Flood Hydrology in an Arid Area – Findings from the Gammon Ranges Project

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Abstract

Monitoring of the Arcoona Creek catchment in the Gammon Ranges commenced in 1988 with the installation of a single pluviometer, and the project now maintains five pluviometers and a stream gauge monitoring a 49.7km^2 catchment with an average rainfall of approximately 250mm to 300mm. The catchment monitoring has extended to include Windy and Emu Creeks, which discharge into the Aroona Dam at Leigh Creek.

Although runoff events are rare there are now four significant flood events in the nearly 20 years of record that can be used for calibration. Calibration was carried out using the RRR model, which allows for several runoff processes to occur. It was found that in most cases there is a significant slow response, as well as a very rapid response occurring in the hydrograph. It is postulated that the large gravel bed of the creek has a significant effect on flood flows, creating large losses and a slow response and for some events a very rapid time of rise as a flash flood occurs when the infiltration rate of the bed is exceeded. Water level data was sourced at the minimum obtainable 5 minute interval to gain some idea of the time of rise, and even then there was a measured rise of up to 1.7m within the five minutes. This flash flood possibility and the high probability of runoff from only part of the catchment for most events means that developing a model for accurate prediction of flood flows will prove very difficult. This paper describes the catchment and the calibration, compares the catchment hydrology with other arid catchments and discusses some of the issues associated with the collection of rainfall and stream flow data.

1. INTRODUCTION

The Gammon Ranges are situated in the far northern Flinders Ranges and consist of a deeply dissected quartzite plateau with steep gorges and spectacular cliffs. The annual rainfall of the Arcoona Creek catchment area, which lies within the western Gammon Ranges varies from approximately 250mm to 330mm, based on the over 20 years of recorded data.

The Gammon Ranges project is managed by the Scientific Expedition Group (SEG), a volunteer organisation that aims to promote and run expeditions of a scientific, cultural and adventurous nature and to encourage knowledge and appreciation of the natural environment. This area was selected (see Figure 1) because it is less popular than the eastern part of the park which means that the scientific equipment is less likely to be disturbed and the data collection trip is in an area of near wilderness which adds to the experience for participants. The project is described in detail in Kemp et al (2008).

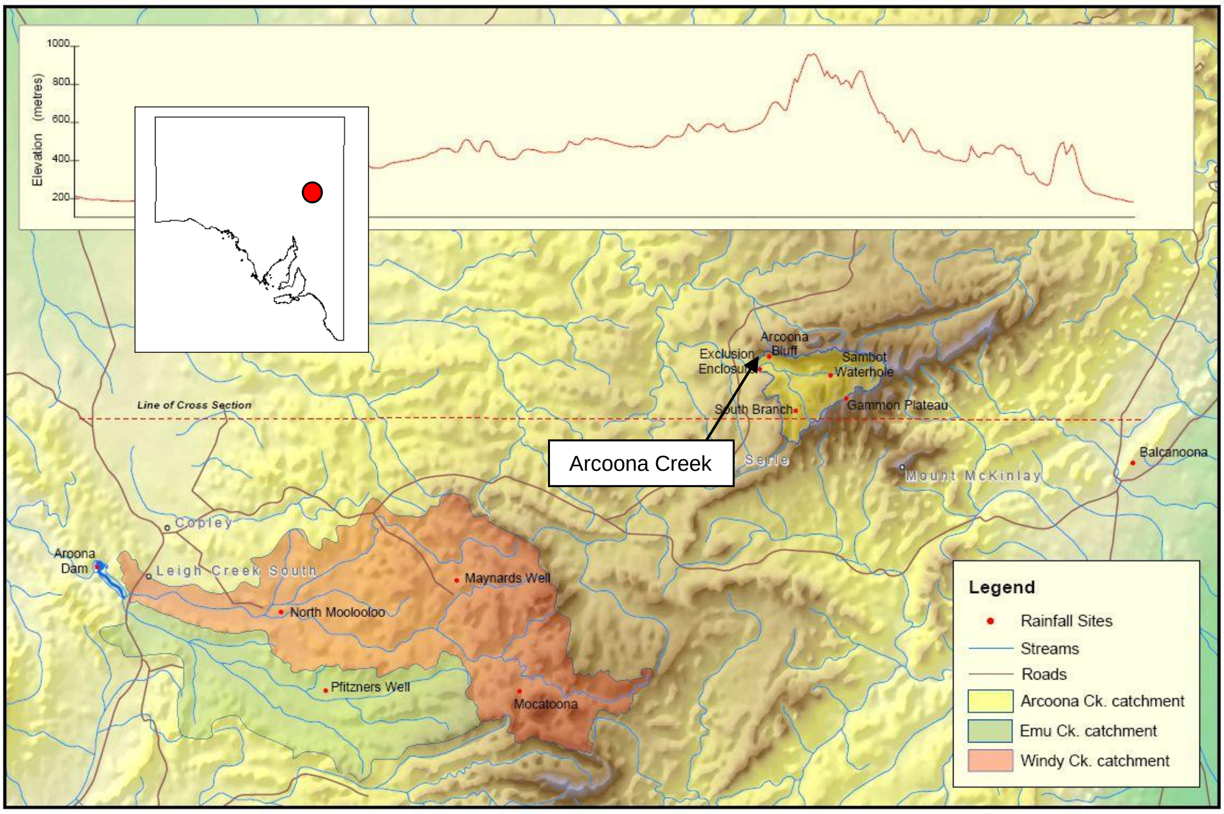


Figure 1 Gammon Ranges Project Catchments

Although the program includes a wide range of biological and botanical monitoring, this paper will focus on the rainfall and stream flow monitoring in the Arcoona Creek catchment.

2. ARID ZONE FLOOD HYDROLOGY

An initial distinction can be made into three broad classes of hydrological systems in arid areas:

- Sloping regions with an integrated stream network,
- Plainlands with a primitive or no stream network, and
- Regions with major inputs of surface water or groundwater from more humid regions.

The Arcoona Creek catchment falls into the first category, with a very well defined stream network, and significant relief. In addition, as with many other streams in the arid ranges of Australia, there is a significant gravel bed in the creek channel.

The problems associated with the modelling of flood hydrology in arid areas is summarised in Pilgrim et at (1988). These include:

- A great temporal and spatial variability of rainfall.
- Channel transmission loss.
- Partial area runoff.
- Rapid time to surface ponding and onset of runoff.
- Translatory waves, or the “wall of water” of folklore that occasionally occur. These are caused by the transmission loss during the rising limb of the hydrograph.
- The long term variation in vegetation.

All of these factors are demonstrated to some extent in the record of the Arcoona Creek.

3. FLOOD RECORD

The gauging station on Arcoona Creek (A0040520) commenced recording in December 1993. It records flow from a catchment area of 49.7km^2.

The station has no fixed control, and the stream bed contains a significant gravel deposit. The catchment is quite mountainous, with an elevation range from 320m to 930m. The rating curve is theoretical, and is based on site survey. There has been no gauging carried out due to the site's remote location. Approximately 10% of the record is missing, most of which is in the early years of monitoring. The reliability of the instrumentation has improved over the years.

In the nearly 20 years of record there have been only 15 significant flows, with only 10 flows exceeding 1m^3/sec. There have also been 9 years with no recorded flow. Two day rainfalls of up to 70mm have occurred without stream flow. Table 1 lists the ten highest recorded flows in the period of record.

Table 1 10 Highest Recorded Peak Flows in Arcoona Creek

Date	Peak Flow (m^3/sec)
15/03/1996	55.4
16/01/1995	24.4
29/02/2012	15.9
12/02/2010	10.8
14/03/2011	9.3
17/01/1995	8.6
6/02/2011	4.3
20/02/2000	3.3
12/12/1993	1.7
13/11/2010	1.1

With this few flows in the record it is not easy to determine flood frequency. Figure 2 shows the partial series plot of Average Recurrence Interval vs. flow. A distribution was fitted to the high flows, using the power law (Malamud and Turcotte, 2006) for flows above 3.3m^3/sec. Table 2 shows a comparison of Arcoona Creek with the regional regression carried out by Zama et al (2012) for catchments in arid South Australia. The Arcoona Creek catchment was not included in this regression.

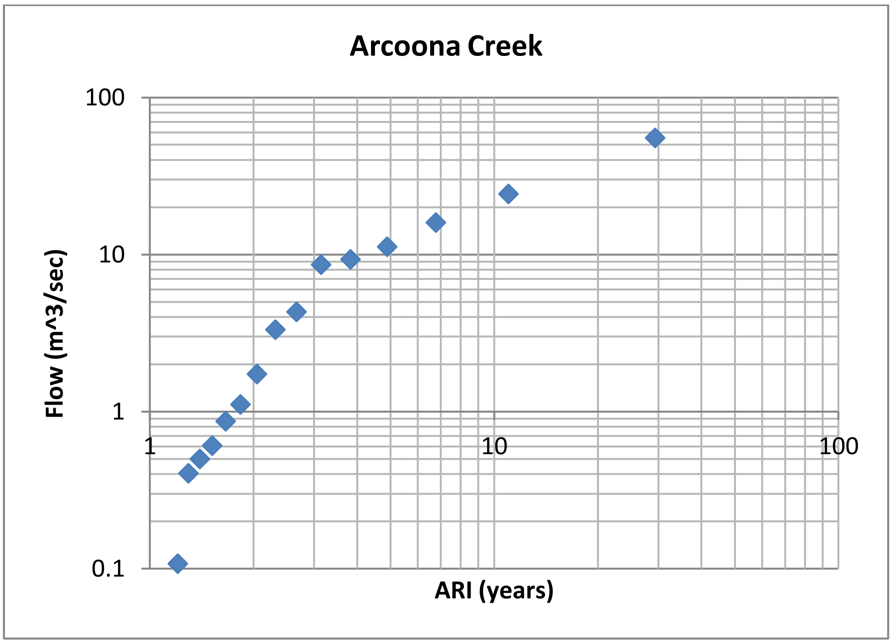


Figure 2 Arcoona Creek Flood Frequency Plot (Partial Series)

Table 2 Flood Frequency for Arcoona Creek

ARI (years)	Arcoona Creek (m^3/sec)	Zaman et al (2012) (m^3/sec)
10	22.0	33.4
20	40.0	50.1
50	87.8	84.4
100	159.2	125.0

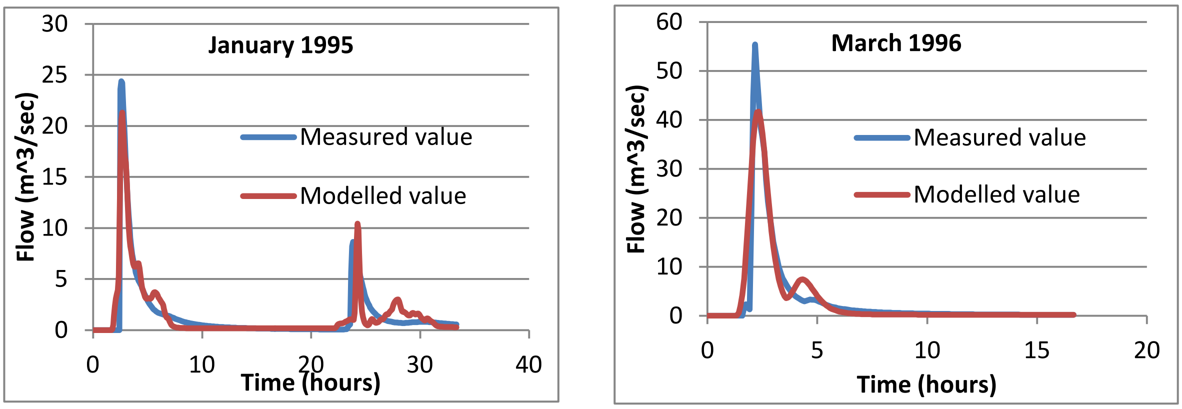
4. FLOOD MODELLED

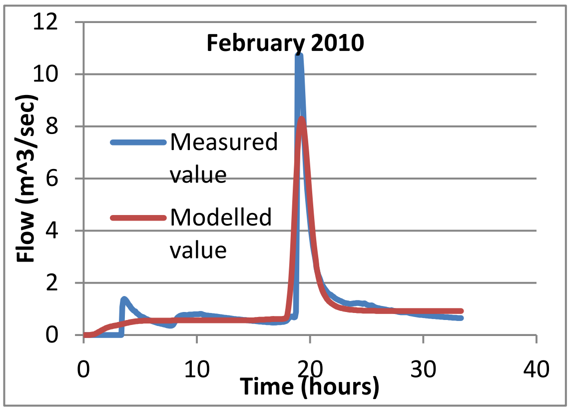
The largest four events were chosen for modelling. Table 3 contains details of the events selected for calibration. Of significance is the low runoff depth compared with the rainfall depth, apart from the 2012 storm, that was of long duration and comparatively low intensity. The runoff depths were quite small for all events, compared with the rainfall, with all runoff events producing less than 18% of the rainfall volume.

Table 3 Events Selected for Modelling

Date	Duration Modelled (hrs)	Peak Flow Depth (m)	Peak Flow (m^3/sec)	Hydrograph Volume (m^3)	Mean Rain (mm)	Measured Runoff Depth (mm)	Runoff Percentage
16/01/1995	36.0	1.181	24.4	182440	72.3	3.67	5%
15/03/1996	24.0	1.642	55.4	197170	37.9	3.97	10%
11/02/2010	48.0	0.845	10.8	152500	52.5	3.07	6%
28/02/2012	96.0	0.992	15.9	786650	85.9	15.83	18%

Figure 3 shows the hydrographs for the events. Of note is the very rapid rise and in general the very short duration of the hydrographs. In order to further examine the time of rise data were obtained at the minimum time step recorded, which was 5 minutes. It was noted when these data were obtained that for the first three events there was a very significant measured rise of up to 1.7m within the five minutes. In the case of the 1995 event, the water level rose from 520mm below the cease to flow to 1.17m above the cease to flow between 3:25pm and 3:30pm. Even given that below the cease to flow there was only a small volume to be filled there is still a rise that can only be explained by the presence of a “flash flood” or translatory wave. This flash flood is the “wall of water’ that has often been referred to, but has seldom been documented in Australia. Figure 4 shows a plot of the measured flow depth vs. time in January 1995, showing the unusual record of flow depth that occurs with this type of event.





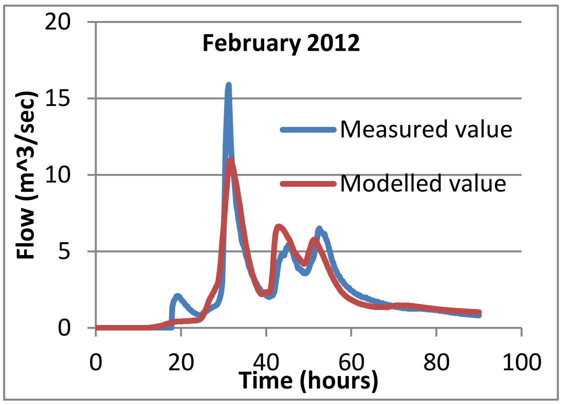


Figure 3 Hydrographs of the Events Modelled

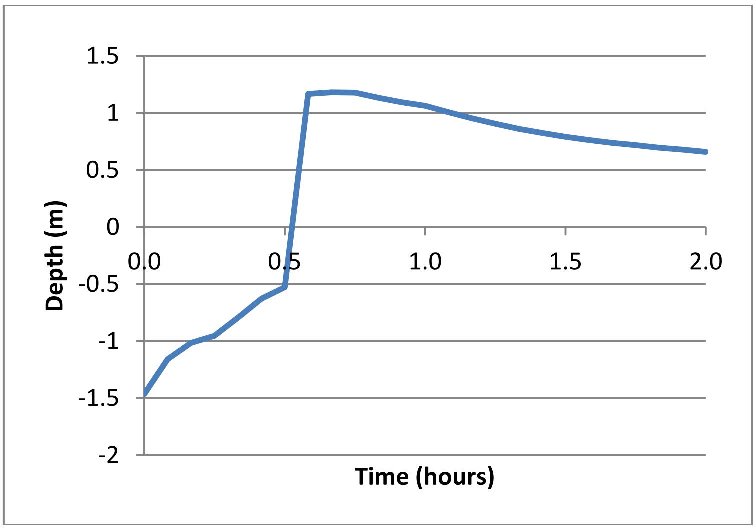


Figure 4 Flow Depth vs Time for the January 1995 Event

These flash floods have been documented in other parts of the world (Desilets et al, 2008, Mudd et al, 2006, Reid et al, 1998). They occur where there is significant infiltration into the stream bed, as the infiltration eats up the leading edge of the hydrograph. The leading edge of flash floods in ephemeral streams typically has a steep walled nose or bore (Leopold and Miller, 1956) that represents a flow discontinuity and is similar to the front of a dam break flood. It could not be expected that the normal runoff routing model could produce a good fit to the part of the hydrograph where the bore occurs.

5. THE RRR MODEL

The RRR model (Kemp and Daniell, 1996) was used for modelling, using a time step of 5 minutes for all but the 2012 event, which used a 15 minute time step. This model was selected as it is a runoff routing model that can model several runoff processes. A previous calibration of Arcoona Creek events (Kemp et al, 2008) found that more than one runoff process was occurring in the two events that were available for modelling at that stage.

The RRR model splits the modelled storage within the catchment between runoff processes that occur as water moves towards channels and the channel storage itself. Any number of runoff processes can contribute to the channels. Each process has an initial loss (IL), a continuing loss (CL) or proportional loss (PL) and a storage parameter k_p. The channel has a storage parameter k.

The model assumes 10 equal length channel segments, with an equal hillside area contributing to each channel segment. Each of the 10 channel storages and the 10 process storages contributing to each of the channel segments follows the form;

$$S = 3600\, k\, Q^{m} \qquad (1)$$

It is assumed that the channel storage is linear (lag does not vary with flow and thus m = 1) whereas the process storages are generally non-linear, with the lag due to the storage varying with the flow through the storage. An m value of 0.8 is used, as is used in the RORB model.

In order to compare storage parameters from catchment to catchment two generalised parameters must be introduced. The first is the channel characteristic velocity, vc which is related to the channel storage parameter k by the following relationship:

$$vc = d/(36k) \qquad (2)$$

where vc	is the channel characteristic flood wave velocity (m/sec)
d	is the measured longest flow path length in the catchment (km)
k	is the channel storage parameter (h)

The second is a series of catchment characteristic lag parameters, cp1, cp2 etc. These are related to the runoff storage parameter kp (for each of the runoff processes) by the following relationship:

$$c_p = k_p\, A^{m-1} \qquad (3)$$

where A	is the measured catchment or sub-catchment area (km^2)
m	is the exponent in the storage equation S = 3600 k_p Q^m (generally taken as 0.8)

6. MODELLING

For the modelling of the four events, the catchment was split into two sub-catchments with the rainfall from the Plateau (A0040517) and the Exclusion Zone (A0040518) applied. Only two sub-catchments were used because of the location of the pluviometers, and the complexity of the parameter estimation. The model was calibrated using the parameter estimation program, PEST (Doherty, 1994), which provides an objective calibration of the storage and loss parameters. Calibration was carried out using both an initial loss-continuing loss model and an initial loss-proportional loss model, and with the assumption of one process only, or two processes occurring. Initial values were based on the previous calibration (Kemp et al 2008). However the results cannot be directly compared, as the gauging station rating has been changed since the earlier work.

The mean square error between the measured and predicted hydrograph ordinates was used as the objective function to be minimised.

7. RESULTS

The model was able to produce good predictions of the recorded hydrograph for all events. However there is no loss model that is clearly the better model. The February 2012 event had parameter values that were quite different to the other events, which may be expected, given that the 2012 event was of much longer duration. In addition it is not clear that there are one or two processes occurring in each event. Table 4 summarises the mean square error of the calibrations, and Table 5 is a summary of the fitted values for two processes and a proportional loss model, as this is representative of the results. Also included is a comparison with mean values from a humid area (Mount Lofty Ranges), documented in Kemp, 2010.

Table 4 Calibration Mean Square Error

Event	2 process, CL	1 process, CL	2 process, PL	1 process, PL
1995	1.318	1.543	1.348	1.459
1996	2.341	2.365	2.851	3.433
2010	0.559	0.886	0.589	0.942
2012	1.384	1.661	0.934	1.204

Table 5 Summary of Fitted Parameters and Humid Area Values (two processes, proportional loss model)

Event	IL1 (mm)	IL2 (mm)	PL1	PL2	c_{p1}	c_{p2}	vc (m/sec)
Range of 1995, 1996, 2010	7.8 - 12.4	4.2 – 46	0.61-0.93	0.84-0.95	6.5-20.4	0.006-0.054	1.75 – 6.28
2012	42.4	86.6	0.90	0.80	3.00	0.26	3.39
Mean Humid Area	0	18.4	0.74	0.63	1.21	0.25	1

It can be seen that there is a substantial difference between the Arcoona Creek values and the Mount Lofty Ranges values. In particular:

- The initial losses for both processes are very large for Arcoona Creek, compared with the Mount Lofty Ranges.
- There is a significant difference between the 2012 and the other events in terms of the storage parameters (c_{p1}, c_{p2} and vc), but the 2012 event is similar to the humid area values, and;
- The characteristic flood wave velocity is much greater for Arcoona Creek than for the Mean Humid Area.

The result indicates that there is a significant difference in the way that the Arcoona Creek behaves compared with more humid catchments. One probable explanation is that the runoff processes are dominated by the large amount of storage within the gravel bed of the tributaries and main streams, which absorbs a significant amount of runoff from the hillsides. Thus the initial loss represents loss in the tributaries and main stream, rather than on the hillsides. The two processes may represent water entering and discharging from the gravel, plus the more rapid surface discharge down the stream. Flow in the main creek can only occur if there is rainfall in part of the catchment that is of sufficient intensity to overcome the infiltration and transmission losses, or the total rainfall is enough to fill the available storage within the creek beds. Following a flood event the water within the creek bed is released back as a flow that has a significant storage lag. If the infiltration capacity is exceeded there can be very rapid response, being the flash flood that has a high velocity.

This explanation is supported by observations in arid western New South Wales (Cordery et al, 1983), which found a reduction in runoff depth with increasing catchment area, attributed to the alluvial beds in the main streams.

The findings from the modelling also support the on-ground observations from the many members of SEG that have observed rainfall events and flows in the Arcoona Creek system. Often rainfall will result in significant overland and tributary flows in parts of the catchment, but there is seldom flow in the main creek unless there has been rainfall over a long period, that can saturate the stream bed. Up to the present time there has been no direct observation of a flash flood.

To confirm the hypothesis that the creek gravel storage is the cause of the observed catchment behaviour would require an assessment of the total volume of storage available in the gravels. This volume would have to account for most of the very large initial and ongoing loss values found in the modelling.

8. CONCLUSIONS

The Arcoona Creek flow record has given a significant insight into the behaviour of a stream in an arid area of Australia. The probable reason for the behaviour is that the storage available in the creek gravels that fill the creek bed has a significant effect on the hydrology of the catchment. Flow only occurs in the channel if the rainfall intensity in part of the catchment is sufficient to overcome the transmission losses, or the total rainfall is enough to fill the storage available. It has shown that flash floods do occur, that occasionally generate a “wall of water” proceeding down the creek channel.

9. ACKNOWLEDGEMENTS

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