Technical Report

Adelaide Coastal Waters Study

***Stage 2** Research Program 2003 - 2005*

Technical Report No. 10 September 2005

Reconstruction of Historical Stormwater Flows in the Adelaide Metropolitan Area

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Reconstruction of Historical Stormwater Flows in the Adelaide Metropolitan Area

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Executive Summary

This report details modelling undertaken to generate representative time-series of daily stormwater flows for the major creeks and storm drains in the Adelaide Metropolitan Zone since 1940. The work is a component of the Adelaide Coastal Waters Study sub-program IS 1 – Input Studies. The modelling was carried out to recreate flows where no data were previously available and, where there were existing flow data, to use modelled flows to complete gaps in those existing records. The modelling approach uses a link between population and urbanised area to simulate the influence of the increasing proportion of impervious surfaces in a catchment as more land is developed for residential purposes. The pre-urbanised hydrological characteristics are based upon contemporary response of an un-urbanised catchment. In addition the influences of reservoir construction are accounted for: these cause significant reductions in run-off in a number of major creeks (although further changes associated with farm dam construction have not been addressed). The complete dataset provides an insight into the historical changes in stormflows from 24 catchments to the Adelaide Coastal Zone, and a research tool for investigating the patterns in loads of contaminants for a 64-year period. The flows account for a total in excess of 8000 GL at an average annual total of 130 GL. The time-series of estimated flows will be archived and made available as a resource to future studies.

Contents

1. Introduction

This report presents a summary of work done to recreate estimates of daily stormflow in the creeks and drains in the Adelaide Metropolitan Area between the Gawler River and Sellicks Creek as part of the Adelaide Coastal Waters Study (ACWS). There were two main aims to this exercise: (i) to provide hindcasts of stormflow to facilitate estimation of the timing and magnitude of historic pollutant loads to the ACWS coastline, and (ii) to provide stormflow estimates for the hydrodynamic modelling of Adelaide Coastal Waters (PPM2 sub-program of ACWS). The report presents the modelling approach used, limitations of the method and a summary of the modelling results and calibration parameters. A site-by-site description of the model application to each stormwater source is provided, and exemplar plots of model output give a visual demonstration of the quality of output. The estimated daily flows may provide a useful research resource for sub-sequent studies.

2. Approach

Archived stormwater flows from the South Australian Department of Water, Land and Bio-diversity Conservation were accessed and used where possible for the purpose of model calibration – fitting the modelled and observed stormwater flows in terms of the overall volume of flow and dynamics thereof. For creeks with impoundments or where reservoirs were constructed during the period of record (1940 to the end of 2004), upstream flows, pre-impounded flows and overspill flows have been used or modelled as required to ensure a realistic representation of the creek system. Rain gauge and air temperature data provided by the Bureau of Meteorology were used as input variables to the model. The choice of input rainfall was influenced by the location of the gauge relative to the main run-off producing area in the catchment and, in addition, this choice was influenced by whether the temporal pattern in daily rainfall quantity matched the observed peaks in stormflow.

The model used is based upon the IHACRES modelling approach described in Littlewood and Jakeman (1993). In the application presented here the model was coded into a spreadsheet form with three flow pathways devised by the author and using the rainfall loss module as described by Jakeman and Littlewood (1993) (see Appendix I). Model calibration was undertaken manually using a combination of statistics to indicate the overall goodness of fit of the modelled flow to the observed flows, the fit of baseflows, the coincidence of the modelled and observed total runoff volume for the calibration period, and, in addition, the volumetric runoff coefficient (VRC - the ratio of rainfall to runoff volumes) and yield (the quantity of runoff expressed as equivalent mm of rainfall which is also ML/Ha). The aim of the model calibration process was to fit the model dynamics and produce the same volume of runoff. In cases where the observed flow dynamics could not exactly be reproduced the flow volume was taken as the primary consideration for calibration.

In production of the final output flow data, two approaches were used which were aimed to maintain temporal consistency within each time-series for each site. Where a large proportion of the entire flow record was available these data were used in preference and the model data only used where gaps in the observed data occurred. In the second case, where the measured flow record was very brief (or did not exist) in relation to the 64-year period, the final data comprise the whole period of model data. Where no observed flows were available model parameters for an adjacent catchment were applied and if additional information was available, such as VRC, the model output was adjusted as required.

The relationship between urbanisation and seasonal patterns in catchment yield was presented in Wilkinson et al. (2004). This investigation showed that un-urbanised catchments in the Adelaide Metropolitan Zone have a short stormwater season with the majority of discharge occurring over a period of three to four months in the late winter period centred on September, this is when extreme soil moisture deficits have been redressed and the potential for surface runoff is at it's greatest. In urbanised catchments the presence of impervious surfaces ensures that stormwater flows can occur at any time of the year. This relationship has been used to simulate the changes in stormwater dynamics in the Adelaide Metropolitan area on the basis of population increase and the associated increase in the number of dwellings and hence developed land area (Figure 1).

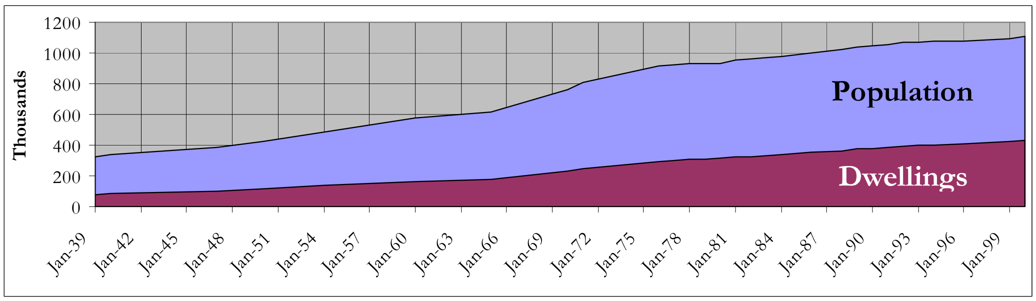


Figure 1: Metropolitan Adelaide population and numbers of dwellings (in thousands) since 1939 (based on data presented in ABS (2003)).

The impact of increasing population on stormwater production has been exacerbated by the tendency to households with smaller numbers of occupants (4.06 in 1933 down to 2.57 in 2001; ABS data), i.e. the growth in impervious surfaces within catchments has been greater than the rate of population increase. This increase in stormwater producing land area has been offset by changing water resource demands that have seen the building of reservoirs since 1940. This impounding of major catchments, increases in impervious surface areas and the domestic demand for water (a large proportion of which enters the sea via wastewater discharges) has radically altered the hydrological cycle of the Adelaide Metropolitan Zone. In areas where, prior to development, for much of the year, rainfall was soaked-up by dry soil, rapid contaminated runoff now occurs. Major creeks that once produced huge stormflows are now impounded and much of the water that would have flowed into wetlands, back dune marshes or to the sea, is now diverted into the water supply network and is used to irrigate europaean style gardens, or flows to sea as waste-water (Figure 2). Thus the timings, locations, volumes and nature of discharges to the sea have altered radically; examples of these changes will be presented in the Input Studies final submission to the Adelaide Coastal Waters Study.

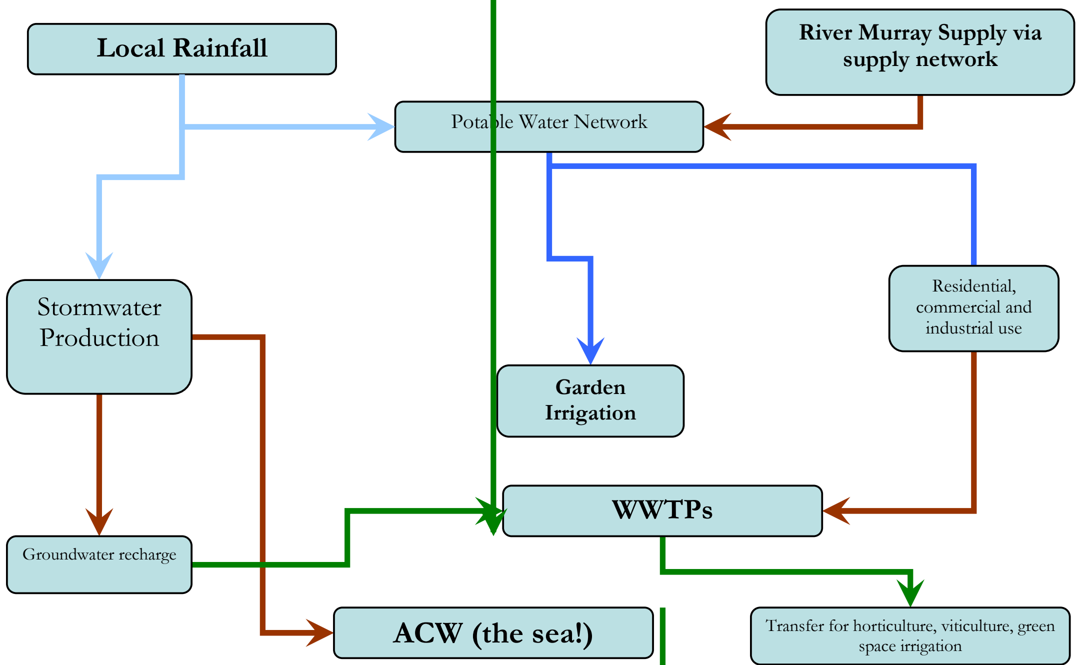


Figure 2: Conceptual diagram of the general flow pathways in the current hydrological and water resource system of Metropolitan Adelaide.

Various approaches were attempted to modify the hydrological model parameters with time to account for the increase in urbanisation, the simplest of these involved using the loss module T_{max} (where T is temperature) parameter as a zero flow threshold, i.e. that for temperatures above T_{max} there would be no effective rainfall. This was found to work satisfactorily but was not sufficiently consistent in its effect between sites. What was found to give the most consistent results and was readily applicable to all sites was a mathematical filter that was applied as an output multiplier to the model flow as described below.

The urbanisation function used to simulate the reduction of the number of residential properties and associated impervious surfaces was based on the sum of opposing cosine functions. The driving variable for the function is the number of dwellings (Figure 3a) which is scaled between 1 and -1 (Figure 3b) for the period of interest such that

$$fd_t = 2\left(\frac{Nd_t}{Nd_{\max}} - 0.5\right)$$

where Nd_t is the number of dwellings at time t and Nd_{max} is the current maximum number of dwellings, fd_t adjusts the opposing cosine such that when Nd_t approaches Nd_{max} , fu_t is approximately 1. When fd_t approaches zero fu_t is a cosine function which varies between -1 and plus 1.

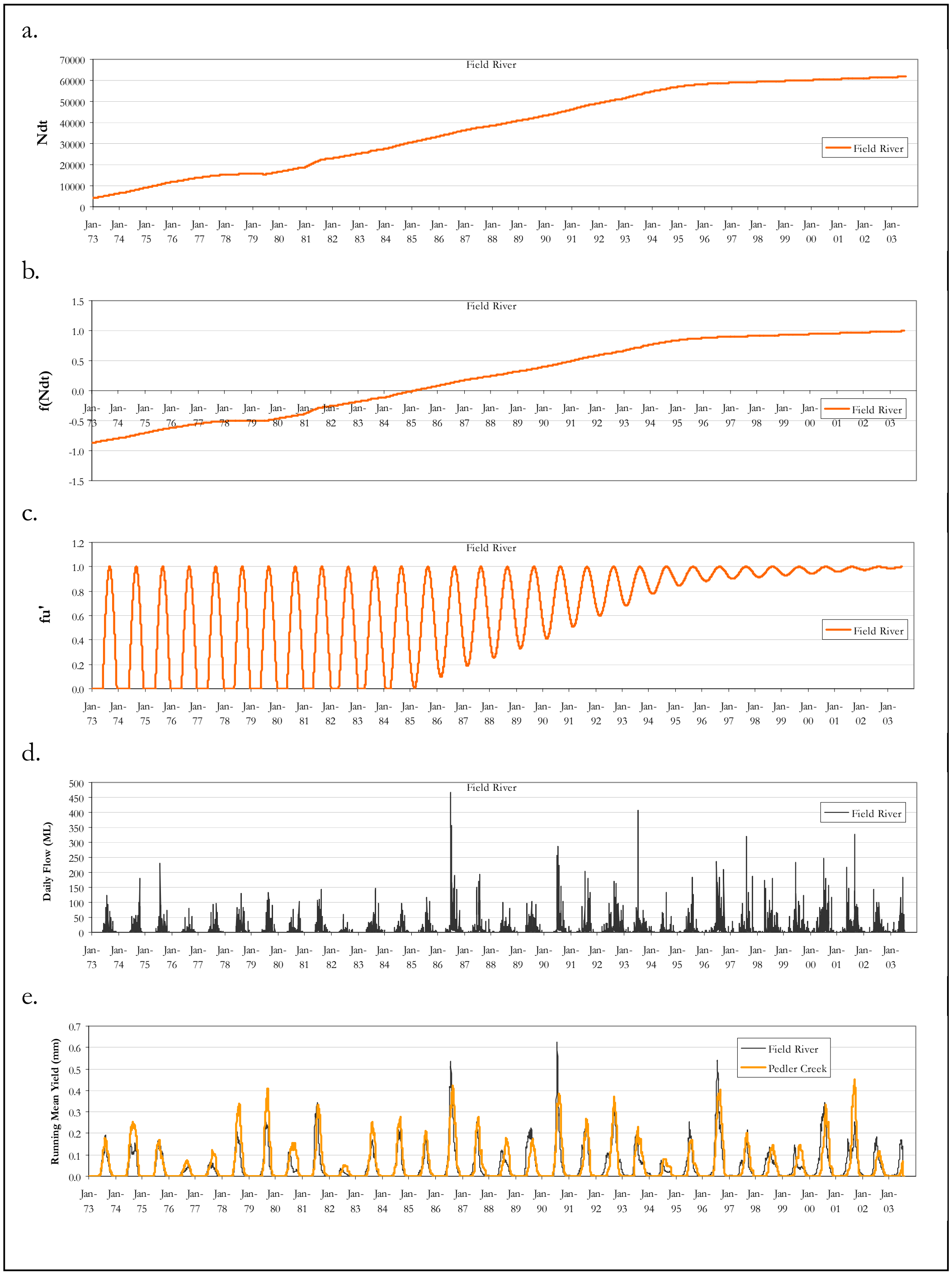


Figure 3: Simulating the impact of reduced impervious land area on stormflows; a. increase in number of dwellings in the Christies Beach WWTP catchment since 1973, b. scaling of dwelling data between 1 and -1, c. function for reducing the stormwater season in relation to the reduction in dwelling numbers, d. modelled daily flows in the Field River demonstrating the change in season width from 1973 to 2003, and e. comparison of the two-month running mean catchment yields for an urbanising catchment (Field River) and an un-urbanised catchment (Pedler Creek),

$$fu_t = 0.5 + 0.5\cos 2\pi\left(t + t_{ph}\right) + fd_t\left(0.5 - 0.5\cos 2\pi\left(t + t_{ph}\right)\right)$$

A phase adjustment, t_{ph}, was required to fit the timing of the highs and low in the function to the observed period of stormwater season.

Since the output flow cannot be negative, the function fu_t must be constrained to zero (Figure 3c),

$$fu_t \le 0,\ fu_t^{'} = 0$$

and an additional index n gives the capacity to further narrow the shoulders of the cosine function, thereby producing a narrower and steeper drawing-in of the run-off season,

$$fu_t > 0,\ fu_t^{'} = fu_t^{\,n}$$

The final output model flow adjusted for reduced urbanisation (Figure 3d) is given by

$$Q_t^{'} = fu_t^{\,n} Q_t$$

where, Q_t is the modelled flow calibrated to recently observed flow data. Values of n between 1 and 2 were found to provide the best match for low urbanisation patterns of catchment yield.

Figure 3e, presents two month running average catchment yield for the un-urbanised Pedler Creek catchment and the urbanised Field River. The purpose of presenting this plot is to demonstrate how the urbanisation function fu_t' causes the season to narrow and that the Field River response has gradually reduced in terms of the width of the hydrological season moving back in time as the number of dwellings declines. In the example shown, Pedler Creek has been calibrated against recent data and the yields are derived from the modelled flows. The Field River was also calibrated for recent data and then the urbanisation function adjusted using n and t_{ph} to fit the yield data in the 1973 to 1976 period, i.e. prior to the main phase of urban development.

3. Calibration Results

Model calibrations were only possible for sites with measured flow for the period of interest (Table 1). Where no calibration data were available, the volume of runoff was adjusted to be consistent with literature values of VRC and or yield. The dynamics of the responses in the un-gauged catchments were matched to catchments which were similar in terms of land use and topography.

Table 1 summarises the model results for all the major stormwater sources between the Gawler River and Sellicks Creek. In most cases, the modelled volumes are within a few tenths of a percent of the observed flow volume for the calibration period. Appendix II lists model parameters for each of the creeks and drains listed in Table 1. Some of the model fits (R_t^2) are very accurate (>0.95) and those which do not score highly when examined visually demonstrate a good correspondence of magnitude and timing of peaks and troughs. In the current study, the overall flow volume is more important than the absolute timing and magnitude of events for load estimation. The daily estimated flows, however, are seen as a resource that may be of value for future studies.

Table 1: Listing of model results for gauged and un-gauged systems.

Stormwater System	Catchment Area km²	Rainfall (mm)	Observed Volume (GL/y)	Model Volume (GL/y)	VRC	Yield (mm)	R_t^2
Gawler R 1940 to 1959	1070.0	755		55.72	0.069	52.1	
Gawler R 1959 to 1992	834.0	755	43.43	43.43	0.069	52.1	0.808
Gawler R 1992 to 2004	834.0	606	12.80	12.81	0.025	15.4	0.267
Smith Creek	205.6	498	*3.29*	3.29	0.032	16.0	
Helps Road Drain	124.0	498		8.52	0.133	68.7	
Little Para (1968-72)	94.6	730	11.85	11.89	0.172	125.2	0.620
Little Para (1999-2002)	44.0	486	*3.67*	3.65	0.171	83.1	
Dry Creek	142.2	578	*10.73*	10.64	0.130	74.8	
Port Catchment	129.2	491		13.46	0.212	104.2	
Torrens (1952-56)	343.0	948	86.20	86.21	0.265	251.3	0.770
Torrens (1999-02)	218.5	707	26.60	26.60	0.173	122.0	0.739
Brownhill Creek	64.2	798	11.98	12.20	0.234	186.8	0.832
Sturt River (2000-01)	116.0	804	9.06	9.06	0.097	78.1	0.962
Patawalonga Stormwater Catchment	32.2	491		0.79	0.050	24.7	
Pier Street	1.5	491		0.15	0.201	98.8	
Broadway	1.0	491		0.10	0.213	104.7	
Marine St	0.8	491		0.09	0.213	104.7	
Harrow Rd	3.4	491		0.42	0.249	122.7	
Wattle Ave	2.1	491		0.27	0.258	127.0	
Edwards St	4.7	491		0.42	0.179	88.3	
Young St	6.0	491		0.56	0.190	93.5	
Marino	1.5	491		0.14	0.190	93.2	
Field River (Main South Road)	34.2	593	3.00	2.99	0.148	87.7	0.716
Field R. (Exc. Main South)	19.1	694		1.09	0.084	58.1	
Field River (Total)	53.3			4.08	0.121	72.0	
Christie Creek	37.8	694	2.99	3.08	0.118	81.6	0.943
Onkaparinga Noarlunga	81.0	748	13.30	13.30	0.220	28.6	0.327
Onkaparinga Estuary	28.2	694		2.39	0.123	85.1	
Pedler Creek (and Southern Creeks)	107.4	617	3.07	3.07	0.046	28.6	0.458

3.1 Limitations and assumptions

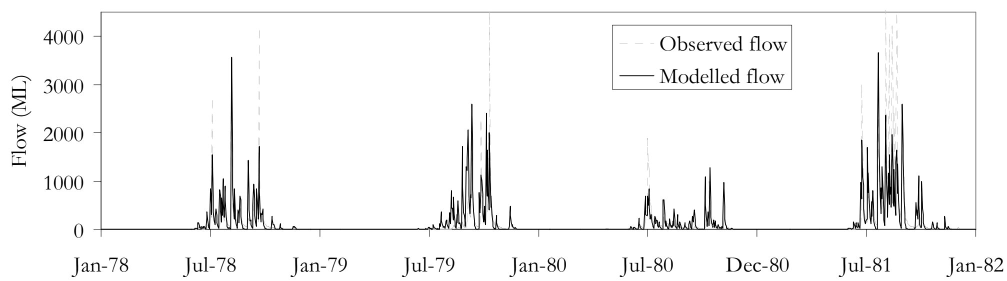
There are certain limitations and assumptions that must be stated about the modelled flows generated by this exercise:.

1. The present day hydrological response of a catchment with minimal residential or urban development is used as the standard that currently urbanised catchments are adjusted backwards towards in terms of their hydrological response.
2. It has been assumed that there has been no shift in the seasonality of rainfall. The urbanisation function is fixed in its phasing relative to the solar year.
3. The relationship changing runoff and the number of dwellings is assumed to be linear.

3.2 Description of modelling for each stormwater system

3.2.1 Gawler River

The Gawler River flows were modelled in three periods (Table 1), 1940 to 1959, 1959 to 1992 and 1992 to 2004. In 1959 the South Para Reservoir was completed and the effective catchment area reduced from 1070 km^2 to 863 km^2. The model was calibrated between 1978 and 1981 with observed flows at the Virginia gauging station (Figure 4a). Flows prior to 1959 were estimated using the same calibration but simply increasing the catchment area. From 1992 onwards the flows measured at Virginia were radically lower than before this period and a third model calibration was carried-out (Figure 4b).



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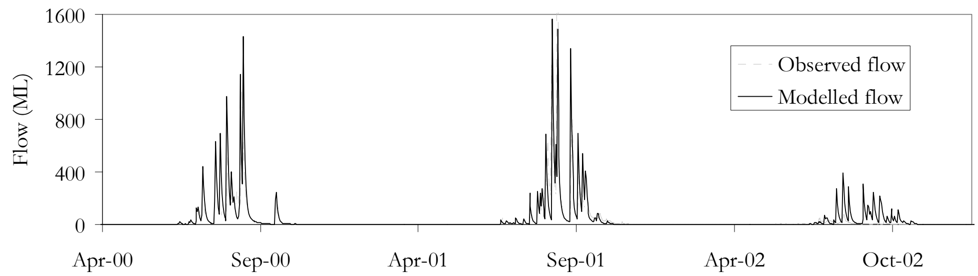

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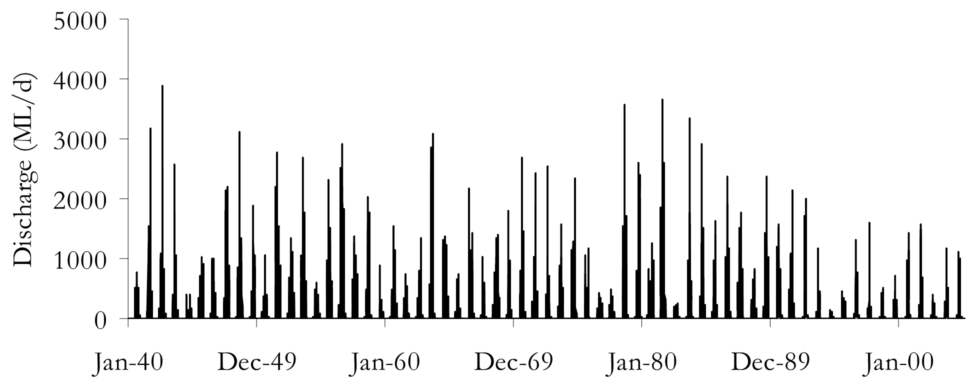

c

Figure 4: Model and observed flows in the Gawler River at Virginia Park (AW 505510) for a. prior to 1992, b. after 1992, and c. modelled flow for the period 1940 to 2004.

Although most of the features of the observed flow were modelled, certain of the extreme events were not readily reproduced. For consistency through time only the modelled flows are used for ACWS purposes (Figure 4c). A further adjustment to the output flows was made by capping at 864 ML (10 m^3/sec), since flows in excess of 864 ML spill out of the Gawler River channel downstream of Virginia to flood the surrounding land. Buckland Park Lake also provides limited stormwater detention at the channel outlet (see Wilkinson et al., 2004).

3.2.2 Smith Creek, Helps Road Drain and Dry Creek

These three stormwater sources were modelled in much the same way as the South Western Drainage Scheme drains. The model parameterisations for Smith Creek and Dry Creek were based on the calibrated model for Pedler Creek. Estimates of VRC based on impervious areas presented in NABCWMB (2003) were used to adjust the volumetric output (Table 2). For Helps Road Drain, the dynamic response parameter values were assumed to be similar to those for Brownhill Creek. The increase in residential area and impervious surfaces was based on the increase in population for the northern Adelaide area. In Smith Creek, from 1996, the Stebonheath Flow Control Park has provided stormwater detention, and flows from this time account for this storage.

Table 2. Mean annual discharge, catchment area and yield for areas draining to Barker Inlet, including overall discharge from this and other studies.

Location	Catchment Area km^2	Annual Flow GL	Yield mm	Reference
Little Para	44.0	3.14	71.36	NABCWMB, 2003
	44.0	3.65	82.95	This study
	44.0	5.28	119.89	EWS, 1991
Dry Creek	142.2	10.73	75.46	NABCWMB, 2003
	142.2	10.64	74.82	This study
	142.2	11.07	77.81	EWS 1991
Helps Rd	124.0	8.51	68.62	NABCWMB, 2003
	124.0	8.52	68.71	This study
	124.0	11.58	93.37	EWS 1991
Smith Ck	205.6	3.29	16.00	NABCWMB, 2003
	205.6	3.29	16.00	This study
	205.6	11.53	56.08	EWS 1991
Port Drains and West Lakes	129.2	13.46	104.18	This study
	133.1	20.52	154.19	EWS 1991
	129.2	15.18	117.46	Clark, 2001
Overall	645.0	40.8	63.33	NABCWMB, 2003; Clark, 2001
	645.0	39.6	61.33	This study
	648.9	60.0	92.42	EWS 1991

Note: Annual flows and yields may differ from table to table due to differing reporting periods. For example the Smith Creek estimate is the value before the loss due to Stebonheath Flow Control Park is applied.

Table 2 sets the present day flow estimates for the stormwater sources to Barker Inlet in the context of past estimates. The values presented in Clark (2001) and NABCWMB (2003) are considered to give a better estimate of flows to Barker Inlet since they account for wetland detention. The EWS (1991) discharge estimates result in consistently higher yields (mm runoff) than the other studies.

3.2.3 Little Para River

The flow time series for the Little Para River exhibits a large step reduction in flows from the end of the 1975 stormwater season. This is due to the commissioning of the Little Para Reservoir. The model application has two parts. A model was calibrated to the pre-reservoir flows for the period 1968 to the end of 1971 using rainfall at Gumeracha and an assumption that changes in land-use did not impact on the hydrological response (Figure 5). A second model was initially calibrated for the post-reservoir period which included compensating dry weather flow from Little Para Reservoir. This was subsequently replaced with a model accounting for the additional storm runoff from the adjacent suburbs in the lower catchment and adjusted to give the flow suggested by NABCWMB (2003). The final output, discharge, was a composite of observed flows augmented by the modelled flows where there were missing data, e.g. prior to 1968 when flow gauging commenced.

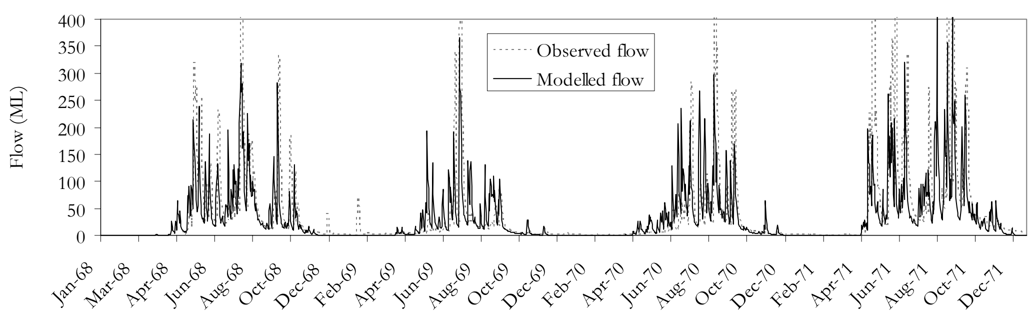

Figure 5: Model and observed flows in the Little Para River at Carisbrooke Park (AW 504504) for the period prior to construction of the Little Para Reservoir.

3.2.4 Port Adelaide stormwater catchment

The Port Adelaide stormwater catchment has an area of 129 km^2 and the total stormwater production from this region was modelled as for the Patawalonga "Ocean" catchment storm drains using rainfall for Pooraka. The VRC and yield for the modelled period were 0.212 and 104 respectively, which is consistent with other storm drain catchments. The increase in urbanisation was linked to the growth in population in central Adelaide.

3.2.5 Torrens River

The construction of Kangaroo Creek reservoir on the Torrens River required a double modelling approach similar to that for the Little Para River. The impact of the new reservoir became apparent in the flow record at Gorge Weir from 1969 onwards. The modelling approach was to model the pre-reservoir flows at Gorge Weir (Figure 6a) using rainfall at Gumeracha. The second component of the model was to calibrate the model on the Holbrooks Road gauged flow (Figure 6b) and hindcast back to 1940 using the central Adelaide population change to drive the urbanisation function; Glen Osmond rainfall was used for this component of the model. The final output, discharge, was the sum of the Gorge Weir discharge up to 1969 plus the additional flow at Holbrooks Road (Figure 7).

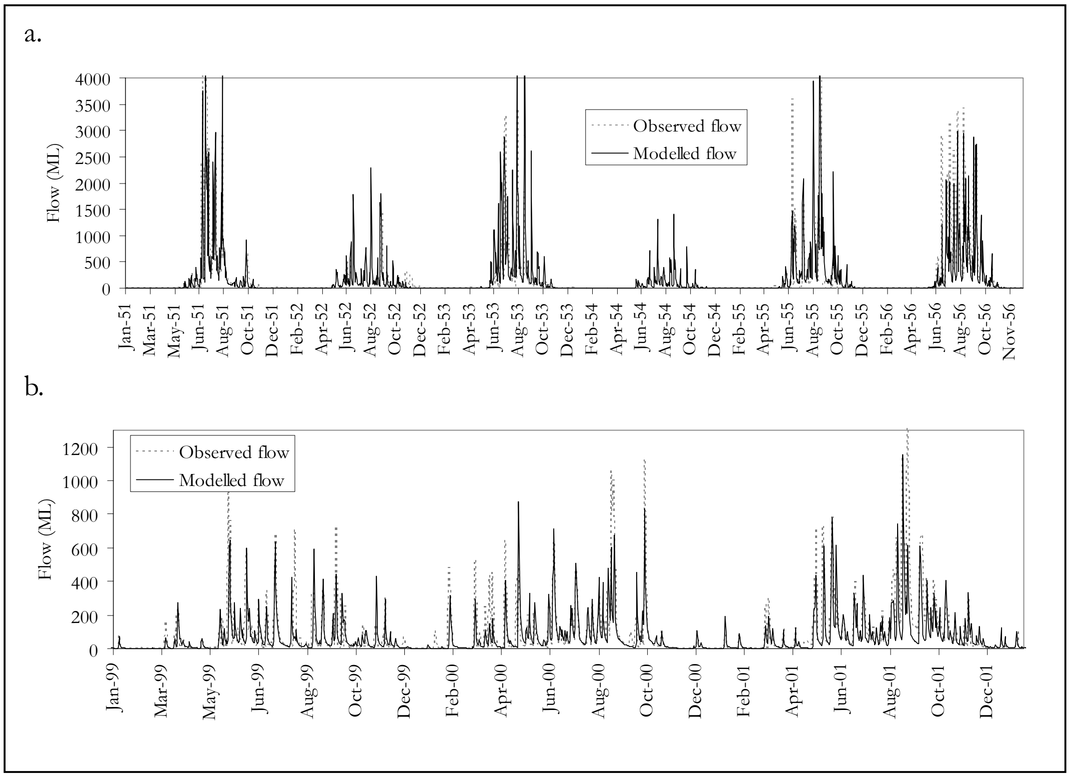

Figure 6: Modelled and observed flows in the Torrens River at a. Gorge Weir in the period prior to construction of Kangaroo Creek Reservoir, and b. at Holbrooks Road after the construction of the reservoir.

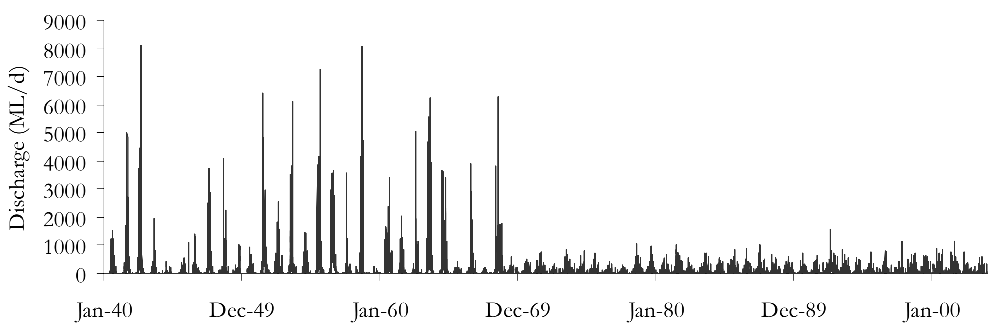

Figure 7: Modelled outflow from the Torrens River since 1940, demonstrating the influence of the construction of Kangaroo Creek Reservoir.

3.2.6 Patawalonga

Flows to the Patawalonga outlet comprise the Sturt River and Brownhill Creek plus additional run-off from residential areas not included in these catchments. Thus three models were used. The first for the Sturt River to Anzac Highway, the second for

Brownhill Creek to Adelaide Airport, and an additional stormwater model for the unspecified area. Rainfall at Branden was used for the Sturt River, Glen Osmond rainfall was used for Brownhill Creek and for the stormwater drainage rainfall at Glenelg Post Office and Coles (Glenelg) car park was used. These three flows were summed to give the resultant flow out of the Patawalonga system (Figure 8). The effect of urbanisation in these catchments was driven by the increase in numbers of dwellings connected to Glenelg WWTP. Note that the increase in baseflow resulting from the growth in discharge from Heathfield WWTP is not incorporated into the model.

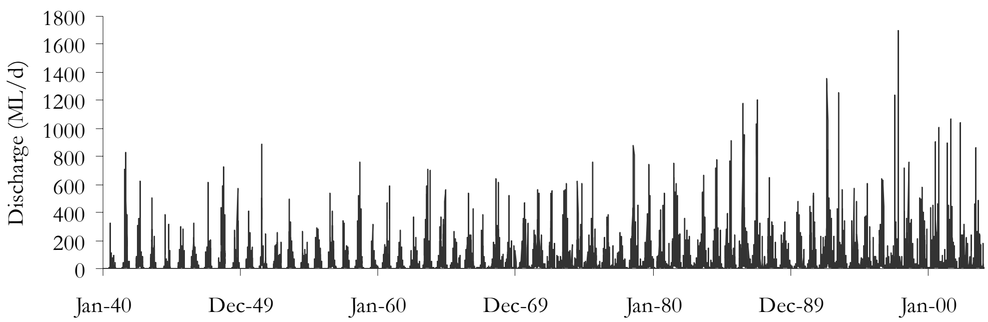

Figure 8: Modelled outflow from the Patawalonga since 1940, demonstrating the increase in duration of the stormwater season and magnitude of peak daily flows.

3.2.8 Patawalonga “Ocean” catchment

Individual storm drain flow series for the drains as listed in Table 1 were generated and the flows adjusted to give the values of VRC reported by Kinhill (1997) and Brown and Root (2001). Since the model time step is one day, the data generated are daily totals and, it has not been possible to reproduce the instantaneous flow peaks of the storm drains. These systems reach peak flow in up to an hour and the entire event may last for less than two hours (see Kinhill 1997; Brown and Root, 2001), however, for the purposes of modelling contamination of the near shore zone in the Adelaide Coastal Waters Study, these flow estimates are adequate.

3.2.9 Field River and Christie Creek

Urbanisation of the Field River and Christie Creek has taken place very rapidly over the last 30 years as evidenced by the near ten-fold increase in population connected to Chrisites Beach WWTP. These data converted to numbers of dwellings have been used to drive the urbanisation function in modelling the impact of this rapid development. In a previous report (Wilkinson et al., 2004) it was reported that Christie Creek appeared to be discharging a far greater quantity of water than would be expected for a catchment of its area. This anomaly has since been investigated and an error in the theoretical rating of the flow measuring control structure has been corrected and the gauged flows are now consistent with other creeks in the Adelaide Metropolitan Area (Table 3).

In addition, the stormwater catchment of Field River was reported as 36.16 km^2, this was calculated by excluding the area above the Happy Valley reservoir dam from the 55.3 km^2 total catchment area, and this, coincidentally, was approximately the same as the total catchment area at the Main South Road gauge site (AW503546) which is

36.2 km^2. In order to estimate discharge at the catchment outlet at Hallett Cove, the discharge at Main South Road was modelled for a catchment of 34.2 km^2 (Happy Valley has a catch of around 2 km^2), to this was added flow from the southern arm and lower portion of the catchment (19.07 km^2). Approximately 80 % of the possible stormwater in the wider catchment of Happy Valley reservoir (19.13 km^2) is diverted around the reservoir for all storms of magnitude less than the 50 year storm (approximately 48 m^3/sec) (Kennewell, pers. comm.). Table 3 presents the updated figures for the Field River.

Table 3. Mean annual discharge, catchment area and runoff per unit area for selected major rivers and creeks in the ACWS study area (as reported in Wilkinson et al., 2004, with the Field River area and Christie Creek flow corrected).

	Effective catchment area (km^2)	Mean annual flow (GL)	Catchment Yield (ML/km^2 = mm)
Gawler River (to Sea)	883.3	15.06	17.0
Smith Creek	205.6	1.13	5.5
Barker Inlet (exc. Smith Ck)	439.4	26.02	59.2
R. Torrens	218.5	21.40	98.0
Patawalonga	212.4	15.18	71.5
Coastal catchment	25.2	2.01	79.8
Field River	**53.3** (36.2)	**4.0** (2.8)	**74.7** (74.3)
Christie Creek	37.8	**2.7** (8.1)	**72.1** (214.3)
L. Onkaparinga	200.8	17.65	88.5
Southern Creeks	221.4	4.01	18.1

Note: For certain catchments the yield may be unrealistically low, e.g. Smith Creek. This is because the total surface water catchment is discontinuous and consequently the actual drainage network that reaches the coast only channels water from a small portion of the catchment.

Christie Creek is known to flow at all times of the year, while the Field River at Main South Road is known to dry out during the summer months as indicated by the hydrometric record. Anecdotal evidence (Scott, pers. comm.) indicates that at the catchment outlet at Hallett Cove the Field River flows has been observed to be flowing during each field visit and at times when other creeks are dry. It is therefore suspected that the Field River receives dry weather flow sustaining groundwater in a similar way to Christie Creek. For Christie Creek, major ion chemistry characteristics indicate that groundwater contributes around 4.8 % of the annual flow (see Wilkinson et al., 2005). Major ion chemistry data at Hallett Cove are not suitable to confirm or disprove that this is the case for the Field River, although the nitrogen chemisty is radically different to that at Main South Road. For the purposes of this exercise it has been assumed that groundwater feeds dry weather flow in the Field River in a similar manner to Christie Creek and the model of the lower river uses a structure and parameterisation similar to that of Christie Creek.

3.2.10 Onkaparinga

The Onkaparinga system presented an interesting challenge to model, given the presence of Mt Bold reservoir and the River Murray transfer through the system.

Initially it was decided to model the inflow to Mt Bold at Houlgrave Weir and also to simulate the demand from the water supply system in order to account for reservoir drawdown and overspills past Clarendon Weir (the off take for water into the reticulation system). This approach was found to be over-complicated and did not render satisfactory results. Recreating the peak flows downstream of Mt Bold reservoir was problematic, Figure 9 presents the final model calibration for the flow at Old Noarlunga which demonstrates an acceptable fit between the model and observed data. The observed and modelled volume of flow were matched in this final version of the model (see Table 1). In addition to the run-off at Old Noarlunga an estimate was made of the stormwater inflows from the 28 km^2 estuarine catchment, which for the purposes of this exercise, was assumed to have undergone residential development at the same rate as Christie Creek.

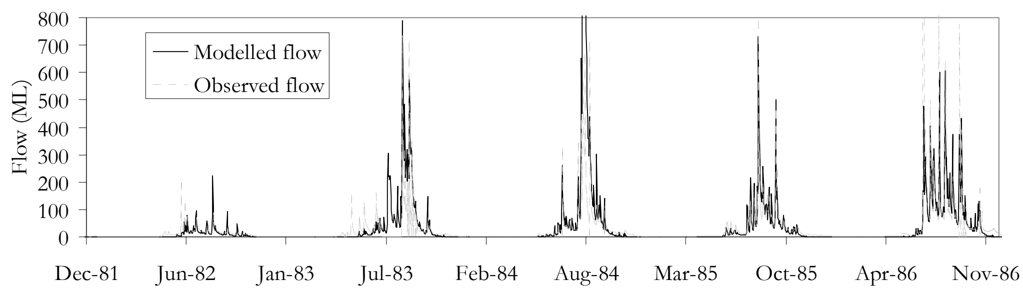

Figure 9: Modelled and observed flow in the Onkaparinga River at Old Noarlunga showing the model calibration period.

3.2.11 Pedler and Southern Creeks

Pedler Creek is the only one of the creeks between the Onkaparinga and Sellicks Beach that has any form of flow gauging. The catchment has minimal residential development in the area leading to the gauged section (AW 505543 Stump Hill Road). This site was assumed to be representative of the runoff characteristics of an un-developed site and was used as a control against which to match the historic runoff yield of urbanising catchments. In addition, it was assumed that the stormwater runoff from the neighbouring creeks was similar in nature to that from Pedler Creek. Some variation in the patterns of runoff to sea from the various creeks may be expected given that the urbanised areas are concentrated at the coast, this is, however, offset by lower rainfall at the coastal margin and also by the fact that most of these creeks terminate in back shore lagoons. The seasonality in flow in Pedler Creek at least gives some indication of when these creeks might be expected to flow to sea and this suggests that during the summer period rainfall losses to soil storage are so great that runoff would only be expected for the most extreme of storms.

4. Summary

This report has presented a summary of work done to recreate estimates of daily stormflow in the creeks and drains in the Adelaide Metropolitan Area between the Gawler River and Sellicks Creek as part of the Adelaide Coastal Waters Study. There were two purposes for this exercise. The first was to provide hindcasts of stormflow to facilitate estimation of the timing and magnitude of historic pollutant loads to the ACWS coastline. The second was to provide stormflow estimates for the PPM2 sub-program of ACWS which is the hydrodynamic modelling of Adelaide Coastal Waters. The report presents the modelling approach used and limitations of the method and provides a summary of the modelling results and calibration parameters. A site by site description of the model application to each stormwater source, or in certain cases the group of sources, was provided. In addition, exemplar plots of model output are provided and give a visual demonstration of the quality of output. The estimated daily flows will be archived and made available as a resource for sub-sequent studies.

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Appendix I: IHACRES model overview

The model used in this study, based on the IHACRES model (Littlewood and Jakeman, 1993), is a lumped conceptual rainfall-runoff model. The original rainfall-streamflow modelling methodology was the result of collaboration between the Institute of Hydrology, Wallingford, UK and the Australian National University, Canberra (Jakeman et al., 1990; Littlewood and Jakeman, 1993, 1994). In principle, the methodology can be applied at any data timestep. There are published accounts of analyses ranging from using 6-minute interval data on catchments less than 1 ha ($0.01 km^2$) to monthly data on a catchment of about 10000 km^2. The model has been successfully applied to many catchments at a daily data time step.

The input data requirements are:

- unbroken time series of rainfall (and streamflow for calibration);
- corresponding air temperature (as an indicator of seasonal changes in evaporative demand);
- catchment size (km^2),

and the model outputs are:

- modelled streamflow time series, and
- modelled catchment wetness index time series.

The model consists of two modules, a non-linear loss module to convert rainfall to effective rainfall, and a linear module to convert effective rainfall to streamflow (Jakeman and Hornberger, 1993). Effective rainfall is that rainfall which is not lost to evapotranspiration which therefore eventually becomes streamflow. Figure A1 is a schematic diagram showing the model with two flow pathways.

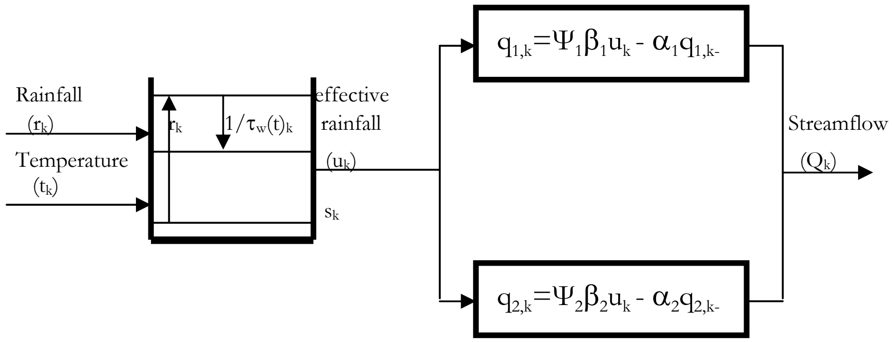

Figure A1: Structure of the basic IHACRES model

In the non-linear module, a catchment storage index s_k is calculated at each time step. It indicates the potential of the catchment to produce streamflow from precipitation (Jakeman *et al*, 1990). The most commonly identified structure in the linear module is two reservoirs in parallel corresponding to quick and slow flow, although in the case of the stormwaters in Adelaide many of these were modelled with a single flow pathway corresponding to the rapid discharge afforded by the piped and culverted drainage system.

The model equations are as follows:

Effective rainfall,

$$r_k^* = 1 - \left(\frac{T}{T_{\max}} \right) r_k$$

where r_k is the measured rainfall, r^*_k is effective rainfall, and T is air temperature. The catchment storage index is represented by

$$s_k = \left(\frac{\tau_w^{-1}}{1-(1-\tau_w^{-1})z^{-1}} \right) r_k^*$$

where τ_w is the time constant of the soil moisture store. The model is presented in the finite difference backwards approximation (see Young and Wallis, 1993). In the discrete time form, z^n is the "z-operator" and is a mathematical convenience to aid notation and to help simplify equations. For example, if the rainfall at time t, $r_t = r_k$ and the sampling interval is given by Δt, then the rainfall at $t + \Delta t$ is r_{k+1}, which is $z^1 r_k$, similarly $z^{-1} r_k = r_{k-1}$, i.e. the previous value of rainfall. The input to the linear streamflow component of the model is the available runoff volume, u_k. This is the product of effective rainfall (m) and catchment area, A (m^2), and adjusted according to soil storage;

$$u_k = A \frac{s_k}{s_{\max}} r_k^*$$

where s_{max} is used to scale soil moisture storage between 1 and 0. In the IHACRES model where the output runoff volume is known, a scaling constant is used to adjust the effective rainfall volume to the observed discharge volume (Littlewood and Jakeman, 1994). In the adaptation of the IHACRES model used in the current study, the model was coded in a three streamflow pathway version with constants Ψ_n to assign the proportion of flow entering each pathway and to adjust the outflow to match the measured flow volume.

The available run-off volume, is routed through the number of streamflow pathways needed to reproduce the dynamics of the observed streamflow record. Two streamflow pathways usually suffice, however, in some cases a third pathway may be required:

$$Q_k = \frac{\psi_1 b_1}{1 - a_1 z^{-1}} + \frac{\psi_2 b_2}{1 - a_2 z^{-1}} + \frac{\psi_3 b_3}{1 - a_3 z^{-1}} u_k \,,$$

The parameter relationships are;

$$a_n = e^{-\Delta t . \alpha_n} \,,$$

$$\alpha_n = 1 / \tau_n,$$

$$b_n = (1 - a_n).$$

τ_n is the time constant for the respective pathway in hours or days. The streamflow pathways that are not needed to fit the model and be “switched-off” by setting the relevant ψ to zero. For ungauged catchments where there may only be an estimate of volumetric runoff coefficient (VRC) or catchment yield the values of ψ_n can be adjusted to give the appropriate value for VRC, and the flow characteristics can be adjusted to give a response that matches a nearby catchment with similar topography and land use.

In the adaptation of the IHACRES model presented here an excel spreadsheet version is used, the best results were achieved by manual calibration. Various measures of model performance are used in the current study and are aimed at matching the peaks and troughs of the model output to the observed, matching the actual flow volume and producing a realistic VRC.

The model header showing model parameters, statistics of goodness of fit and volumetric accuracy is presented in Figure A2.

Three pathway rainfall-runoff model based-on Littlewood and Jakeman (1994)

												r2 = 1	rt2 = 1	rmae > 0		
Tot. rain (mm)				694.1	T_max	τ_wet		τ_1 hrs	τ_2 dy	τ_3 dy	Sepn. Ratios = 1	*R^2*	Rt^2	RMAE	VRC	Yield
Rain vol. ML				26237	37 °C	12 days		10	24	200	Ψ1 0.382	0.652	0.9434	1.07	0.118	81.602
Catchment Area				37.8	km^2	tw =	0.07996	0.091	0.959	0.995	Ψ2 0.03	Model		Observed		
					15236.1	Volume	7368.6	0.347	0.001	0.0000	Ψ3 0.01	3084.5	vol. ML	2992.6	7.25E+04	1.01E+06
395			34.05	% loss	41.9	0.936	4.433	max		0.184	Total 0.422	88.2	% loss	88.6	2.08E+05	1.79E+07
Date, time	Dwell-ings	season squeezer	Rainfall	Temp	R-star	Soil_ moist	U_k	Q_1	Q_2	Q_3	Q2+ Q3	Model Q		Obs. Q	7.81	
365.2461538	0.621					0				0.000		0.00				
01/01/1940	275.0	0.00	0	22.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
02/01/1940	275.0	0.00	0	31.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
03/01/1940	275.0	0.00	0	27.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
04/01/1940	275.0	0.00	0	25.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
05/01/1940	275.0	0.00	17	20.45	7.60	0.61	0.00	0.00	0.00	0.00	0.00	0.00				
06/01/1940	275.0	0.00	0	17.55	0.00	0.56	0.00	11.59	0.04	0.00	0.04	0.00				
07/01/1940	275.0	0.00	0	19.05	0.00	0.51	33.37	1.05	0.04	0.00	0.04	0.00				

Figure A2. Header section for the model of Christie Creek.

R_t^2 is a statistic of goodness of fit used in time-series modelling (see Young and Benner, 1991, Price et al., 2000) and tends to highlight errors in fitting the high flow peaks and the timing of the rapid dynamics of the response;

$$R_t^2 = 1 - \frac{\sigma (y_k - \hat{y}_k)^2}{\sigma (y_k)^2}$$

where, $\sigma(y_k - \hat{y}_k)^2$ is the variance of the squared model errors and $\sigma(y_k)^2$ is the variance of the squared observed values. When the model errors are small R_t^2 tends to 1.

The R^2 coefficient of determination is similar to R_t^2;

$$R^2 = 1 - \frac{\Sigma(y_k - \hat{y}_k)^2}{\Sigma(y_k - \bar{y}_k)^2}$$

where, $\Sigma(y_k - \hat{y}_k)^2$ is the sum of the squared model errors and $\Sigma(y_k - \bar{y}_k)^2$ is a measure of the variation of the observed values from the mean. When the model errors are small R^2 tends to 1.

The third measure of fit is specifically intended for the improvement of the fit of the recession limb of the modelled flows (Jakeman et al., 1993), this is the Relative Mean Absolute Error RMAE and is given by;

$$RMAE = \frac{1}{n}\sum\left|\frac{y_k - \hat{y}_k}{y_k}\right|$$

In addition, for the purposes of load estimation an indication of the modelled and observed flow volume for the calibration period is of value. This is because the goodness of fit statistics can indicate that the model fits the timing and highs and lows of the observed data to a high degree of accuracy, yet the estimated flow volume might be as much as 20 % in error, in which case these statistics alone are not sufficient to fit the model. Where the rainfall data used in the model is representative of the actual rainfall received in the catchment, VRC gives an additional cross-check on model accuracy;

$$VRC = Q/r.A\,.$$

If the rainfall is not well representative the value of VRC will be in error, in which case yield gives a better estimate of volumetric accuracy, since it is an absolute measure of the runoff independent of the rainfall, i.e. by adjusting the model yield to fit the observed yield the inappropriateness of the rainfall data is compensated for.

Appendix II: Hydrological model parameters

Stormwater System	τ_{wet} (d)	τ_1 (hr)	τ_2 (d)	τ_3 (d)	Ψ_1	Ψ_2	Ψ_3	τ_{ph} (d)	n	squeeze
Gawler River (1940-1959)	37	30			0.29			125	0.5	**-0.9**
Gawler River (1959-1992)	37	30			0.29			125	0.5	**-0.9**
Gawler River (1992-2004)	37	42	10.0		0.31	0.05		125	1.0	**-0.9**
Gawler River at outlet										
Smith Creek	*40*		*1.8*			*0.08*		*120*	*2.0*	***-0.4***
Helps Road Drain	40	15	10.0		0.46	0.13		120	1.0	
Little Para (1968-72)	40	35	15.0	100	0.50	0.16	0.06	145	1.0	
Little Para (1999-2002)	40	*30*			*0.13*			140	2.0	
Dry Creek	*200*		*1.5*			*0.29*		*120*	*1.0*	
Port Catchment	*12*	*3*			*0.71*			*120*	*2.0*	
Torrens (1952-56)	25	24	18.0		1.21	0.20		130	2.5	**-0.5**
Torrens (1999-02)	150	26	10.0		0.27	0.12		120	1.5	
Brownhill Creek	200	15	10.0	30	0.35	0.13	0.02	120	1.0	
Sturt River (2000-01)	4	20			0.42			120	2.0	
Patawalonga Stormwater Catchment	*12*	*3*			*0.17*			*120*	*2.0*	
Pier Street	*12*	*3*			*0.67*			*120*	*2.0*	
Broadway	*12*	*3*			*0.71*			*120*	*2.0*	
Marine St	*12*	*3*			*0.71*			*120*	*2.0*	
Harrow Rd	*12*	*3*			*0.83*			*120*	*2.0*	
Wattle Ave	*12*	*3*			*0.87*			*120*	*2.0*	
Edwards St	*12*	*3*			*0.60*			*120*	*2.0*	
Young St	*12*	*3*			*0.64*			*120*	*2.0*	
Marino	*12*	*3*			*0.64*			*120*	*2.0*	
Field River (Main Sth Rd)	20	12	8.0		0.29	0.06		120	1.0	
Field River (exc. M Sth Rd)	12	10	24.0	200	0.25	0.03	0.02	120	1.0	
Field River (Total)										
Christie Creek	12	10	24.0	200	0.38	0.03	0.01	120	1.0	
Onkaparinga Noarlunga	80	24	18.0		0.40	0.30		130	2.0	**-0.7**
Onkaparinga Estuary	*12*	*3*			*0.45*			*120*	*1.5*	
Peddler Creek (and Southern Creeks)	50		1.8			0.25		120	3.5	**-0.5**