# Modelling Flow Routing and Transmission Loss Processes in Arid Zone Floodplain Rivers

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**Abstract:** Arid zone (dryland) ephemeral rivers are characterised by discharge decreasing downstream in the lower reaches due to transmission losses. Australian dryland rivers of the Lake Eyre Basin are also characterised by very low gradients, complex flow paths, wide braided/anastomosing channel systems and a paucity of gauged hydrographic data to describe their flow regimes. Modelling the flow regime of dryland, rivers requires data on the spatial and temporal distribution of transmission losses in the lower reaches. In this study, the routing and transmission losses are modelled for a 330km reach of the Diamantina river in southwestern Queensland, where the floodplain width varies from 5 to 60km. Analysis of gauging station data at each end of the reach from the Diamantina Lakes to Birdsville indicates that transmission losses are between 75 and 94% for floods with total discharge <1200GL. Travel times through this reach are non-linear but, unusually, increase with increasing discharge, for floods of total discharge <1200GL. This is hypothesised to be due to the longer and higher roughness flood paths travelled by larger floods in the complex channel system of this reach. The flow routing and transmission losses are modelled using a grid-based (5km*5km cell size), daily time-step conceptual bucket model incorporating flow routing algorithms. Satellite images are used to identify the flow-paths used by the range of flood sizes and to identify threshold flow volumes for initiation of flow into new flow-paths. The grid-based approach allows for representative routing of flow through the reach and representation of the spatial variability in the transmission loss process, including losses resulting from evaporation, channel/floodplain infiltration and terminal flow storage. A combination of gauging station data and satellite images is used in the calibration of the model parameters.

***Keywords:*** Ephemeral river; Arid Zone; Transmission loss; Flow routing

## 1 INTRODUCTION

### 1.1 Arid Zone Floodplain Rivers

Arid zone (dryland) ephemeral rivers are characterized by discharge decreasing in the lower reaches due to transmission losses [Knighton and Nanson, 1997]. Many of these rivers flow into arid areas with low population bases and so there tends to be a paucity of gauged hydrographic data describing their flow regimes. Modelling the flow regime of these rivers requires data on the spatial and temporal distribution of transmission losses in the lower reaches. The interplay between discharge and transmission losses determines the extent and pattern of flow in most internally draining dryland rivers with major consequences for water resource and ecological modelling of the river system. Areas of enhanced transmission loss can have a high biological productivity as water loss from infiltration can support important areas of vegetation growth and in-reach surface water storages provide temporary refuges and resources for arid zone fauna. The complex flow paths and large transmission losses in dryland rivers, in combination with the paucity of hydrographic data, presents challenges to the modelling of the flow regime.

Transmission losses are due to the following factors:

- Evapotranspiration,
- Infiltration to channel store and/or floodplain soils, and

- Ponding in terminal, ephemeral pools, channels and other wetlands.

The relative importance of these factors with respect to hydrology varies among arid catchments, depending on characteristics such as the size of the catchment, stream gradient, stream/floodplain sediments and seasonal timing of flow. Studies of small to medium sized catchments with low-moderate gradients in Arizona [Walters, 1990], India [Sharma and Murthy, 1995] and South Africa [Hughes and Sami, 1992] have found that infiltration to the near-surface channel aquifer was the major cause of transmission losses.

Limited work has been done on the modelling and quantification of the processes involved in transmission losses in the rivers of the Lake Eyre Basin, central Australia. Analysis of gauging station data to determine transmission losses in a 420km reach of Cooper Creek in the Lake Eyre Basin [Knighton and Nanson, 1994] demonstrated that the losses were extremely large and varied non-linearly with discharge. A simplified, whole of basin modelling approach was taken by Kotwicki [1986], using the RORB model. A detailed rainfall-runoff-routing model was developed for Cooper Creek using the Sacramento and IQQM models [Schreiber, 1997]. That study routed streamflow along a link-node representation of the channel system using a multi-layered Muskingum routing procedure. The approach allowed for explicit flow routing through a simplified channel system and consideration of non-linear routing and transmission loss behaviour as discharge increased. The impact on transmission losses of variable flow paths used be different sized flood events was not addressed and the differing transmission loss processes were not considered separately.

This study presents preliminary results on the utility of using a semi-distributed, grid-based conceptual bucket model of the flow regime of the Diamantina River, Lake Eyre Basin, along with remotely sensed data for model development and testing. The hypothesis that transmission losses are dominated by infiltration to sub-surface aquifers in arid zone rivers of the Lake Eyre Basin is also tested. In particular, the importance of other hypothesized loss processes, evapotranspiration and terminal ponding are examined. Gauging station data from a 330km reach of the Diamantina River are analysed to determine the magnitude of transmission losses as a function of discharge. A grid-based, daily time-step routing model is developed for the reach and calibrated and tested against gauging station data.

## 1.2 Lake Eyre Basin Rivers

The arid zone floodplain rivers of the Lake Eyre Basin, one of the world's largest endorheic basins, have a number of distinguishing features that result in these rivers having amongst the most variable flow regimes in the world [Puckridge et al, 1998]. The rivers develop over very low gradients and commonly have complex flow paths with extensive braided/anastomosing channel systems, resulting in floods with slow travel times (weeks to months). The rivers have greatly varying widths of active channel and floodplain. During large flood events, floodwaters can inundate thousands of square kilometres and the floodplain can be up to 60km wide. The rivers predominantly transport clay-sized particles and areas of significant floodplain expansion and wetland development are covered by cracking clays. Floodplain infiltration losses may be limited by the sealing of the swelling clay floodplain substrate once their crack capacity is exceeded [Knighton and Nanson, 1994].The flow regimes of these rivers are dominated by late summer flow events resulting from highly variable monsoonal related rainfall in the upper catchments.

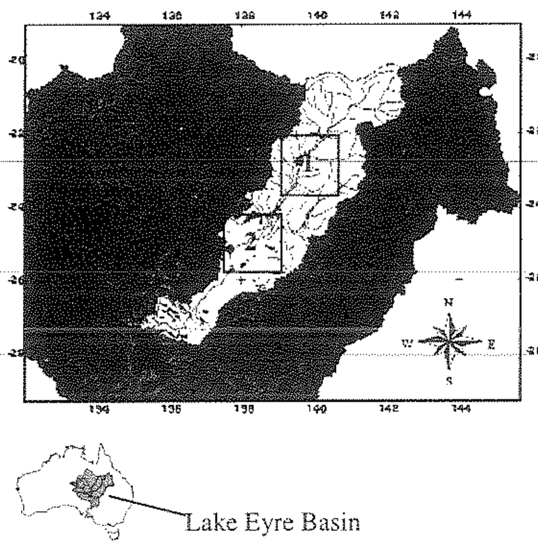


**Figure 1.** Location map of Diamantina River catchment. Gauging stations at Diamantina Lakes (1) and Birdsville (2) shown as dots.

These factors enhance the opportunity of transmission loss due to evaporation. Finally, the complex flow patterns of the low gradient rivers of the Lake Eyre Basin enhance the potential for water loss to terminal in-reach storage. Transmission losses due to terminal flow storage in dryland rivers and streams are interpreted over a large range of flood magnitudes, from sub-bankful flow events [Dunkerley and Brown, 1999] to large floods [Knighton and Nanson, 1994].

The Diamantina River is a major river of the Lake Eyre Basin and the major contributor to Lake Eyre [Kotwicki, 1986]. The lower and middle reaches are characterised by a complex system of braided/anastomosing channels and wide floodplains. With the exception of Farrar and Eyre Creeks, tributaries of the lower catchment are small. Like many arid zone rivers, the Diamantina has few gauging station records along its 1000km length with only one station currently operating at Birdsville (Figure 1).

## 2 ANALYSIS OF FLOW DATA

### 2.1 Methodology

Flow pulses at the Diamantina Lakes gauging station were correlated with flow pulses at Birdsville and transmission losses and travel times were compared. The correlation of pulses over the 330km reach was facilitated by the flow occurring as discrete pulses and often starting and ending in zero flow at the upper and lower ends of the reach. A gauging station at Diamantina Lakes (see Figure 1) operated between November 1966 to December 1988 but has a poor rating (33% of maximum stage). This station provides the only hydrological dataset for the upper reaches of the river. Event based stage records also exists from near the Diamantina Lakes gauging station for large flood events in 1991, 1997 and 2000. In the lower reaches, a more reliably rated (61% of maximum stage) gauging station operates at Birdsville with records beginning in 1949.

### 2.2 Results and Analysis of Flow Data

The plot of all correlated pulses is shown in Figure 2, with the ratio of upstream to downstream pulse volumes on the y-axis and the upstream input pulse volume (Diamantina Lakes) on the x-axis. This plot shows the degree of transmission between the two gauging stations. Flow pulses with significant input from downstream of Diamantina Lakes have not been separated. The transmission throughput increases non-linearly with flood size for the Diamantina Lakes to Birdsville reach. Transmission losses are extremely high (75-94%) for flood events <1200GL total volume at Diamantina Lakes and achieve maximum losses for floods of approximately 1000GL total volume.

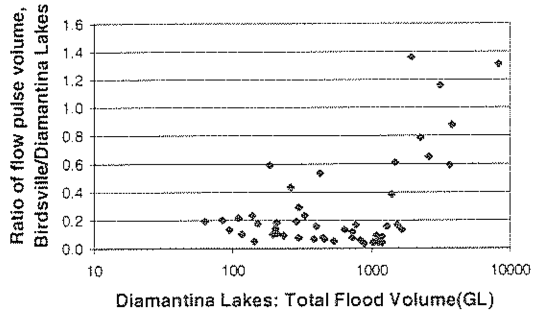


**Figure 2.** Transmission losses of Diamantina Lakes to Birdsville reach of the Diamantina River.

The sharply increased transmission throughput of floods with total volumes of >1200GL is considered to reflect very significant runoff input from downstream of Diamantina Lakes. This is certainly indicated for events with volume ratios >1. In addition, transmission losses (as a percentage of the flood volume) may decrease with increasing size of large flood events. The initial stages of flooding and downstream local rainfall runoff may satisfy most of the infiltration losses and fill many in-reach stores, so restricting further transmission losses. The average total volume ratio (i.e. transmission), excluding flood events with ratios >1, was 0.22. This is very similar to the 420km Currareva-Nappa Merrie reach of Cooper Creek with an average volume ratio of 0.23 (Knighton & Nanson 1994). In addition, the transmission – discharge plot for that reach of Cooper Creek showed similar trends to those observed in Figure 2.

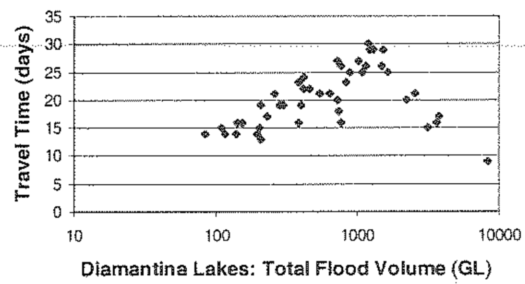


**Figure 3.** Travel time for Diamantina Lakes-Birdsville reach.

The travel time for floods in the Diamantina Lakes–Birdsville reach is displayed in Figure 3. Unusually, the travel times increase with increasing discharge, for floods of total discharge <1200GL and then decrease as discharges increase over the 1200GL threshold. This indicates that floods in the <1200GL range experience increasing surface roughness and/or longer flow paths in this reach.

This coincides with a dramatic widening of the channel network and increase in available flow paths, particularly in the downstream half of the reach.

## 3 FLOW MODELLING

### 3.1 Model Description

The flow routing and transmission losses along the Diamantina River are modelled using a grid-based (0.05*0.05 degree cell size), daily time-step conceptual bucket model. This semi-distributed modelling approach allowed for the explicit routing of the complex flow patterns within the reach and some spatial representation of different morphological units of the reach (i.e. channels versus floodplains). The grid cell size was chosen to coincide with that of spatially interpolated rainfall data (not yet incorporated into the model) and provided sufficient flexibility to represent flow paths and spatially variant elements without over-burdening the model with unnecessary detail in the absence of suitable collaborating data.

The model allows flow into and out of the cells from multiple directions to replicate the complex flow paths occurring at the scale of the grid cell. Different templates of cell connectivity are set for inflow discharge ranges at the upstream end of the reach, which allow for flow paths to become connected at physically realistic discharges. During flow recession, the template of the last flow pulse maximum is maintained and triggering of a new flow template occurs again on the next rising limb.

The explicit connectivity between cells utilized a ten-digit code for each cell (e.g 1000000703). The first digit (1) was used to maintain the code length and the following nine digits defined the connectivity with the surrounding eight cells (one of the nine digits allowed the cell to act as a sink). Zero indicated that a particular surrounding cell was disconnected whilst any digit from 1-9 signified connection and gave the percentage of the cell discharge that it received. The discharge received could take values of deciles of 100% and the sum of discharge percentages had to sum to one. In the example code given, one cell receives 70% of the discharge whilst another receives 30%. In the case of a single connecting cell, the digit one denoted 100% discharge into that cell (e.g. 1000000010). In practice, a maximum of three connections per cell were required.

Topographic maps and satellite images (Landsat and NOAA-AVHRR) were used to identify the flow-paths used by the range of flood sizes and also to define land types. The Landsat images were critical in identifying flow events (and approximate threshold volumes) that utilize different flow paths.

### 3.2 Conceptual Modelling

A lumped parameter, water balance model was calculated for each grid cell. Two land-type classes were used in the model. The first represented the primary channel system of the reach and the second covered the secondary channel system and extensive floodplains. Separate parameter values could be used for the different land types to capture some of the spatial variability driving the hydrological processes. In total, nine parameters were incorporated into the conceptual model.

The relationship between the discharge of a flood event and the area inundated is critical for measuring realistic transmission losses due to evapotranspiration and infiltration. The grid cell size requires that sub-grid cell processes are considered in the conceptual modelling of the river flow, in particular, the grid cell scale relationship between storage and area inundated. The model uses Equation 1 to divide the area of the cell into inundated and non-inundated portions, where SS is the calculated total surface storage in the cell and VM is a calibration factor representing the volume required to completely inundate the cell. As the storage approaches VM, the percentage of the cell inundated approaches one.

$$\text{Area inundated} = 1 - e^{(-0.01 \cdot SS/VM)} \qquad (1)$$

Losses due to evaporation are removed from the surface cell storage (see Figure 4) at the areal potential rate and at a calibrated evapotranspiration rate when the surface store is empty. The maximum sub-surface store is set at a calibrated value and must be filled before flow out of the cell occurs. Losses due to deeper infiltration are then set at a calibrated daily rate. Following removal of water from the surface store due to evapotranspiration and infiltration, a proportion of the store is placed in a terminal cell store with a calibrated maximum volume. This simulates the terminal cell storage that is not available for further routing and is only depleted by evapotranspiration and infiltration to the subsurface store. The remaining water in the surface store is available for routing. A two-parameter kinematic storage, flow-routing iterative algorithm was used for the routing and calculated the average daily (flow-available) storage and discharge within the cell. Discharge of return flow from the sub-surface store back into the surface store for routing was set at a calibrated proportion of the sub-surface store.

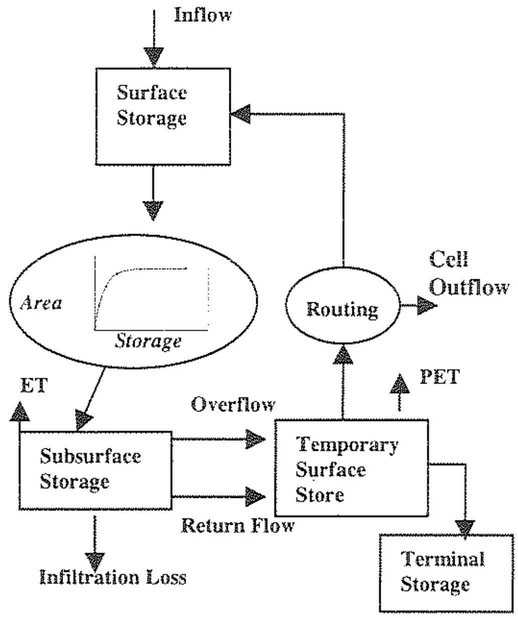


**Figure 4.** Flow diagram of conceptual water balance model for each grid cell. Note that inundated surface increases with storage.

## 3.3 Model Calibration

The model was calibrated only on flood events of total volume <1300GL as these are interpreted to receive minimal downstream input and interpolated rainfall input was not yet incorporated into the modelling procedure. Model output was calibrated against daily discharge data from Birdsville for the periods of 1967-1970 and 1982-1986 and tested against data from 1978-1980.

The definition of the extent of flooding for particular flood events was used in the "spatial" calibration of the model. The grid-based output was compared to Landsat images covering different flood events and the cell connectivities were set to enable a reasonable match between the modelled and actual spatial extent of the flooding at that time. The flood paths were defined from observed water flow during the flood event and from vegetation greening following the passage of floodwaters from images taken after the flood event. Significant flow path differences and inundated areas were noted for the two flood events in December 1984 (peak flow 73GL/day, total volume 537GL) and February 1986 (peak flow 136GL/day, total volume 1,187GL).

Flow pulses with peak flow volumes of <40GL at Diamantina Lakes experience less transmission losses in percentage terms than higher volume floods and significantly less in absolute terms. Results during calibration indicated that the longer flow paths utilised by the larger flood events were not sufficient for achieving the required transmission losses whilst allowing some transmission of lower volume flows. This indicated that the lower volume flows were using a well-connected channel system with faster travel times and less transmission losses than the larger floods and provided justification for using two land-type classes in the spatial modelling even though this doubled the number of adjustable parameters in the conceptual bucket model. Parameters of the conceptual water balance model were manually optimized for a best consistent fit between modelled and actual hydrographs at Birdsville.

## 3.4 Modelling Results

Modelling fits were adequate, as shown in Figure 5 for the 1978-1980 test period, but with two main exceptions. Flow pulses derived from, or receiving substantial contribution from downstream rainfall and runoff could not be properly modelled due to the current lack of precipitation data. Secondly, if smaller flow pulses occur soon after larger pulses the cell connectivity is set to the lower volume range template. As a result the transmission losses for the larger pulse can be significantly underestimated (see February 1979 and 1980 events in Figure 5).

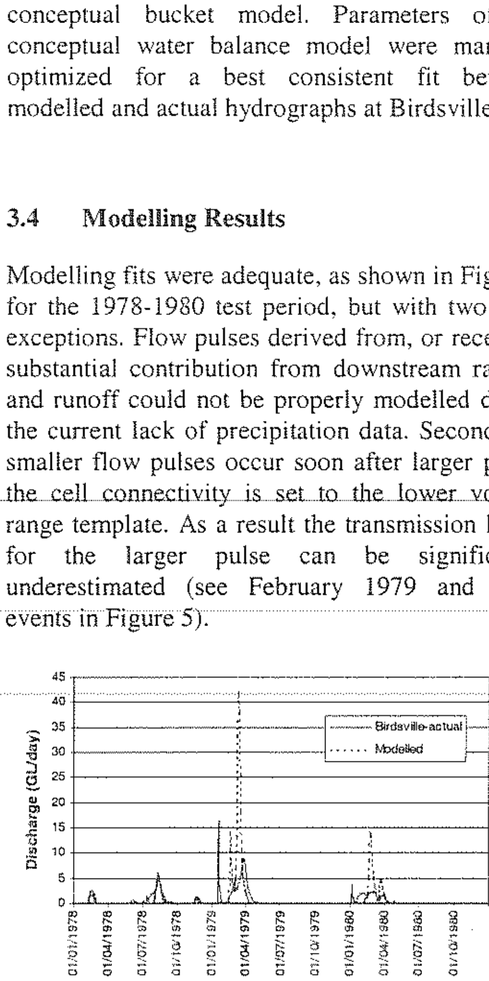


**Figure 5.** Modelled versus actual discharge at Birdsville gauging station for the period 1978-80.

Reach-scale cumulative plots of transmission losses for the period 1977-1980 (allowing for the flood events of 1977 to provide baseline conditions for the remainder of the period) are shown in Figure 6 along with cumulative inflow, cumulative modelled outflow and combined outflow and transmission losses ("Total Out") curves.

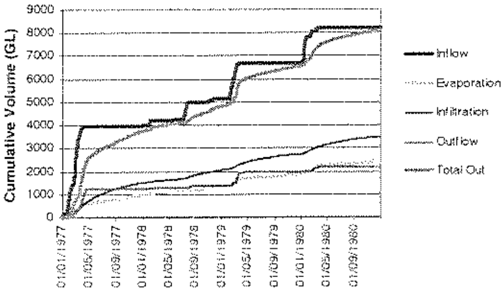


**Figure 6.** Reach water balance for period 1977-1980.

Evapotranspiration losses accounted for 30% of the total losses for the period 1977-1980 and were of a similar scale to the modelled outflow for the period. Losses due to infiltration were higher than for evapotranspiration but the calibrated infiltration rate was set at 5mm/day and this is probably excessive in areas of cracking clay soils. Infiltration losses to deep aquifers are poorly constrained by field data and so the present model structure could significantly overestimate losses from this process. The balance of the water loss is due to terminal in-reach storage and this storage remained above 90 GL for the entire test period. If the infiltration losses are overstated then the terminal storage would rise in compensation.

## 4 CONCLUSIONS

The use of a grid-based conceptual bucket model shows considerable promise in the modelling of transmission losses and streamflow routing in the low gradient dryland rivers of the Lake Eyre Basin. This approach allows for two factors that are critical in estimating transmission losses and flow timings over a large discharge range.

- Explicit representation of routing and the spatial distribution of flooding.
- Influence of different land types on cell storage and routing parameters.

The model will be further improved by accounting for downstream rainfall-runoff and refining the modelling of the deep infiltration process. Another area requiring improvement is the switching of cell connectivity templates at threshold flow volumes. Ideally this should be occur when individual cells reach threshold volumes or depths and not be dependent on the inflow volume at the upstream end. Further work will examine mechanisms for achieving cell-level flow switching. The use of remote sensing data along with traditional flow data was critical in developing and testing the flow threshold and flood-plain connectivity components of the model.

## 5 ACKNOWLEDGEMENTS

Funding for this project was provided by the Natural Heritage Trust, an initiative of Environment Australia. This work is also an associate project of the CRC for Catchment Hydrology.

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