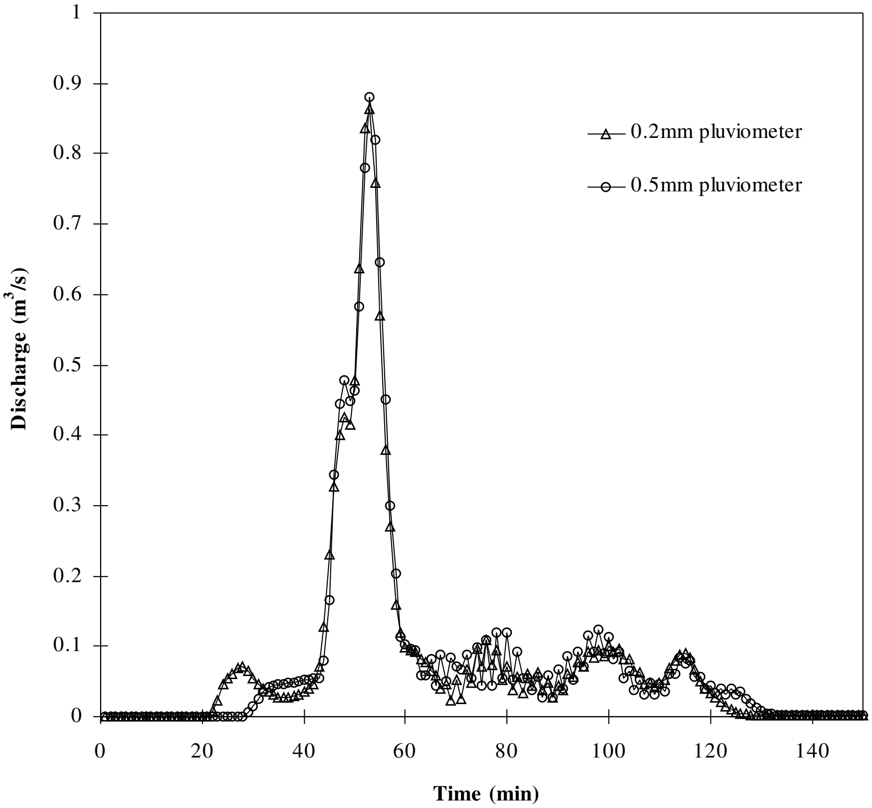


Fig. 8. Comparison of modelled hydrographs from ILSAX for different tipping bucket resolutions.

2.7. *Effect of accuracy of measuring equipment on urban stormwater modelling*

The effect of the tipping bucket resolution of pluviometers on the runoff hydrographs from urban stormwater models was investigated using ILSAX (O'Loughlin, 1993 urban stormwater drainage model. ILSAX is a relatively simple mathematical model, which can be used to design and analyse components of urban stormwater drainage systems, such as pits, pipes and channels. This model was developed from the ILLUDAS (Illinois Urban Stormwater Area Simulator) computer software (O'Loughlin, 1993. ILSAX is widely used by local government authorities and consultants in Australia. The sensitivity of urban storm event hydrographs to the model parameters of ILSAX has been presented in Dayaratne et al. (1998).

One-minute rainfall totals of some selected storm events obtained from 0.2 and 0.5 mm pluviometers were used in ILSAX to calculate the corresponding runoff hydrographs. Fig. 8 shows one such event. This figure shows that the modelled hydrographs are almost the same except for the periods with very low rainfall. With respect to the pluviometers used in this study, the same data logger and tipping bucket could be calibrated to give 0.2 and 0.5 mm tipping resolutions, and the 0.2 mm pluviometer attracted only a very little extra cost (i.e. about 8% of the capital cost). Therefore, 0.2 mm pluviometers were used to measure rainfall. However, in situations where fine resolution rainfall data (e.g. 0.2 mm) are not available, data with coarser resolutions up to 0.5 mm can be used in computer models to obtain reasonably accurate results.

As stated in Section 2.4, the use of logging intervals greater than two-minutes decreases the recorded peak runoff and increases the time to peak. Consequently, if the runoff data obtained with logging intervals greater than two-minutes are used for calibration and testing of model parameters, it can cause significant errors (e.g.

errors due to underestimation of modelled hydrograph peaks and overestimation of time to peak) in model results and predictions. Therefore, flow data obtained with logging intervals up to 2 min are recommended for use in urban stormwater simulation models.

3. Summary and conclusions

Despite the necessity of good quality hydrologic data to develop and calibrate urban stormwater simulation models, such data are not available for most urban areas in Victoria, Australia. Therefore, a comprehensive data acquisition program was undertaken by Victoria University of Technology in 1996. Various aspects of this data acquisition program were presented in this paper. These include the selection of suitable monitoring sites and appropriate equipment, the calibration and installation of selected measuring equipment, and data retrieval and diagnostic checks of data.

The effect of measuring resolution of pluviometers and data logging interval of flowmeters on the accuracy of measurements was investigated. It is recommended to use pluviometers with small tipping resolutions (e.g. 0.2 mm) because they give more accurate temporal variation of storm events. It was also found that one and two-minute logging intervals for flowmeters gave almost the same runoff hydrographs, whereas the use of logging intervals larger than two-minutes tend to decrease the measured peak runoff and increase the time to peak. Therefore, a two-minute logging interval is recommended for flowmeters to obtain good representation of stormwater runoff.

The possibility of using a combination of low cost simple measurements and high cost sophisticated measurements was also investigated in order to reduce monitoring cost while maintaining the accuracy of the data. The results of this study revealed that flow depth measurements obtained from simple depth loggers could be used to compute discharge using statistical relationships (or rating curves) between flow depth and discharge at the site. For a given monitoring site, it is possible to develop good regression relationships for these rating curves between discharge and flow depth, based on measurements of a sophisticated flowmeter. Consequently, the number of expensive sophisticated flowmeters can be substituted by simple depth measuring equipment, resulting in significant reductions in the cost of a data acquisition project. Furthermore, the rating curves between discharge and flow depth can be used to fill gaps in flow data series due to inaccurate velocity readings and/or the gaps in velocity measurements, which could occur in some instances.

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