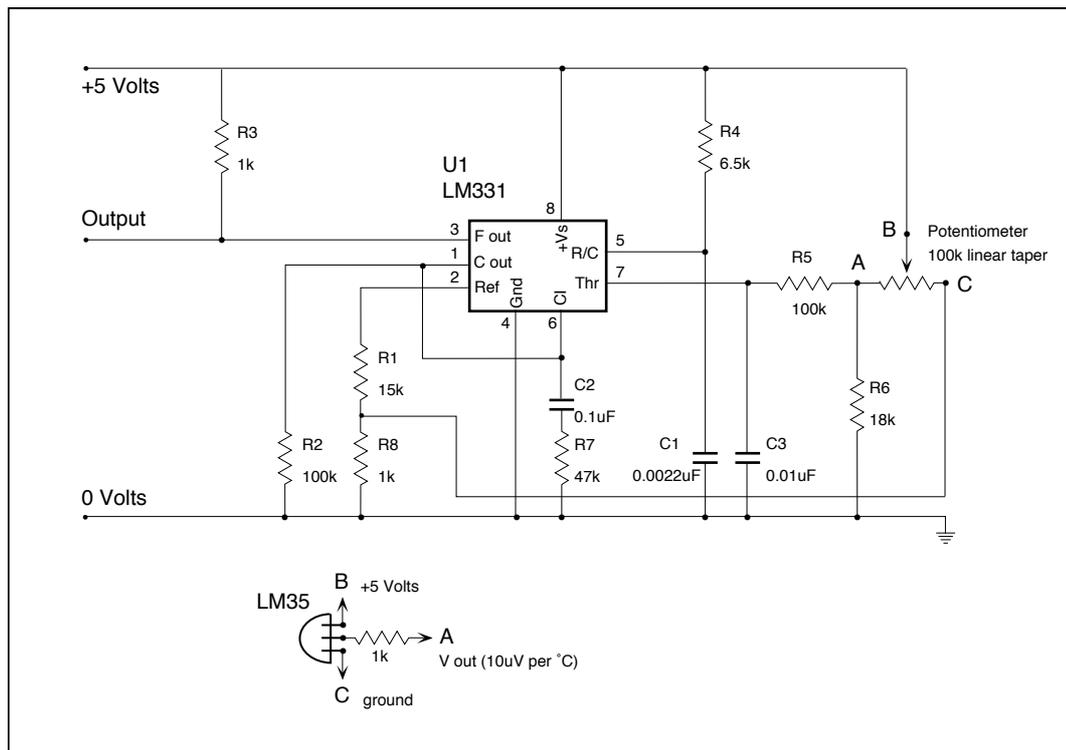


Appendix 5.1 Individual Drain Calibration

Individual drain calibration was a complex process, made more difficult by the different construction techniques employed in each drain. Float arm logger data was obtained from the East Main (EM) and Basketball Stadium (BB) drains. The float arm logger employed a Dataflow 392 logger with voltage to frequency converter originally used for temperature logging with an LM35 temperature sensor. This was replaced with a 100k linear taper potentiometer mounted on the swing arm logger. With the circuit configuration shown here a frequency shift of about 7000Hz was obtained over a potentiometer shaft rotation of 180 degrees.



In its original configuration the LM35 temperature sensor was connected at the points marked A to C. The logger and V to F converter was calibrated for each drain after installation. Gearing of the potentiometer was required to provide adequate resolution.

Perry East 'PE' Drain

A series of storm events July 5-7 1997 was used to calibrate the drain against float arm data. Figure 1a shows water height in the sediment trap and pipe for individual storm events A to J. A phase lag of variable length occurs between the water height in the sediment trap and the water height in the pipe, measured by the swing arm logger at the pipe exit 234m distant. An additional complication is run-off from Meagher Drive and car parks adjacent to the basketball stadium which enter the PE drain between the gauged sediment trap and the lake. This in part, explains why levels in the pipe are consistently greater than levels in the sediment trap. Overall similar rainfall was assumed for the drain catchment and Meagher Drive. Placing the float arm logger at the pipe exit therefore allowed these additional inputs to be included in the PE discharge. When examined in detail (Figure 1b) an approximate 4 minute phase lag is evident at higher pipe depths. Figure 1c demonstrates how water velocity (mean velocity as defined by Manning's equation) and phase lag between the two monitoring points varies with water depth in the pipe. At the heights encountered at storm peaks (pipe depths 0.1-0.5m) this lag varies from 5.3 to 3.1 minutes. A final calibration expression was derived by plotting water height in pipe against water height in sediment trap adjusted for phase lag.

Manual Calibration

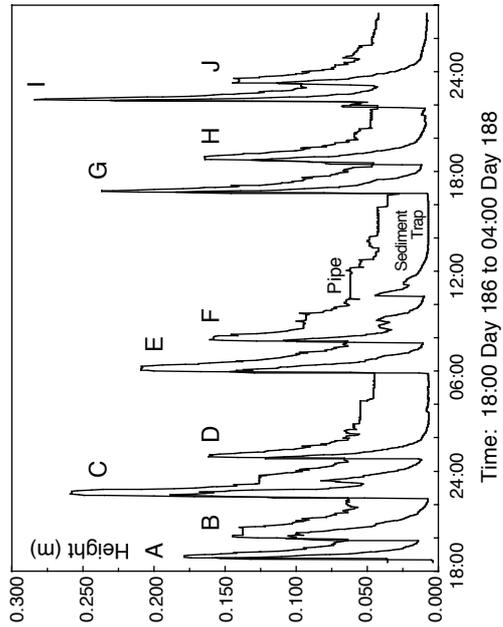
Manual calibration data was collected during an intense storm event June 17, 1996 by measuring water depth (difference from top of pipe to top of flow) at the pipe exit. The measurements were made an arms length inside the pipe to preclude any head losses close to the exit. The resulting expression based on only five points (Figure 1d) is not affected by the errors in pipe 'zero real depth' (see below) and produced a very linear fit ($R=0.994$) and included one of the highest recorded flow depths in the PE pipe, 0.435m (0.64 pipe internal diameter).

Calibration Using the Float Arm Logger

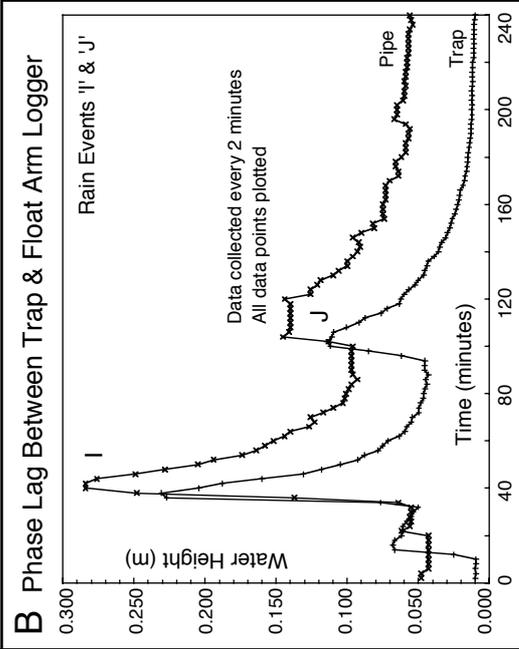
Sediment trap data was collected at 2 minute intervals, while the float arm data was collected at 1 minute intervals. Phase lags of 1-6 minutes were tested to derive linear and polynomial curve fits (the relationship between water height and arc created by the pivoting arm is not quite linear due to the fixed rather than self adjusting float design). A four minute lag adjustment produced the best linear fit ($R=0.946$), Figure 1e. Polynomial curve fitting (not illustrated) produced little improvement ($R=0.950$).

One significant design problem with the swing arm logger was slop in the gear train and a tendency for the float to rest slightly off pipe centre as water receded. These two faults

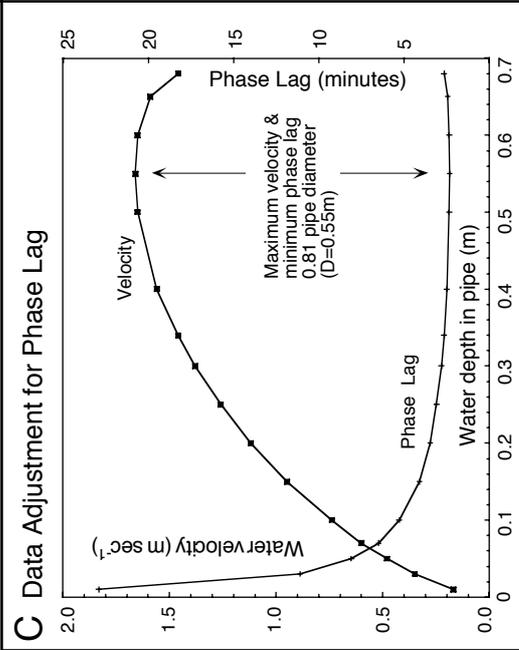
A Calibration Event July 5-7 1997
Individual rain events are labelled A-J



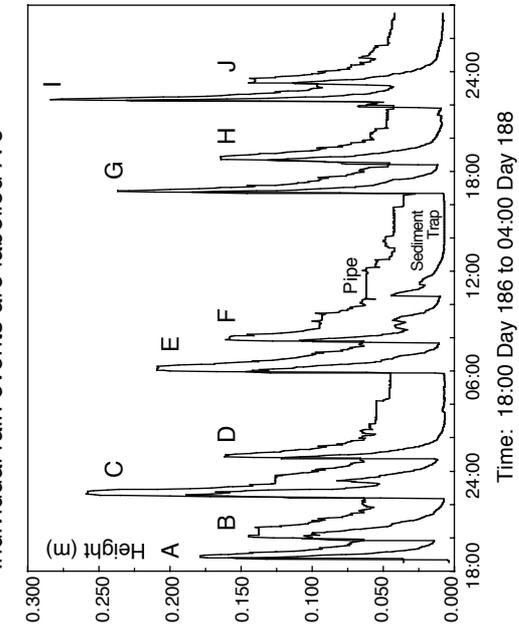
B Phase Lag Between Trap & Float Arm Logger



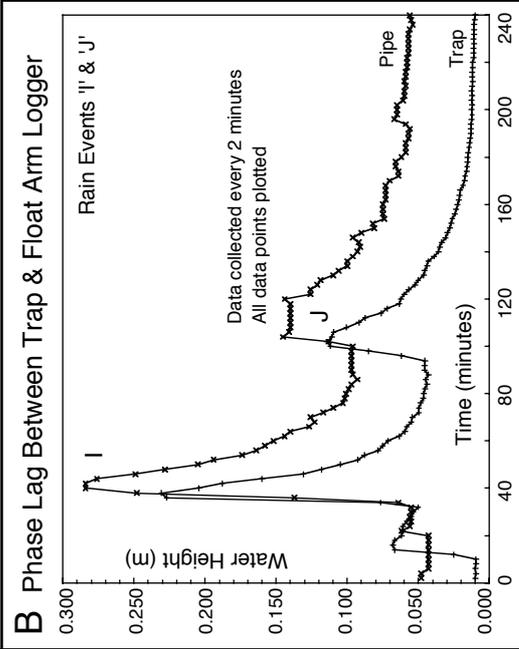
C Data Adjustment for Phase Lag



D Trap:Pipe Manual Calibration



E Calibration by Float Arm Logger, All Data



F Calibration by Float Arm Logger, Receiving Data

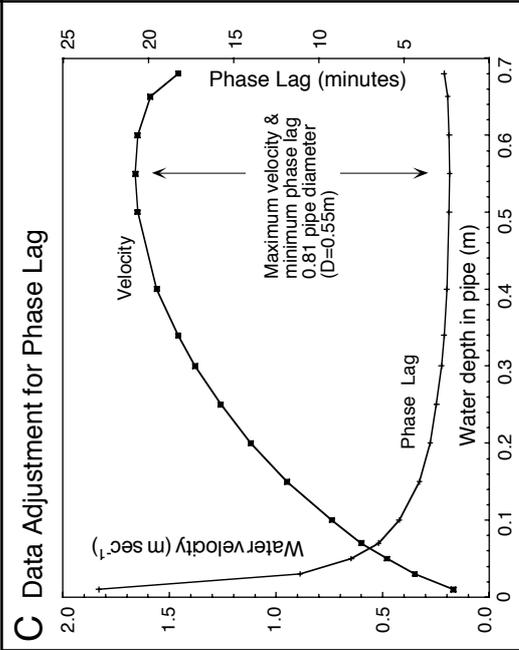


Figure 1
Appendix 5.1

combined frequently resulted in about 40mm of water indicated at zero real depth (notice in Figure 1e the 'y' intercept of 43mm). As a final attempt to produce a best fit, receding level data only was used (peak to 0.1m) from events A to J. The use of receding water level data also eliminates the generally poor correlation between trap and pipe during the initial surge as the pipes commence flowing. Receding data (Figure 1f) produced an improved linear fit ($R= 0.964$) but with a greater 'y' intercept, which ideally should be zero. Given the wide variation between the float arm and manual calibration coefficients, a range of coefficients between $1.046(x)$ and $1.358(x)$ were tested in the final calibration.

Basketball 'BB' Drain

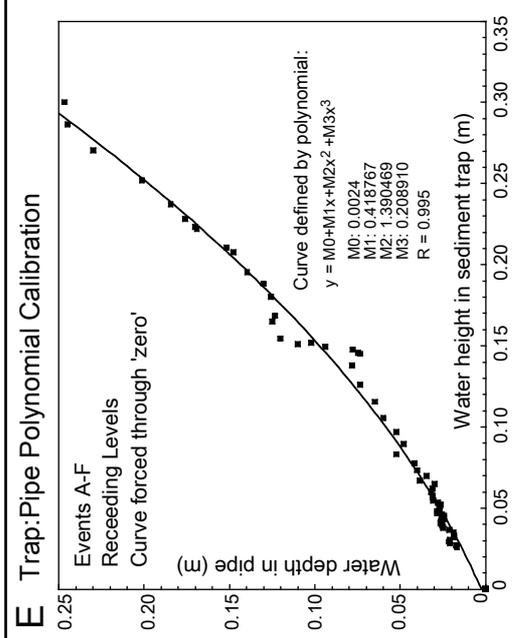
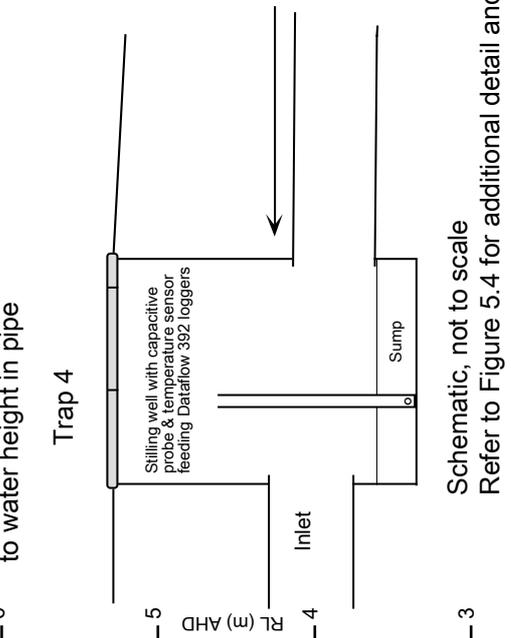
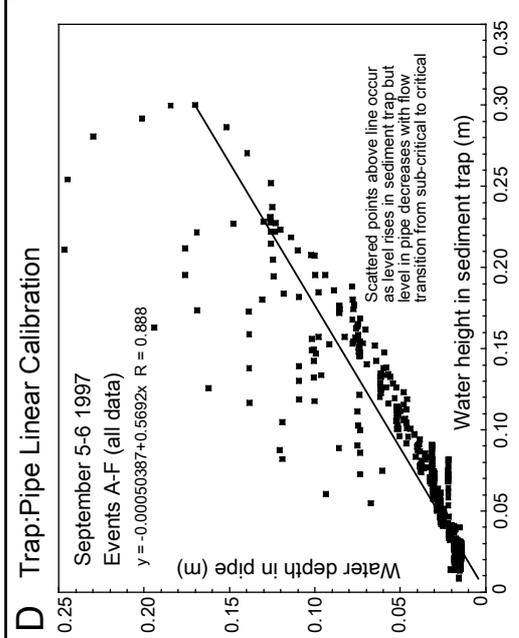
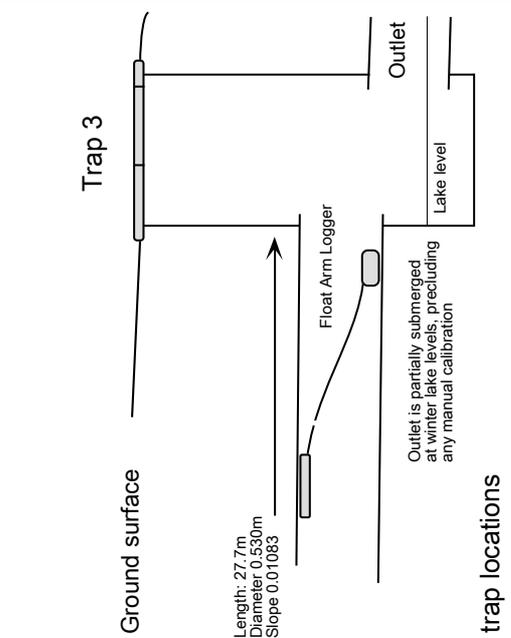
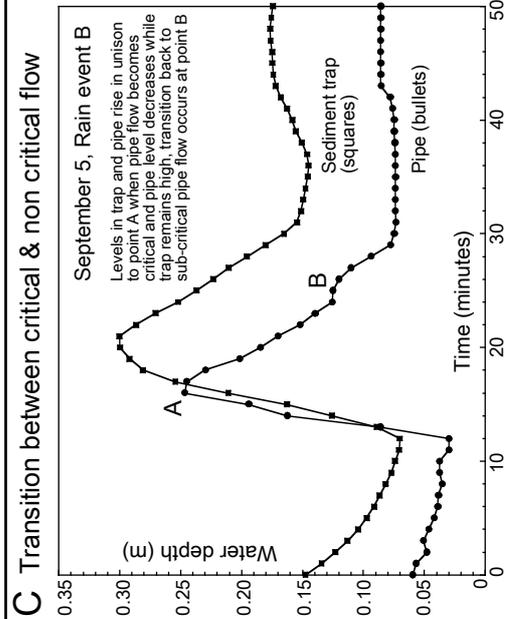
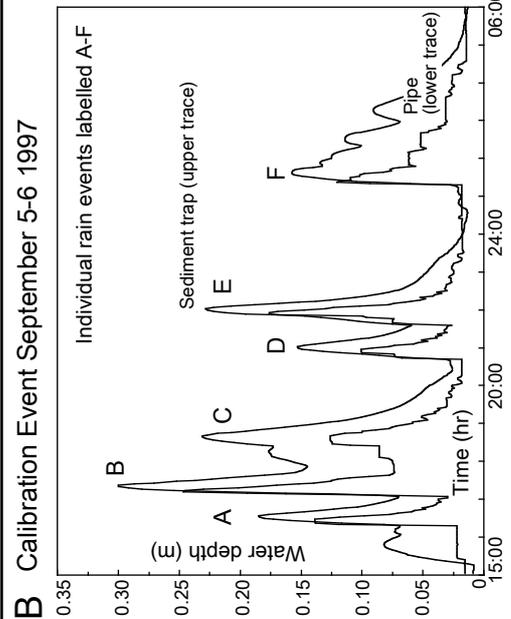
The Basketball drain carries roof and surface run-off from the athletic and basketball stadium complexes. It consists of a series of cascaded sediment traps, the last two of which are illustrated in Figure 2a. The outlet to East Lake is partially submerged at winter lake stages, precluding any manual calibration. A series of storm events (Figure 2b) September 5-6 1997 was used to calibrate the water height in sediment trap 4 against depth in pipe. The small pipe diameter (0.53m) precluded physical access to mount the float arm logger directly to the upper pipe surface. Instead it was secured to a rigid steel channel secured within and extending from trap 3.

Calibration Using the Float Arm Logger

Sediment trap data was collected at 2 minute intervals, while the float arm data was collected at 1 minute intervals. The internal clocks in all loggers were reset from the same PC. The loggers assume the time of the PC internal clock and are therefore synchronous. No phase lag was expected due to the very short distance (27m) between the sediment trap and the float arm. Detailed analysis of data from individual rain events however displayed an unexpected relationship between trap and pipe data. As a storm event commenced, trap and pipe levels commence rising synchronously. Pipe levels then commence falling while trap levels continue to rise and peak. Both levels then fall but with a later rise or plateau in pipe levels which is not accompanied by a similar rise in trap levels (Figure 2c). Theoretical velocity-discharge analysis (see below) confirmed that this section of the drain was cycling between subcritical and critical flow. The 'spiky' pipe flow trace evident in Figure 2b at pipe depths around 0.05m is likely caused by unstable transitional flows close to Froude Number 1 (Figure 3b) which are typically wavy or undulating (Hamill 1995). Better trap:pipe relationships, expressed as polynomial expressions were generated using receding level data only (Figure 2e) however in the final integrated calibration using all four drains against lake volume changes, the linear expression provided the best fit. This probably reflects the fact that it represents an averaging of both flow regimes.

BB Drain Calibration

Appendix 5.1 Figure 2



Schematic, not to scale
Refer to Figure 5.4 for additional detail and trap locations

September 5, Rain event B
Levels in trap and pipe rise in unison to point A when pipe flow becomes critical and pipe level decreases while trap remains high, transition back to sub-critical pipe flow occurs at point B

Calibration was achieved by assuming that the linear relationship evident at low flows could be extended and assuming all flow to be non critical. In Figure 2d, a linear relationship with little data scatter is evident up to trap depths of about 0.07m. This linear trend then continues but with considerable scatter above the line. Detailed analysis of Figure 2 c&d show that this scatter is largely generated during the initial phase of each rain event where pipe depth is greater than trap depth. Once critical flow is established, this relationship is reversed. The linear relationship in Figure 2d is therefore a simple average which, over an entire storm event or balance period, provides a good estimate of water height in trap to water height in pipe and ultimately total flow volume.

CSIRO 'CS' Drain

Calibration of the CS drain was achieved using data collected manually during two rain events in 1996 and 1997 which provided a mean trap:pipe coefficient of 0.815. Despite the theoretical velocity-discharge analysis (Figure 4) which suggested critical flows would dominate, obvious critical flows were not observed in visual inspections during storm events.

Underwood 'UW' Drain

The UW drain has the steepest gradient and probably exhibits critical flows most of the time. Visual inspection of trap 7 (refer Figure 5.4 in thesis text) during storm events indicated that trap and pipe depths appeared roughly similar (*i.e.* trap:pipe depths of about 1:1). This seemingly linear relationship probably results from the increased flow resistance within narrow diameter pipes. A number of possible linear relationships were tested in the integrated calibration with a final relationship of 0.8 trap height providing the best overall fit.

Supercritical and subcritical flow in Perry Lakes Drains

The initial problem calibrating the BB drain prompted the generation of theoretical velocity-discharge curves for all Perry Lakes drains. Velocity, discharge and Froude number plots were generated at water depth increments of 0.01m over ranges of Manning's 'n' typical of cast concrete pipes (Figure 3). Above Froude number 1 supercritical flow can occur, characterised by an increase in velocity and decrease in depth. The West Lake and Perry East Main ('PE') drains display subcritical flows over all water depths. Artificial open channels, which includes storm drains are typically constructed at gradients of about 0.001 (French 1985). This is approximately the gradient utilised in the West Lake drains which operate at Froude numbers <0.6 (Figure 3e). The Perry East drain (Figure 3a) exhibits Froude numbers which just exceed unity (maximum 1.038 at $n=0.010$) and approach unity (maximum 0.943 at $n=0.011$). The remaining

Velocity-Discharge Analysis

Notes Appendix 5.1 Figure 3

Each plot contains three sets of velocity, volume and Froude No curves, generated for different values of Manning's 'n':

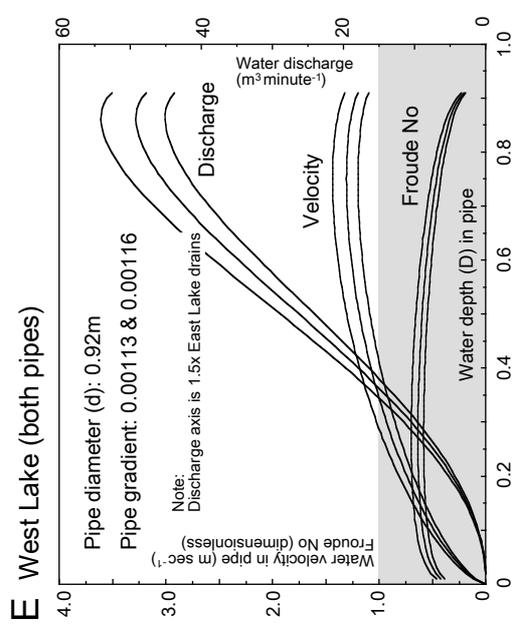
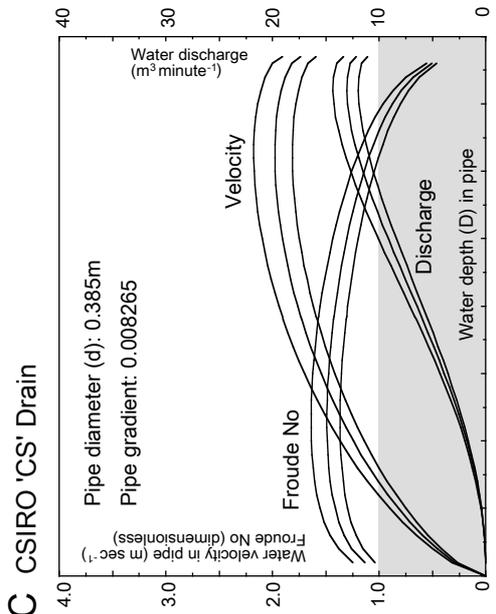
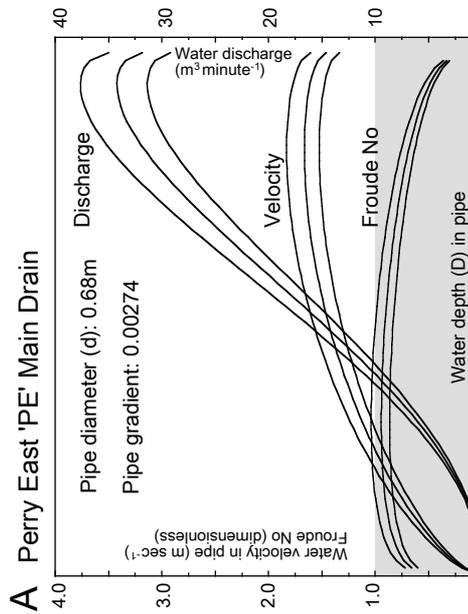
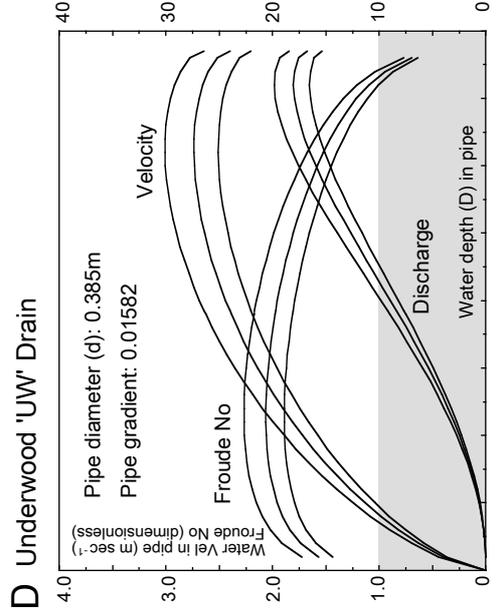
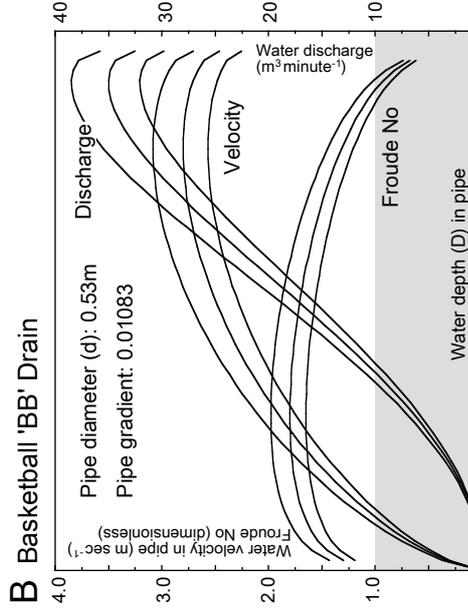
- 0.010 (upper curves)
- 0.011 (middle curves)
- 0.012 (lower curves)

Where Froude Number exceeds unity, critical flow conditions may occur. Sub-critical flow occurs within the shaded area of each graph

High Froude Numbers in the smaller BB, CS & UW drains result from abnormally steep pipe gradients approximately 10x greater than those in the West Lake & PE drain

Maximum discharge occurs at $D=0.95d$
Maximum velocity occurs at $D=0.81d$

Note that discharge axis for West Lake drain graph is 1.5x that of the East Lake drains



small diameter drains have Froude numbers >1 over most of their operating range. These drains probably oscillate between subcritical and supercritical flow during storm events.

In summary, estimates of discharge are based on

- the fact that for a given specific energy, two alternate depths of flow are possible representing subcritical and supercritical flow (Chow 1959 p41)
- for the BB, CS & UW drains calibration expressions and discharge volumes have been derived which *assume* subcritical flow throughout

Therefore while the actual depths which may occur in the pipes during supercritical flow will be less than those used in the calculations, the estimated volumes will be similar.

Final Calibration East Lake

For each drain a number of possible depth in sediment trap to depth in pipe co-efficients were computed based on manual and float arm data and other factors such as variable time lag in the PE drain where the float arm and manual data was collected over 200m from the trap site (see above). Discharge from each drain therefore, was described by a 'family' of rating curves defined by the trap:pipe and pipe friction coefficients (Manning's 'n').

These are summarised in Table 1. There are 120 possible combinations.

Table 1 Trap:pipe factors tested for 'best fit' against lake volume changes

Perry East 'PE'	Basketball 'BB'	CSIRO 'CS'	Underwood 'UW'
1.046(x)	0.569(x)	0.815(x)	0.800(x)
1.165(x)	polynomial 1		1.000(x)
1.200(x)	polynomial 2		1.100(x)
1.250(x)	polynomial 3		1.200(x)
1.300(x)			1.450(x)
1.358(x)			

Notes

PE: 1.046 & 1.165 from float arm logger, 1.358 from manual calibration. Additional intermediate coefficients tested (refer text).

BB: 0.569 is general linear fit of all float arm data. Polynomial expressions developed from float arm data, levels receding from peak.

	Polynomial 1	Polynomial 2	Polynomial 3
M0	0.006476	0.016735	0.002489
M1*x	0.381904	0.0110965	0.418767
M2*x ²	0.371370	4.285177	1.390469
M3*x ³	3.642878	-5.614196	0.995492

CS: the excellent manual data fit for the CS drain was accepted without modification

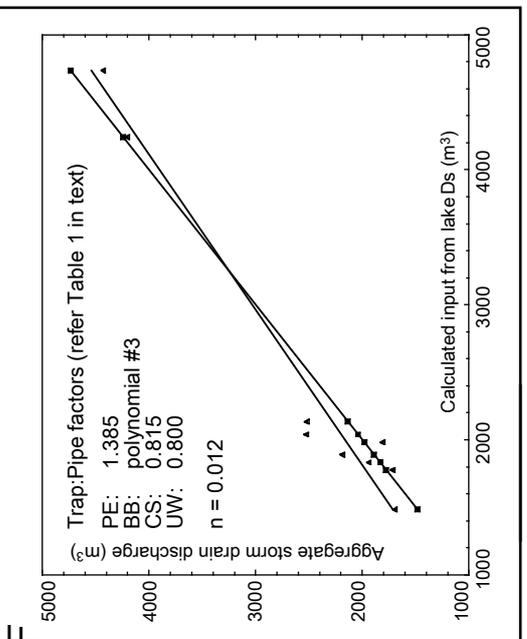
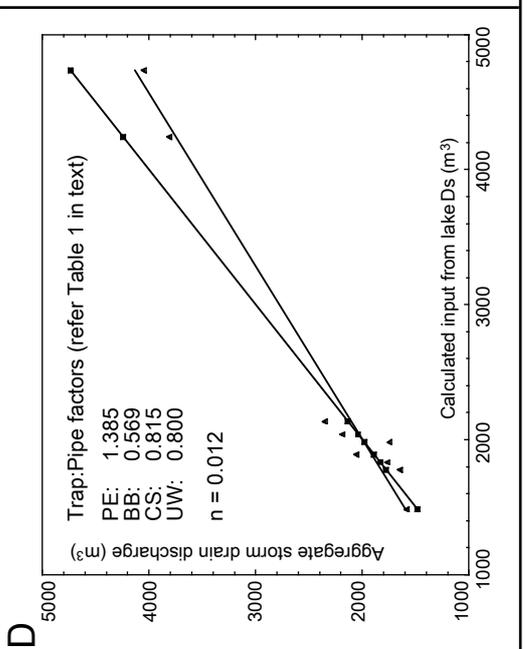
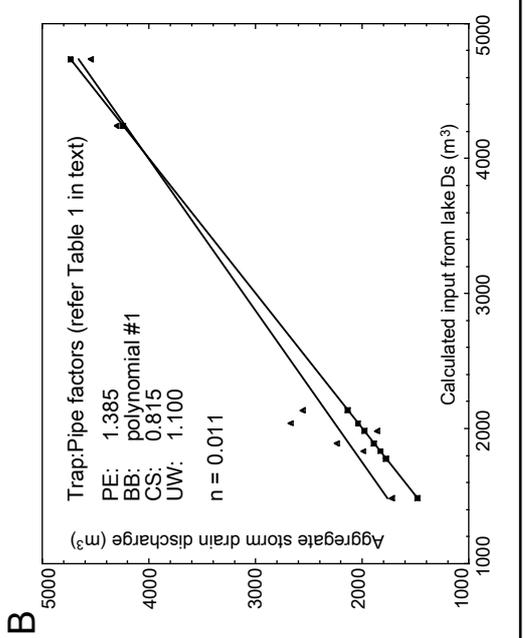
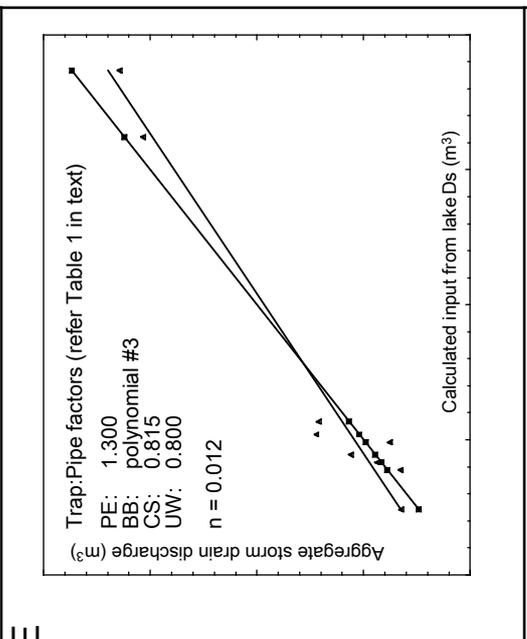
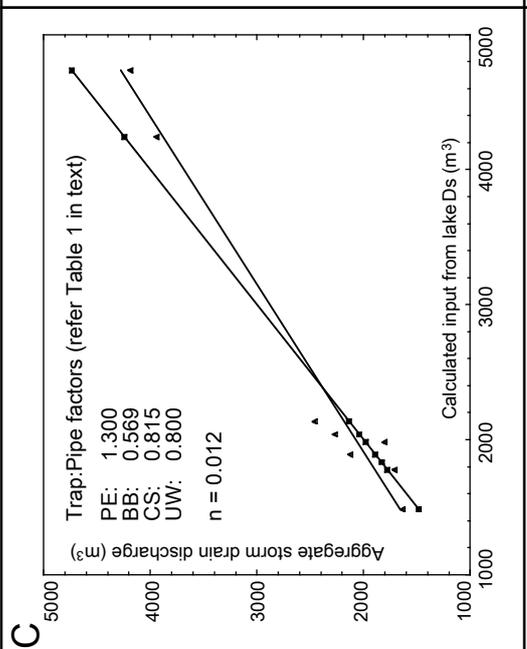
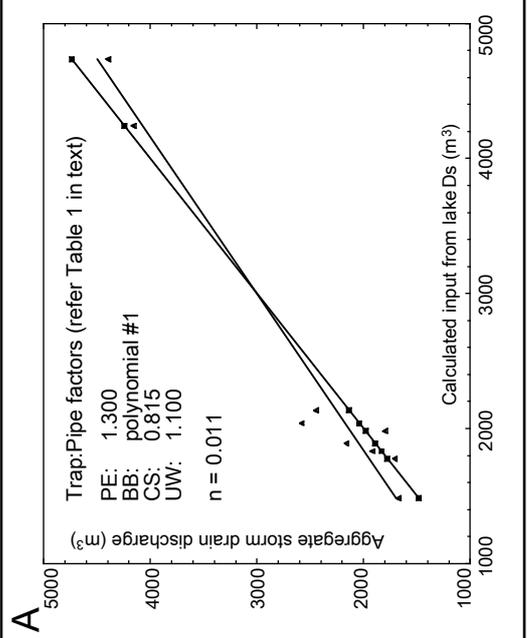
UW: manual calibration 1.450(x) was based on a very poor data fit. Field observation suggested discharge from the UW drain was small. The range of smaller coefficients was tested against best fit total discharge.

Aggregate Drain Calibration

East Lake

Appendix 5.1
Figure 4

Key
Squares: theoretical perfect match where lake Ds = aggregate drain discharge
Triangles: fit for individual drain rating curves as shown



Aggregate discharge using all permutations of pipe discharge were plotted against data derived from lake volume changes for 9 rain events. A perfect match is defined by a line of slope =1 and y intercept of 0. Data combinations which appeared close using 'n' = 0.011 were retested with 'n' =0.010 and 0.012. Examples of various 'close fits' are included in Figure 4. Final drain discharge was computed using the following trap:pipe coefficients: PE: 1.300, BB: 0.569, CS: 0.815, UW: 0.800. This was based on the better fit for storm events in the discharge range 1500-2500m³, which are more typical of winter frontal passages than the extreme 4000-5000m³ events.

Calibration West Lake Drains

Individual Microcom¹ DDT-200 loggers operated in the two West Lake drains continuously from July 7, 1996 to January 3, 1998. Each instrument was set to log drain flow depth (height minus dry height) at a one minute scan rate. The loggers also measure air temperature in the drains which is used to correct the final data for sound velocity changes. Flow volumes were calculated using Microcom 'II Study' inflow analysis software (V2.35) employing Manning's equation. The optimal value for Manning's 'n' was determined by independently estimating discharge for discreet rain events using the same methodology applied at East Lake. Aggregate discharge for these events was also estimated using the II Study software set at various values of Manning's 'n' (Figure 5).

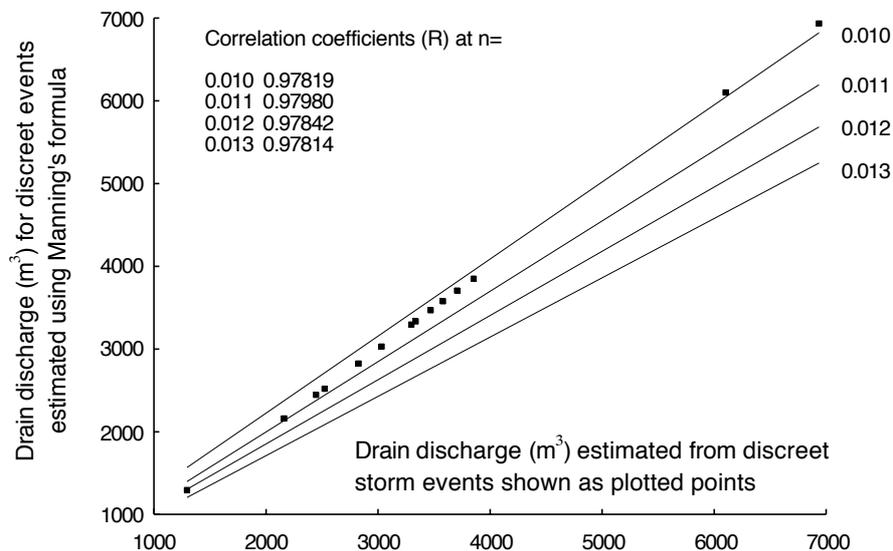


Figure 5 West Lake storm drain calibration, discharge estimates from hydrographs vs estimates at various values of Manning's 'n'

¹ Microcom Pty Ltd P.O. Box 1182 Fremantle W.A. 6160

In all cases the same value of 'n' was applied to both drains which are of a similar age and construction. The slope of the line representing the estimated values differs from the linear best fit plots at different values of 'n'. This presumably represents inaccuracies in the estimates which rely on assumptions concerning seepage, direct rainfall and evaporative losses from a water body whose area is changing rapidly over hours. It is also likely that at low discharge, sand in the drains results in an effective rise in 'n' while at high discharge effective 'n' is decreased. Discharge rates were calculated using 'n' of 0.011 which is considered 'normal' for concrete pipes free of debris (Chow 1959). Discharge events exceeding 3000m³ were calculated at 'n' of 0.010, corresponding to Chow's 'minimum' value for drains of this construction.

Appendix 5.2 Estimation of Missing Data

Balance periods 1-5 (East Lake) and 1-6 (West Lake) predate complete instrumentation of the drains. Estimates of total drain inputs for each lake for rain events during these balance periods were calculated using relationships derived from rainfall versus total measured drain flow where complete data was available (Figure 1 a&b).

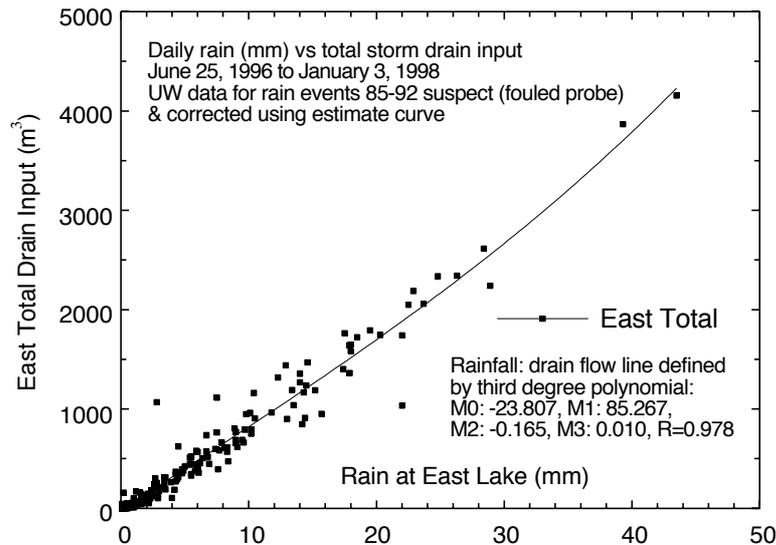


Figure 1a East Lake Rainfall vs Total Drain Input (PE, BB, CS & UW drains)

This method of estimation assumes that rainfall measured at Perry Lakes was consistently equal to that occurring everywhere in the drain catchment. It also assumes that rainfall-run off relationships did not vary seasonally (Viessman *et al* 1989). Neither assumption is strictly valid however curves were considered sufficiently accurate to provide reasonable estimates of drain flow.

Correction of Flow Peak Suppression

The depth range over which the DDT-200 transducer operates is approximately 0.4 to 5.0m. Transducer-water distances less than 40cm occupy a 'dead zone' within which no or erroneous data will occur. Normal installation procedure is to place the transducer at a height where the maximum anticipated water height occurs outside the dead zone. Height limitations in the West Lake drain saddle traps (Figure 5.4) meant that during a number of extreme rain events levels in the West Lake, drains entered the dead zone.

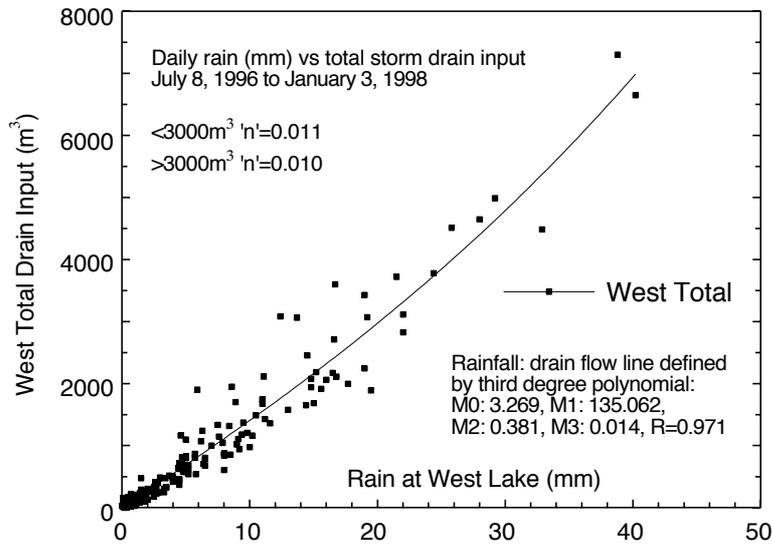


Figure 1b West Lake Rainfall vs Total Drain Input (East & West pipes)

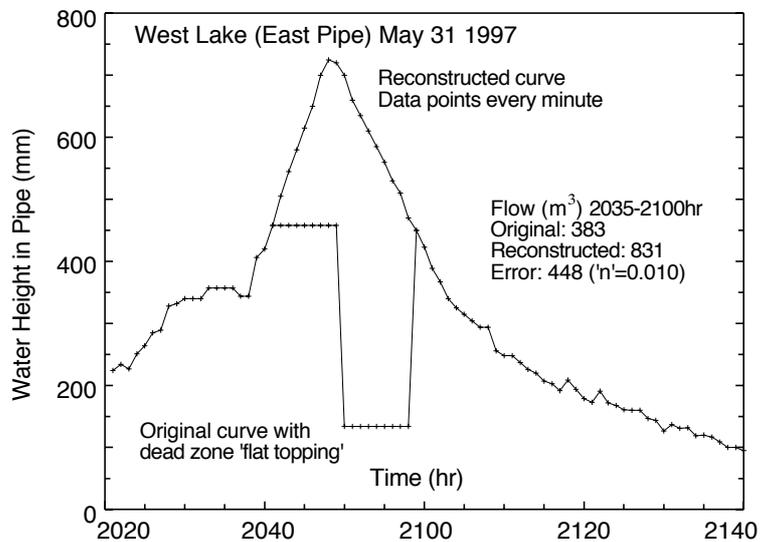


Figure 2 Typical correction for peak flows within acoustic transducer 'dead zone'. Trend of slope each side of the dead zone was extrapolated, curve shape adjusted to match that in adjacent pipe

These incursions are expressed either as 'flat topped' flow peaks and/or sudden reversion to very low flow values (Figure 2). Incursions into the dead zone were recorded on 15 occasions. Flow values were corrected by reconstructing the curves (extrapolating the rate of rise and fall) and calculating the missing flow volumes.