Flow Regime, Salt Load and Salinity Changes in Unregulated Catchments. Interpretation for Modelling the Effects of Land-use Change

Warrick Dawes, Glen Walker, Lu Zhang and Chris Smitt

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Interpretation for Modelling the Effects of Land-use Change

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Data for Pine Creek and associated catchments was supplied courtesy of HydroTechnology, Rural Water Corporation, Victoria.
EXECUTIVE SUMMARY

With the push to plant trees as a remediation measure for dryland salinity, it is necessary to understand and be able to predict changes to the stream flow and stream salinity regime following land-use change. It is well established that estimates of whole-catchment water balance components, such as total excess water, can be made in a routine manner. In an equilibrium situation, total excess water will be equal to the amount of water appearing at the outlet of a catchment in a stream flow record. This is made up of two components: surface water and groundwater. We are concerned in this report with both these components, and how the time-scales associated with each of them affect water and salt fluxes from catchments.

For small catchments, the time to reach a new water-balance equilibrium may be as little as a decade. Flow and salinity data collected for small catchments throughout the Murray-Darling Basin show consistent behaviour that allow us to treat salinity as relatively constant, and therefore stream salt load as a simple function of stream flow. Two intensively studied catchments show quite similar behaviour given they are from either side of the Australian continent and have been subjected to contrasting land-use changes. A feature was the transient change in stream salinity, which may or may not persist depending on the conceptual model applied to the system. In the simplest case, stream salinity will return to a set level following a transitional phase after a new hydrologic equilibrium is established. In more complex cases with interactions between salt storages, stream buffering and changes in the relativity of water balance components, a change in salinity may reach a new average value.

Conceptual models for the simple and buffered cases are presented, but two outstanding issues remain. The first is the prediction of where new water balance equilibria result in changed relativities of runoff and recharge, and the detection and modelling of buffer zones. This report strongly recommends more fully exploring transitional and persistent salinity changes in streams, by developing complete conceptual models for small-scale groundwater flow systems, and comparing with detailed data records.
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1. BACKGROUND

It is well established that changes in land-use, specifically when removing or replanting native and perennial vegetation, result in corresponding changes in stream flow patterns. What is less obvious is if there is a flow-on effect on the salt export behaviour following land-use change. There are two relationships that describe the changes in catchment salt and water export: the flow duration (FD) curve and flow-salinity (FS) curve. The FD curve describes the distribution of flow rates at the catchment outlet, while the FS curve shows how flow rate and salinity are related.

When a catchment is disturbed by large-scale land-use change, we expect that the FD curve will change to reflect the increase or decrease in total flow. There is a need to understand and possibly be able to predict however, how and when the FS curve changes with the FD curve. In a relatively fresh system with high rainfall and well-flushed storage zones, we might expect that there is no change in the salinity of water exported from the catchment regardless of land-use. In small-scale flow systems with high salt storage however, the mobilisation or activation of additional salt sources following changes to the water balance will affect the FS curve.

The larger the flow system, the more likely it is that storages internal to the catchment will modify the FS patterns. In addition, larger systems are also more likely to be modified by stream regulation, have water off takes or groundwater pumping for domestic and commercial purposes, or aquifer and stream characteristics that mean recharge water does not discharge with the catchment itself. This raft of complications in general defies reliable prediction of changes by introducing effects that modify or dominate any natural changes induced by land-use change.

It is not the intention of this report to detail a predictive framework that explains changes in the FD and FS curves following land-use change, but rather to explore some of the data available within Australia. With this information, inferences and interpretations can be made that capture the observed variation without necessarily establishing any causal relationships. Conceptual models for the simplest cases can be developed, while other behaviours require more consultation and understanding.
2. FLOW AND SALINITY DATA

As a general statement, small upland catchments export water at a relatively constant salinity. The result is that the salt load from the catchment is linearly related to the stream flow rate. A search of the state stream databases for catchments with reasonable length of flow and salinity records reveals 11 with useable records which are fresh, e.g. less than 100 mg/L at high flows, plus three others. Figures 1 to 14 show the catchment's flow versus salt load and flow versus salinity graphs.

Least-squares lines have been fitted to the flow and salt load, under the general hypothesis that salinity is relatively constant. An exponential model is fitted to flow and salinity, which allows for great variation at the low-flow end due to evaporative concentration, and a long-term decrease to a near constant value. The linear correlations between flow and salt load are uniformly good, exceeding 0.90 in most cases, and strongly support the base hypothesis.

![Figure 1](image1.png)

**Figure 1**: Flow-Salt load and Flow-Salinity curves for Guy Fawkes Creek, 204008.

![Figure 2](image2.png)

**Figure 2**: Flow-Salt load and Flow-Salinity curves for Kiewa River, 402223.
Figure 3: Flow-Salt load and Flow-Salinity curves for Nariel Creek, 401212. An outlier is shown circled in red.

Figure 4: Flow-Salt load and Flow-Salinity curves for Fifteen Mile Creek, 403213.

Figure 5: Flow-Salt load and Flow-Salinity curves for Rose River, 403217.
Figure 6: Flow-Salt load and Flow-Salinity curves for Boggy Creek, 403226.

Figure 7: Flow-Salt load and Flow-Salinity curves for Delatite River, 405214.

Figure 8: Flow-Salt load and Flow-Salinity curves for King Parrot Creek, 405231.
Figure 9: Flow-Salt load and Flow-Salinity curves for Campaspe River, 406208. An outlier is circled in red.

Figure 10: Flow-Salt load and Flow-Salinity curves for Wild Duck Creek, 406235.

Figure 11: Flow-Salt load and Flow-Salinity curves for Creswick Creek, 407214.
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Figure 12: Flow-Salt load and Flow-Salinity curves for Bet Bet Creek, 407220.

Figure 13: Flow-Salt load and Flow-Salinity curves for Jim Crow Creek, 407221.

Figure 14: Flow-Salt load and Flow-Salinity curves for Avoca River, 408202.
The nature of the FS curve requires more interpretation. For most of the cases (402223, 401212, 403213, 403217, 403226, 405214, 407214, 407221) the exponential model fits visually very well, with correlation coefficients in the range 0.40 to 0.70. The exceptions are in the very low flow end where salinity appears almost random, but higher than average values. Two catchments, 204008 and 405231, have very low correlations between flow rate and salinity. However the data supports the thesis that salinity is not related to the flow rate, i.e. it is quite constant for 204008, or random in the case of 405231. Both catchments still produce excellent linear fits of flow versus salt load, reinforcing the soundness of the approach. This means that even when salinity is high, the flow rate is so low that the error in salt load is small overall. The three most saline catchments, 406235, 407220 and 408202, show much greater scatter in salinity and salt load, but still yield moderate correlation coefficients for both.

As a further point of interest, the slope of the best-fit linear regression in Figures 1 to 14 is an estimate of average stream salinity, accounting for flow weighting and unit conversion. Multiplying the slope of the best-fit line by 1000 converts into mean mg/L of stream salinity, corresponding to the fitted data. Thus in Figure 2, for example, station 402223 on the Kiewa River has a flow weighted average salinity of 12.9 mg/L.

Table 1: Physical properties, rainfall and tree cover for the fourteen catchments in Figures 1 to 14. Catchments indicated by an asterisk (*) in the Elevation Range column have upland areas of significant slope suggesting a concave shape profile. Elevation is in metres, the mean elevation measured above sea level, slope is in degrees, and rainfall in millimetres. The data sources for percentage tree cover are Ritman (1995) for M305, and Kitchin and Barson (1998) for ALCC.

<table>
<thead>
<tr>
<th>Station Number</th>
<th>Mean Elevation (m)</th>
<th>Elevation Range (m)</th>
<th>Mean Slope (degrees)</th>
<th>Mean Rainfall (mm)</th>
<th>Cover % M305</th>
<th>Cover % ALCC</th>
<th>Mean Salinity (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>204008</td>
<td>1323</td>
<td>263*</td>
<td>3.0</td>
<td>1398</td>
<td>N/A</td>
<td>38.1</td>
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<tr>
<td>401212</td>
<td>1051</td>
<td>1231</td>
<td>11.5</td>
<td>1567</td>
<td>98.9</td>
<td>99.5</td>
<td>19.8</td>
</tr>
<tr>
<td>402223</td>
<td>1037</td>
<td>976</td>
<td>16.3</td>
<td>1798</td>
<td>98.3</td>
<td>99.4</td>
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<td>541</td>
<td>838</td>
<td>6.9</td>
<td>1154</td>
<td>77.9</td>
<td>72.8</td>
<td>27.1</td>
</tr>
<tr>
<td>403217</td>
<td>636</td>
<td>1231*</td>
<td>10.1</td>
<td>1341</td>
<td>84.8</td>
<td>86.2</td>
<td>18.7</td>
</tr>
<tr>
<td>403226</td>
<td>460</td>
<td>658</td>
<td>6.4</td>
<td>1106</td>
<td>55.7</td>
<td>55.0</td>
<td>34.1</td>
</tr>
<tr>
<td>405214</td>
<td>687</td>
<td>1413*</td>
<td>6.5</td>
<td>1228</td>
<td>54.8</td>
<td>53.7</td>
<td>34.4</td>
</tr>
<tr>
<td>405231</td>
<td>523</td>
<td>526</td>
<td>5.0</td>
<td>1116</td>
<td>84.0</td>
<td>84.1</td>
<td>49.9</td>
</tr>
<tr>
<td>406208</td>
<td>676</td>
<td>140</td>
<td>1.6</td>
<td>967</td>
<td>72.5</td>
<td>76.1</td>
<td>47.9</td>
</tr>
<tr>
<td>406235</td>
<td>378</td>
<td>463*</td>
<td>2.8</td>
<td>714</td>
<td>8.7</td>
<td>16.4</td>
<td>312.5</td>
</tr>
<tr>
<td>407214</td>
<td>459</td>
<td>423*</td>
<td>1.8</td>
<td>765</td>
<td>25.2</td>
<td>24.4</td>
<td>180.2</td>
</tr>
<tr>
<td>407220</td>
<td>292</td>
<td>388*</td>
<td>1.2</td>
<td>599</td>
<td>16.9</td>
<td>23.3</td>
<td>365.5</td>
</tr>
<tr>
<td>407221</td>
<td>520</td>
<td>530</td>
<td>3.1</td>
<td>886</td>
<td>60.8</td>
<td>62.7</td>
<td>106.0</td>
</tr>
<tr>
<td>408202</td>
<td>403</td>
<td>460*</td>
<td>3.8</td>
<td>686</td>
<td>31.1</td>
<td>30.1</td>
<td>753.1</td>
</tr>
</tbody>
</table>
The records of the catchments in Figures 1 to 14 are all within the last decade or so, and there is little information on recent land-use history to suggest that major changes have taken place over the course of the record period. Given that most of these catchments are small and, in the absence of information to the contrary, their land-use has not changed for some time and we might expect that the data recorded represent the current equilibrium condition. To make further inferences it is necessary to have knowledge of the before and after catchment state and associated data.

Small Upland Catchments: There is no clear evidence that the flow duration curve and salinity duration curve will be different in the catchments described, except by a linear constant that converts between the units of interest. As such, we cannot conclude that separate flow duration and flow salinity modelling needs to be done. With appropriate handling of the flow duration curve and known representative discharge salinity, these small upland catchments are well described.
3. THE LEMON CATCHMENT EXPERIMENT

The Lemon Creek catchment in Western Australia has had detailed data collection that allows analysis of the effects of land clearing on stream flow and salinity. It was set up with two other catchments, Ernie and Don, as part of a larger experiment within the Collie River Basin, south-west of Perth (Ruprecht and Schofield, 1991). Ernie was retained under native cover while Don and Lemons were partially cleared in the summer of 1976/77. Water levels were measured reaching the land surface nearly 12 years later in 1988. Lemon Creek covers an area of 344 ha and had the lower half only of the catchment cleared. Figures 15 to 19 show the flow-salt load and flow-salinity relationships at Lemon Creek for blocks of 5 years of record since 1974.

Figure 15: Lemon Creek Flow-Salt load and Flow-Salinity for 1974 to 1979.

Figure 16: Lemon Creek Flow-Salt load and Flow-Salinity for 1980 to 1984.
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**Figure 17:** Lemon Creek Flow-Salt load and Flow-Salinity for 1985 to 1989.

**Figure 18:** Lemon Creek Flow-Salt load and Flow-Salinity for 1990 to 1994.

**Figure 19:** Lemon Creek Flow-Salt load and Flow-Salinity for 1995 to 1999.
Figure 20 summarises the fitted curves over all blocks of data, and allows us to see how the load and salinity have changed over time. The total flow from the catchment has increased, as has the peak stream flow and salinity of the stream. The two blocks of data prior to groundwater levels reaching the surface are similar to each other, but in the period when surface discharge starts there is a significant change. From the point data in Figure 17 we see two families of points, one above and one below the best-fit line, and a significant increase in the salinity of the stream flow. The data continues to be scattered in the final two blocks of data, but while the flow against salt load line appears to be changing slowly, the flow-salinity curve continues to rise steadily.

The average regolith depth in Lemon Creek is 26.9 m, the salt storage is 590 t/ha, the groundwater salinity is approximately 6000 mg/L (Johnston, 1987), and the catchment average recharge rate post-clearing is estimated at 35 mm/yr (Silberstein et al., 2002). Using the Zhang Method to estimate excess water (Zhang et al. 2001) from the average 710 mm of rainfall, values are 65 mm and 190 mm for native and cleared conditions respectively. With clearing of 50% of the catchment, this translates into an increase from 65 mm of stream flow (9% of rainfall) to 127 mm (18% of rainfall). Analysis of the flow record by Silberstein et al. (2002) revealed that the Runoff Coefficient, i.e. the ratio of total stream flow to rainfall, increased from 1-8% (7-57 mm) in the decade before groundwater levels reached the surface to 15-25% (106-178 mm) over the last 5 years of record. The ease with which the water balance terms can be estimated is supported by the work of Lane et al. (2002) and Zhang et al. (2002).

While it is possible that estimating absolute changes to total volume yielded from a catchment is relatively straightforward, the changes in salinity of the stream are not so clear. Silberstein et al. (2002) estimated that the total increase in water stored in the Lemon Catchments was 360 mm with an average recharge rate of 35 mm/yr. It is clear from these numbers how it could have taken over 10 years for the flow and salinity behaviour of Lemon Creek to change dramatically.

Figure 21 presents an analytic solution to a contamination problem. First we assume that a buffer or storage is full and at a fixed salinity, and then that some volume of more (or less) saline water enters and completely mixes each year, with a corresponding volume of water discharged. On the left panel we assume that the current stream salinity is at a maximum and
fit the relative amount of water that enters the storage zone. In this case an amount of water equal to one-fifth of the storage volume provides a reasonable fit to the observed increase in flow-weighted stream salinity (from Silberstein et al., 2002).

Figure 21: Theoretical solution (solid line) for an alluvial buffer becoming salinised by discharging groundwater. Left panel has discharge volume one-fifth of the buffer size, initial salinity of 100 mg/L with 1750 mg/L water entering, right panel has discharge volume one-tenth of the buffer size, initial salinity of 100 mg/L with 3000 mg/L water entering. The dashed line is flow-weighted mean salinity of Lemon Creek (from Silberstein et al. 2002) with 1987 as time Zero.

In the right panel of Figure 21 we assume that we know the relative amount of water entering each year, from the recharge and change in storage values, and fit a salinity value for the contaminating water. In this case a value of 3000 mg/L provides a good fit to the years over which stream salinity has been increasing rapidly. The final salinity would be reached in 50 to 60 years, and at the current rate of salt export it would take another 250 years to flush the estimated stored salt completely. As noted before, the measured groundwater salinity prior to clearing was approximately 6000 mg/L. Combined with an estimate of Baseflow Index, i.e. the proportion of annual stream flow that is base flow, for Lemon Creek from Silberstein et al. (2002) that has risen from 10% in 1974 to 40% in 1997, it is possible that the stream salinity will continue to increase to near the fitted value of 3000 mg/L. The rise in the proportion of base flow might either be a result of the development of saturated areas after 1988, or that the groundwater system is still responding to changes in recharge regime, and pushing through relatively more water than under an equilibrium condition.

Lemon Creek: In this catchment, both the flow duration curve and flow-salinity relationship has changed following clearing. The quality of a linear fit between stream flow and salt load has deteriorated with the large increase in salinity, although the correlation coefficient remains above 60%. The use of a mixing model for salt concentration changes proved to be a powerful tool, and fitted well with available data. With good flow duration curve modelling and an estimate of the time response to salinity changes, no separate modelling of the flow-salinity relationship is needed.
4. THE PINE CREEK EXPERIMENT

Pine Creek is a tributary of Sunday Creek in the south-western corner of the Goulburn River catchment, Victoria. It covers an area of 320 ha, has considerable relief of 250 m, and average rainfall of 785 mm (Lamson, 1991). In 1986 and 1987 the whole of the Pine Creek catchment was converted from open grassland to pinus radiata plantation, while the two main tributaries remained lined with native forest. The aim of this experiment was to detect and quantify significant changes in the hydrologic processes within the catchment. By inference it is hoped to observe the reverse of the Lemons Catchment result, and see stream flow and salinity decrease over time.

The raw annual totals are shown in Table 2. Using the Zhang Method for estimating total excess water (Zhang et al., 2001) and annual rainfall of 785 mm yields 232 mm and 85 mm of water for cleared and forested conditions respectively. As for Lemons Catchment, the bulk water balance values are reliably generated with minimal data.

<table>
<thead>
<tr>
<th>Year</th>
<th>Rainfall (mm)</th>
<th>Stream Flow (mm)</th>
<th>Salt Fall* (t)</th>
<th>Salt Load (t)</th>
<th>Average Salinity (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>865</td>
<td>215</td>
<td>19.3</td>
<td>153</td>
<td>222</td>
</tr>
<tr>
<td>1990</td>
<td>643</td>
<td>83</td>
<td>14.4</td>
<td>119</td>
<td>448</td>
</tr>
<tr>
<td>1991</td>
<td>647</td>
<td>51</td>
<td>14.5</td>
<td>92</td>
<td>564</td>
</tr>
<tr>
<td>1992</td>
<td>857</td>
<td>96</td>
<td>19.2</td>
<td>93</td>
<td>303</td>
</tr>
<tr>
<td>1993</td>
<td>914</td>
<td>75</td>
<td>20.5</td>
<td>41</td>
<td>171</td>
</tr>
</tbody>
</table>

* Based on an average rainfall salinity of 7 mg/L from Kyabram site data (Jolly et al., 1997).

The values in Table 2 allow for several threads of interpretation. Firstly, it took 3 to 4 years for the establishment of the forest and therefore imposition of control over excess water fluxes. There is a marked difference in stream flow and salt load between 1989 and 1992, for example. Secondly is the apparent increase in salinity of the stream during the two drier years of 1990 and 1991. There are three possible reasons for this: either water was left on the surface for longer periods and concentrated by evaporation, the groundwater system had not yet fully responded to the recharge changes, or a combination of both. Another point of interest is the effect of the drier years on the apparent time taken to reach the new equilibrium state. It may be that this series of years so depleted the water stored in the soil and regolith, that it approached the equilibrium state under a more mature forest, and was maintained into the average and wetter years that followed.
Salinity and position of groundwater was measured at two sites in Pine Creek: D1 is adjacent to the main drainage line approximately 500 m south-west of the stream gauging station, and D2 is in a lower slope position above the confluence of the two main branches, a kilometre to the south of D1. Since establishment of plantations, the water level in D1 has fallen from 5 m to 8 m below the surface, while at D2 it has declined from 21 m to 23 m below ground level. HydroTechnology (1994, 1995) inferred that these drops were due to reductions in groundwater recharge. Groundwater salinity in D1 has approximately seasonal variation within the range of 1900 to 2500 mg/L, while D2 has declined from 1200 mg/L in 1988 to an average of 650 mg/L from 1990 to 1994. Assuming that all of the salt in the stream is derived from groundwater baseflow and the salinity at D1 is constant and representative, then the Baseflow Index at Pine Creek has varied from 11% in 1989, peaked at 28% in 1991, and was 9% in 1993. While this is a wetter catchment than Lemon Creek, the Baseflow Index values show general agreement with each other.
5. RAINFALL VERSUS STREAM SALINITY

For small flow systems that drain freely and react predictably to changes in rainfall and recharge regime, we might expect that above some threshold annual rainfall the system would be well flushed and not subject to large changes in stream salinity. Such catchments will not store salt in the regolith or aquifer for long periods, thus conventional evaporative concentration processes will not occur to create reservoirs of more saline water.

From Table 1 in §2 it is very difficult to discern or derive any coherent pattern between average stream salinity and the physical characteristics of the catchments, such as elevation, slope, or tree cover. However, it is possible to correlate annual rainfall with average stream salinity, with higher rainfall resulting in lower salinity, and vice versa. The relationship and fitted curve is shown in Figure 23.

\[ y = 72.9x^{-3.66} \]
\[ R^2 = 0.90 \]

**Figure 23**: Relationship between long-term average stream salinity and annual rainfall for the 14 catchments in Table 1. Rainfall is expressed in metres, rather than millimetres, to keep the parameters of the exponential equation reasonable.

An exponential equation is fitted to the data from Table 1, the same as used for the point measurements of flow versus salinity data from each catchment. The lower limit as annual rainfall increases simply reflects the rainfall salinity concentrated into all the water that is not evaporated or transpired. For example, if three-quarters of the rain is returned to the atmosphere and no salt is stored, or lost, by the catchment regolith, then the concentration of the stream water will be four times the rainfall salinity. In a similar manner, as the annual rainfall drops and a greater proportion of rainfall is lost to evaporation and transpiration, the greater would be the stream salinity as a function of rainfall salinity.

Some types of geology inherently have more salt in them due to their weathering products. Aquifers that do not drain freely are likely to retain water that can be evaporated later and thus concentrate or store salt. The Groundwater Flow Systems (GFS) Framework seeks to identify systems that exhibit dryland salinity in a predictable manner (Coram 1998; Coram et al. 2000). Mapping was based on bedrock geology, surface slope, regolith terrain, and monthly
rainfall and evaporation. The inherent rate of groundwater flow, different base geology and climatic regime should therefore be represented in a GFS map. The catchments that went into making Figure 23 are all from the same GFS. Differences in stream flow salinity from the line in Figure 23 could therefore be primarily attributed to the different GFS a particular catchment lies within.

Figure 24 shows data from Jolly et al. (1997), which reports salt and water balances of rivers in the MDB. Victoria catchments, upon which the relationship is primarily based, are shown as circles, catchments in the NSW Murray and Murrumbidgee are triangles, and tributaries of the Darling River are squares. The curve fitted in Figure 23 is used down to 600mm rainfall, after which a straight line is shown. The exponential function produces unreasonable values at low rainfalls. Error lines are plotted around the relationship. A bound of 40% was placed on the stream salinity due to a maximum of 20% error measuring both stream flow and catchment rainfall.

Victorian catchments are well represented by the central tendency, with only three of the 22 data points lying outside the estimated error bounds. NSW Murray and Murrumbidgee catchments show a generally lower trend at approximately half of the Victorian values for rainfall below 800 mm. The Darling River catchments in north NSW and Queensland are more of a shot-gun scatter and taking these is isolation there is a temptation to say that stream salinity increases with rainfall in the north. However they are in a relatively narrow rainfall band and the majority of catchments still lie within the error bounds.

A point made at the start of this section, is that stream salinity is a function of rainfall salinity and evapotranspiration. For the same annual rainfall in Victoria and southern Queensland, there may be a very different amount of evapotranspiration, thus causing scatter in Figure 24. The other point is the rainfall salinity, which can be mapped using the study of Blackburn and McLeod (1983), as corrected by Simpson and Herczeg (1994). From Jolly et al. (1997) and the rainfall mapping work, gauging stations in Victoria typically have rainfall salinity of 6 to 7 mg/L, in the NSW Murray and Murrumbidgee between 4 and 5 mg/L, and in the Darling
River catchments from 3 to 5 mg/L. To examine the direct effect of rainfall salinity, an arithmetic adjustment was made to the observed river salinities based on the ratio of rainfall salinity relative to the Victorian catchments. For NSW Murray and Murrumbidgee catchments this was an increase of 1.444, and in Darling River catchments an increase of 1.625. Figure 25 plots the adjusted stream salinity against the relationship from Figure 23. Visually, the low salinity Darling River and NSW Murray and Murrumbidgee catchments all come closer to the central relationship, while some of the Darling River catchments are now above the error bounds in the 700 to 800 mm rainfall zone.

**Figure 25**: Rainfall versus Stream Salinity adjusted for rainfall salinity of different regions. Victorian catchments are shown as circles (●), NSW Murray and Murrumbidgee as triangles (▲), and Darling River catchments as squares (■).

Factors other than GFS will affect the average stream salinity. These include many engineering works along the length of the stream, such as offtakes and returns from irrigation areas, groundwater extraction for commercial and domestic purposes, surface water extraction for commercial and domestic use, dams and storages, locks and other navigation structures, and natural flow regulators such as swamps, wetlands and floodplains. Net transfers of water out of one river valley to another affect total flows and salt loads in both catchments, but only modify the salinity of the receiving river. Such catchments have been left in this analysis to demonstrate the maximum scale of variation that appears in the measured data.

**Rainfall-Stream Salinity Data**: There appears to be a solid relationship between average annual rainfall and flow-weighted average stream salinity, despite the variation in rainfall salinity, GFS, and possible engineering interference. Further consideration of this relationship requires much more extensive stream data, which will allow culling of inappropriate catchments and show expression of GFS influences.
6. CONCEPTUAL SALT-BALANCE MODELS

The final paragraph of the Background of this report defines this section:

> It is not the intention of this report to detail a predictive framework that explains changes in the FD and FS curves following land-use change, but rather to explore some of the data available within Australia. With this information, inferences and interpretations can be made that capture the observed variation without necessarily establishing any causal relationships. Conceptual models for the simplest cases can be developed, while other behaviours require more extensive consultation and understanding.

The various catchments across the MDB detailed in §2 showed two important things. Firstly that very little synchronised flow and salinity data exists within Australia, despite several decades of concern and activity in the area of dryland and irrigation salinity. The catchments presented are 14 of 28 found where sufficient length of record existed to make reasonable inferences and fit linear correlations. **Figure 26** is an example of a catchment that was not included in previous analyses, not because the correlations were not good enough but because of apparent structure in the data that are symptomatic of regulated or man-altered flow patterns.

![Figure 26](image)

*Figure 26: Rejected station example, showing data scatter and preferential vectors that cannot be modelled simply.*

The second important inference is that constant representative groundwater salinity appears to be able to explain changes in salt load with total flow. Much of the data scatter occurs under low flow conditions, where errors in estimating total salt load will be the smallest. All the flow versus salinity graphs show clear levelling of the salinity as flow increases, which indicates that salt storage is not the limiting factor in salt export. The data from both Lemon Creek and Pine Creek could be modelled simply using a constant groundwater salinity that explained much of their behaviour over the short-term when salinity was changing most rapidly.
6.1 The 2-Store Model

A conceptual model for small local groundwater flow systems is:

1. All recharge and discharge occur within the boundaries of the catchment, which may be defined from the topographic surface catchment.
2. In the short- to medium-term, say less than 50 years, groundwater salinity is constant and values measured adjacent to a stream are representative of that discharge water.
3. Gross water-balance terms for the whole catchment can be estimated by the method of Zhang et al. (2001).
4. A time constant associated with groundwater response can be estimated by the method of Gilfedder et al. (2002).
5. The balance between the time taken for surface and groundwater processes to equilibrate following change, and any change to the ratio of surface flow to groundwater recharge, can explain the transient and longer-term changes in stream salinity following land-use change.

The most difficult parts of the conceptual model are salt storage and changes to recharge. In some catchments there may be little salt stored so that flushing can occur on a timescale that is less than either the surface or groundwater process equilibration time. In such a case, the assumption of constant groundwater salinity will fail, but long-term salinity will be easy to predict based solely on rainfall salinity and total volume of excess water. The second problem is more difficult to predict, and revolves around the premise that the ratio of excess water directed to surface flow and to groundwater recharge is constant and not affected by land-use change. In the case of Pine Creek this was a reasonable assumption and fitted the available data well. However in Lemon Creek the proportion of baseflow, a good indicator of the runoff:recharge ratio, has not decreased with the length of record available, thus either the groundwater response time is much longer than anticipated, or there has been a fundamental shift in how excess water is partitioned. Without varying the salinity of the surface and groundwater pathways, there would be no other way to change the long-term salinity of the stream. Determining where and when this occurs, and whether it is a characteristic of cleared as opposed to reforested catchments is yet to be determined.

6.2 The 3-Store Model

The next level up in the hierarchy of conceptual complexity is a small-scale groundwater flow system, which has some buffering capacity between surface and groundwater fluxes before they are discharged to drainage features. The 3S conceptual model was successfully fitted to the data from Lemon Creek, illustrating the need to differentiate between this and the simplest case. When a buffer exists within a catchment, additional time constants may be introduced that allow for filling of the buffer before its influence is fully felt. This model can be thought of as the activation of a second salt store in addition to the groundwater-regolith mixture. At whatever flow system scale this behaviour exists, the 3S model can be fitted to represent it.

The work of Gallant and Dowling (in press) on detecting flat valley bottoms, in association with soil-type mapping, may provide a routine method of locating catchments with potential groundwater discharge buffers in alluvial deposits surrounding streams, and in estimating their extent.
A conceptual model for small groundwater flow systems with a buffer is as follows:

1. All recharge and discharge occur within the boundaries of the catchment, which may be defined from the topographic surface catchment.
2. In the short- to medium-term, groundwater discharge salinity is constant and values measured in aquifer material away from the stream and any alluvial deposit is representative of that discharge water.
3. Gross water-balance terms for the whole catchment can be estimated by the method of Zhang et al. (2001).
4. A time constant associated with groundwater response can be estimated by the method of Gilfedder et al. (2003).
5. The location and size of the stream buffer can be estimated using the method of Gallant and Dowling (in press), while the physical characteristics can be found through the Groundwater Flow Systems framework.
6. The balance between time constants of the surface, groundwater and buffer systems, along with the changes to runoff:recharge ratio and salinity over time within the buffer, can explain transient and long-term changes in stream salinity.

This model fundamentally assumes that there will be a change in the salinity of water discharged to a stream over time. Whether it becomes diluted or more concentrated is determined by actual parameter values, and this model does require additional parameters than for the simple 2-Store model. In reality the 2S model is a special case of the 3S model, where two parameters drop out, thus description of catchments with the 3S does not lose any generality. Figure 27 shows conceptual diagrams for the 2S and 3S models, highlighting the main difference, being the zone where salt and water mixes and allows modification of the long-term salinity of discharge to the stream.

![Figure 27: Conceptual diagrammatic representation of the 2-Store (left) and 3-Store (right) models.](image)

The data requirements for the 2S and 3S model are similar. As can be seen from the 2S and 3S model fitting to Lemon Creek and Pine Creek the most basic requirements are synchronised stream flow and salinity monitoring for a reasonable period.; 5 years was enough at Pine Creek, and annual totals proved sufficient for the 2S fit. Groundwater information is also necessary, most critically the groundwater salinity, and then any additional information on the aquifer size and any storage buffer between the main aquifer and the stream. The development of surrogate measures of the possible size and extent of near-stream
buffers by Gallant and Dowling (in press) has the potential to simplify the estimation of this quantity. Finally information on how full the aquifer is from groundwater level records can assist with model fitting.

6.3 Salt Delivery Mechanisms

Central to the 2S and 3S models is the mechanism of salt delivery to the stream. Clearly in 2S there is direct connection of the surface and groundwater system with the stream, and the use of time lags and representative salinity values adequately describes these systems. As this usually applies to upland catchments with inherently relatively low salinity stream flow, there is no general salt store and the delivery of salt to the stream is not impeded.

In a 3S catchment there may be no direct connection of either near surface or groundwater to the stream itself. We expect that the size of, and rate of flow through, the intervening alluvial buffer will determine the salt delivery to the stream. In this case they may be considered to have slower flow processes controlling salt delivery.

Much of the western and central MDB is covered by regional alluvial GFS, where “wash off” processes dominate salt mobilisation. In these systems, a large volume of groundwater travels through highly transmissive aquifers that are covered by an extensive semi-confining layer. High, or near surface, groundwater heads in the lower aquifer forces a small amount of upward leakage to the much more saline storage zone. This salt in the near surface zone is concentrated then mobilised by fast surface water flows, or “wash off”. This behaviour is well represented in the 3S model, as the small inflow pushes out more saline water to the stream.

There are only relatively small areas that have “slow flow” salt mobilisation. These appear where there is little surface flow, or where there is a good connection directly from the parent groundwater system to the stream. The remainder of the MDB can be classified as “mixed” and includes much of the most interesting upland areas, where Dowling et al. (2004) have prioritised tree planting for salinity control.

Catchments with “mixed” wash-off and slow-flow processes deliver salt to streams depending on catchment specific factors. Catchment relief, slope, degree of regolith weathering, annual rainfall amount and seasonality, all contribute directly and in combination to control the delivery of salt to streams. For example, catchments with high slope, which are topographically high in a system, and have more than 1000mm of annual rainfall, could be expected to have a relatively unweathered aquifer with good connection through the surface material to the stream. Such catchments might have a relatively large proportion of total stream flow travel through this pathway usually considered to be the “slow-flow” route.

As the degree of weathering of the regolith increases slopes generally flatten, and such areas are often found in foothills and rolling country. Alluvial deposits may be present and with lower hydraulic conductivity and slopes, lateral groundwater transfers decrease and can become dominated by vertical processes. In such catchments the deep groundwater system may be slowly leaking salt to the near surface environment where it can be mobilised by individual rainfall events with wash off and throughflow processes. This means that while groundwater remains the main salt store in the catchment, without a direct connection to the stream it is not the delivery mechanism.
Determination of the salt mobilisation process in a particular catchment is central to the questions of data collection strategy, model complexity required, and salinity remediation measures.

### 6.4 Sub-annual Flow Measures

Direct calculation of annual average values is an area usually addressed by empirical top-down models, e.g. the Zhang Curve approach to annual water yield as used in this report (Zhang et al. 2001). However, currently in Australia there is great interest in how the FD curve may change over time and with land-use change, for example Lane et al. (2002). Policy for the Murray-Darling Basin is increasingly being specified in terms of flow percentiles rather than total salt loads, or exceedance probabilities, for example End-of-Valley Targets and the salinity at Morgan are couched in terms suggesting stream salinity should not exceed a target value for 80% of the year.

Much of the preceding work has examined data and represented it as changing slowly over the course of years or decades, and as such may have little to contribute to some of the more detailed questions being asked. However, as with the stream salinity versus rainfall work in §5, it may be possible to determine an underlying relationship between the annual average values and some critical point on the FD or FS curves. This approach applies the same philosophy as Lane et al. (2002), where they changed individual percentile values on a FD curve based on the observed data, rather than trying to reconstruct these each time from detailed daily water balance modelling.

Figure 28 shows the fitted linear relationships between the easily calculated annual variables total water yield and average stream salinity, and the 80th-percentile flow values from the FD and FS curves for 12 catchments from Table 1. Strong linear correlations are found for both annual measures, and imply that in some conditions at least, as experienced in the catchments analysed, that more pertinent information can be derived from simple numbers. Much more data from unregulated catchments around Australia is required to extend the robustness of relationships such as those in Figure 28.
Given the simple to estimate average flow and salinity values look at long-term stable numbers, we would expect them to be good estimators of the central percentiles for a given climatic and vegetation regime, while the extreme percentiles are more likely to be controlled by more episodic events and behaviours. In concert with the work of Lane et al. (2002) adjusting percentiles of FD curves and estimating changes in zero-flow days, the independent empirical estimation of a specific point, such as the 80\textsuperscript{th}-percentile of flow or salinity, may provide a good starting point for estimating future changes. Further, departures from these simple relationships can provide more information as to the net effects of the underlying groundwater flow systems and stream regulation.

The FD curves in regulated catchments are greatly affected by water storage management, and therefore will not generally be amenable to the simple analysis shown in Figure 28. Dam releases of large amounts of relatively fresh water will skew daily FD and FS curves, artificially increasing the 80\textsuperscript{th}-percentile flow and decreasing the 80\textsuperscript{th}-percentile salinity, for example. More complex tributary models that can deal with resource demand and allocation are required to deal with this level of detail.

**Conceptual Salt-balance Models:** Simple and robust conceptual models exist for describing the salt and water discharge to streams for a 2-store and 3-store system. For upland unregulated catchments these should provide sufficient generality to describe long-term behaviour. Salt delivery in these catchments is a mixture of slow and fast flow processes, determined by catchment specific properties that need to be critically assessed at the time of model conceptualisation. Simple long-term annual averages can provide information on flow percentiles, but not for the extreme high and low ends.
7. CONCLUSIONS AND RECOMMENDATIONS

Flow Duration Curves and Flow-Salinity Relationships are strongly linked. Two clear cases exist with land-use change: where flow regime changes but salinity remains constant, and where both flow regime and salinity change. Conclusions of sections are reiterated, along with further recommended work.

- In unregulated upland catchments which are relatively well flushed and are not deeply weathered, constant surface and groundwater salinity values can describe the flow and salt load behaviour. Separate modelling of the flow duration curve and flow salinity relationship is not needed.
- In unregulated catchments that can store salt and release it as a consequence of increased excess water fluxes, we propose a three store model incorporating a mixing zone before discharge to the stream can describe flow and salt load behaviour. As a generalisation it can also describe the simpler case in Point 1.
- A solid relationship can be developed between long-term average flow-weighted stream salinity and annual rainfall. Corrected for the rainfall salinity and considering a raft of engineering interferences on stream flows and salt loads, the range remains relatively tight and provides a powerful tool for highlighting intrinsic differences due to climatic regime and GFS.
- It is possible to develop conceptual models of 2- and 3-store models of salt and water discharge, with algorithms and procedures based on published work. These models provide a level of catchment analysis between desktop water-balance work and more detailed process-based catchment models, and are adequate for most upland unregulated catchments.
- Determining the mechanism of salt delivery to streams is crucial in planning data collection, model development, and control or remediation strategies within a catchment. Using broad-scale GFS data as a starting point, other techniques may be applied, or need to be developed, that analyse physical catchment attributes, from a DEM for example, or stream flow data, to determine the conditions that cause individual processes to dominate others.
- Further investigation of the relationship between stream salinity and annual rainfall is warranted, given the apparent robustness. Careful selection of catchments is required to remove as many external variables as possible, and isolate either climatic or GFS effects.
- Further investigation of the relationships between average flow and salinity and desired percentiles of the flow duration curve is warranted. Complimentary work by Lane et al. (2002) may provide a clearer picture of sub-annual effects of land-use change, and help isolate the effects of external variables, such as GFS, climatic trends, or stream regulation.
- A clear data gap exists for synchronised stream flow and salinity across Australia. Collection of such data, nested down river valleys, would greatly facilitate many water related studies, along with providing excellent information resulting from land-use and engineering changes being made, and being proposed, within catchments. Such basic monitoring data is also essential for many policy purposes, including environmental flows and end-of-valley targets.
REFERENCES


