NSW coastal rivers salinity audit

Predictions for the Hunter Valley Issue: 1
December 2000

N S W D e p a r t m e n t o f L a n d a n d W a t e r C o n s e r v a t i o n

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CHAPTER ONE

EXECUTIVE SUMMARY

The historic data for the Hunter Valley from 1975 to1999 shows evidence of a background rising trend in groundwater pressures across geologies and the catchment as a whole. Although the number of bores analysed is small in proportion to the area of the whole catchment, rising trends that were identified previously were confirmed by further fieldwork in the course of this study.

An analysis of stream salinity trends for 10 locations across the catchment did not, on the whole, indicate a worsening stream salinity problem in the Hunter Catchment. However, analysis of trends within the stream salinity data for the base assessment period is confounded by the paucity of data and the very significant changes imposed on the catchment hydrology by development. Therefore conclusions regarding positive, negative or nil trends in the historic stream salinity are difficult to make with confidence. Recent rising trends in the upper Hunter River at Muswellbrook may support a link with rising water tables, although falling trends at Liddell and Greta may be the result of several factors.

For example, the following factors may all play a part:

- falling groundwater trends in alluvial aquifers in the lower catchment;
- changes to river regulation following the commissioning of the Glennies Creek dam; or
- the effect of the introduction of the Hunter River Salinity Trading Scheme (HRSTS).

DLWC (2000) in the State of the Rivers Report shows rising trends in the Hunter River at Singleton for the period 1970 to 1979, and falling trends from 1980 to 1998. Falling trends in the Goulburn River at Sandy Hollow are at odds with rising water tables in the catchment, but may be influenced by groundwater pumping in the alluvial aquifers.

Assuming that rising groundwater trends will lead to increased stream salinity, this study has undertaken to quantify the likely impact of increased salt export from groundwater on stream salinity in the Hunter River and its tributaries to the nominal end of system at Greta.

Salt load and salinity predictions have been calculated for the target dates 2010, 2020, 2050 and 2100. The groundwater analysis covered the whole of the Hunter River catchment, but the surface water analysis covered only the contributing area upstream of Greta.

The audit should be considered in four parts.

1. Discrete and/or continuous flow and salinity data existed for most tributaries for varying periods from 1975. Relationships were established between salt load and flow using observed data for tributaries where it existed. Salt load parameters were regionalised for tributaries without observed salinity data, producing time series of salinities for all the tributaries for 1975 to 1998.
2. The river system comprises unregulated tributaries feeding into mainstream reaches that are regulated via storage and release from two supply dams. The tributary contributions were input and the groundwater contributions were adjusted to calibrate the Hunter Integrated Quantity and Quality Model (IQQM) on observed flow and salinity data on the mainstream for 1993 to 1998.
3. These contributions were then input into the IQQM 'current' conditions model which applies river operation and development as at 2000 for the entire 1975 to 1998 climatic period. By

definition, the unregulated tributary and groundwater contributions are unchanged by the 'current' conditions scenario. In the mainstream reaches 'current' conditions specifically refers to modelled flow and salt loads from the Hunter IQQM scenario, reflecting the variability of the base climatic signature, whilst complying with the most up to date flow rules and development. The results from the 'current' conditions model for the 1975 to 1998 climatic period were then used as a base case to which future increase scenarios could be compared.

4. The future conditions scenarios are the 'current' conditions scenario, with the addition of future increases in salt loads derived from observed groundwater trends at the target dates 2010, 2020, 2050 and 2100. There are limitations to this approach. The evidence for its likelihood is concrete but the size of the groundwater data set is small compared to the area to which it has been extrapolated. Although landuse change is generally thought of as the cause of rising water tables, no clear link has been established with the groundwater rates of rise examined in this study. The rates of rise have been extrapolated uniformly across all sub-catchments by association with geology; despite the fact that catchments vary in land use, vegetation and climate: and therefore in recharge and discharge potential.

Perhaps the most important lesson to be learned from the study of this scenario is that the solutions to the problem of the trends identified in this study must be addressed in the tributary and residual catchments since they are the source of the trends. The study has also identified that salt wash off from the tributaries is not the main driver of high salinity in the currently observed salinity distribution in the mainstream. Groundwater fluxes from the major fault zones are the prime determinant of high salinities observed during periods of low flow. If groundwater pressures continue to rise in the future, salt loads from fault zones may also rise. The magnitude of such an impact could be very significant, emphasising the need to address the rising trends at their source. The study shows that dilution flows via dam releases are a significant modifying factor to the observed salinity distribution in the mainstream.

Since 1995, reported discharges of salt to the river from coal mining in adherence with the protocols of the HRSTS have amounted to approximately 11,000 t a year. In this study it is predicted that an additional 5,000 t a year will pass through the Hunter River at Greta by 2020 as a result of rising groundwater pressure and dryland salinity processes in the tributary catchments. The simulated load passing beyond Greta represents only approximately 60% of the salt inputs to the model generated in the catchment as a whole. That is, the whole of the predicted additional salt load arising from dryland salinity is likely to reach a similar magnitude to that contributed by the HRSTS. (Total additional salt from groundwater = 8,800 t a year at 2020). Although the impact of this additional load on salinity is relatively small it may restrict the window of opportunity of the HRSTS currently and limit expansion of the scheme in future.

As further development of mining in the Hunter Catchment occurs additional pressure on the trading scheme will result as both the amount of salt to be discharged increases and the window of opportunity for such disposal shrinks. Although the trends in median and 80^{th} percentile salinities reported in this study are unlikely to shrink that window radically, the amount of salt coming on-stream is set to increase both as new mines are commissioned and old ones are decommissioned. No account of the impact of mine closure and the fate of salt within voids on future salt pollution has been attempted in this study.

Overall the trends in salinity predicted in the study are not great. In the mainstream, salinity values are predicted to rise by no more than 10% over the next 100 years. Change in some tributaries will be greater with a 10%, 13% and 33% change over 100 years predicted for Wybong Creek, the Goulburn

River and Dart Brook respectively. Water users across the catchment are already experiencing the management risk implications of the salinity levels identified in the study. Surface water salinity already presents threats to the wine industry, power generation and town water supplies. The trends show a gradual worsening of these current threats.

1.1 Overview of the study method and results

The methodology used in this study is consistent and broadly comparable with the method used by Beale et al. (2000) in the Murray Darling Basin (MDB) by both NSW and Victoria. In brief, the method has five steps:

1. Predict the mass of additional salt discharging to the land surface at the target dates based on observed rates of groundwater rise.
2. Establish the daily pattern of stream flow and salt load for the system inputs based on observed data. A statistical relationship between stream flow and salt load is used to fill in the gaps in the observed flow and salt load time series for each of the tributaries for the period 1975 to 1998.
3. Input the tributary contributions and adjust the groundwater contributions to calibrate the Hunter IQQM on observed flow and salinity data on the mainstream for 1993 to 1998.
4. Distribute the catchment salt and flow balance for 'current' conditions by routing tributary and groundwater inputs through the mainstream system while accounting for river regulation.
5. Predict the distributions of in-stream salt loads for future conditions by adding the predicted groundwater salt flux to the ‘current’ in-stream flow and salt balance.

In the Hunter Catchment the inclusion of a topographic index, giving a more reliable estimate of the maximum possible area through which discharge to the land surface can occur has provided a better approximation of the fraction or potential discharge area likely to contribute salt at the target dates. This has led to an improved calculation of the potential groundwater delivered salt load at the target dates. Routing of salt using the Hunter IQQM has facilitated a more representative estimation of stream salinity distribution while accounting for current regulation and flow rules applicable to the whole catchment.

Calculated potential salt loads from groundwater discharging to the surface were assumed to transfer directly into the stream. The analysis is based on calculations of salt load, but salinity rather than salt load is seen as a relatively more important indicator of catchment health in the Hunter Catchment. Therefore care has been taken to ensure the highest quality representation of salinity distribution achievable with the data.

Two methods of transferring the salt were used, matching of the salt delivery to the flow and salt load distribution currently observed in-stream, and a simple addition of a constant daily loading for each tributary and contributing sub-catchment. The choice of method had only a small impact on the calculated in-stream salt load in the Hunter mainstream but made a considerable difference to the predicted distribution of the salinity. The first method results in slightly higher estimates of salt load export, but returns lower median and 80th percentile salinities. Although the first method is considered to give a more realistic result, the latter constant loading method is also reported as a possible worst case scenario.

In this study, salt load refers to the mass of salt passing a particular location within a given time frame and is generally measured in tonnes per day or tonnes per year. Salinity on the other hand is a measure of the concentration of salt in a given volume of water. The concentration of salt in water affects the electrical resistance of the solution. Therefore the electrical conductivity of a solution is a convenient measure of salinity usually expressed as EC units where 1 EC = 1 micro Siemens per centimetre ($\mu S.cm^{-1}$) at 25^0 C. A conversion factor of 0.64 has been used throughout this study to convert EC to Total Dissolved Solids (TDS) for the calculation of salt load.

The basic unit of investigation in this study has been the tributary or contributing residual area sub-catchment. Tributaries are usually gauged at some point upstream of their confluence with the main river and their catchment is defined as the area above the gauge contributing flow. The remaining ungauged area downstream of the gauge that is referred to as a residual catchment, also contributes to flow in the mainstream reach. Individual sub-catchments range in size from 90 km^2 to 1900 km^2, with the exception of the Goulburn River catchment being 6,800 km^2.

■ Potential salt load from groundwater

Potential salt loads from groundwater discharge were calculated for each of these catchments based on the geology and location within the Hunter Catchment as a whole. Six geologies were used and catchments were divided between four provinces, those in the west, the north, the southeast and those lying in the central area of the Hunter Valley. Calculated salt loads per unit area of discharge for each geology and province ranged from zero in the southeastern alluviums to 31 $t.km^{-2}$ a year in the western Triassic sediments with an average of approximately 12.7 $t.km^{-2}$ a year for all geologies and provinces.

A maximum possible discharge area for each sub-catchment was calculated using the Fuzzy Landscape Analysis GIS model (FLAG) (Dowling 2000) topographic wetness index. The area calculated compared favourably with mapped areas of dryland salinity in the Hunter Catchment and ranged from 2.5% to 30% of sub-catchment area. This also compares with values reported in the literature (Freeze et al. 1979), with a calculated overall maximum possible discharge area occupying 11% of the whole Hunter Valley including the Williams Allyn and Patterson River systems. A predicted potentially salinised area for each sub-catchment was calculated at each target date as a proportion of the maximum wetness area using standing water level trends for each geology.

Although the predicted rates of annual salt load per unit of discharge area can be quite high, the predicted additional potential salt loads on a whole sub-catchment basis are relatively low. They remain less than 4.5 $t.km^{-2}$ a year for the most extreme sub-catchment during the 100 year forecast period. The range in potential salt loads per square kilometre of sub-catchment area under current conditions and at the target dates is shown in Table 1.

	Range in annual predicted potential salt load per unit area of contributing sub-catchments ($t.km^{-2}$ per year)				
Year	**2000**	**2010**	**2020**	**2050**	**2100**
Average	0.16	0.42	0.60	0.98	1.19
Maximum	0.58	1.67	2.35	3.63	4.46
Minimum	0.01	0.09	0.12	0.20	0.25

Table 1. Summary of sub-catchment statistics for groundwater salt discharge to the land surface expressed as salt load per unit area of each sub-catchment at the target dates

The average annual loads as at 2000 vary between sub-catchments with a maximum of 371 t a year and minimum of 7 t a year for any individual sub-catchment. It is assumed that this present loading is already incorporated in the observed stream flow and salt load.

■ 'Current' and predicted in-stream salt loads

Only the increment of predicted new salt discharge from the groundwater analysis is added to the stream to predict the in-stream salt loads and salinity at the target dates. The salt load determined for 'current' conditions for the in-stream analysis is used as the base figure, and the 2000 groundwater load is assumed to be already accounted for within it. When predicting for future dates only the difference between the 2000 groundwater estimate and the groundwater estimate for the target date is added to the 'current' in-stream load.

All sub-catchments in the Hunter Valley were accounted for in the groundwater analysis including the Allyn Patterson and Williams River systems. However, the in-stream analysis was limited to only those catchments contributing to the mainstream Hunter River above Greta.

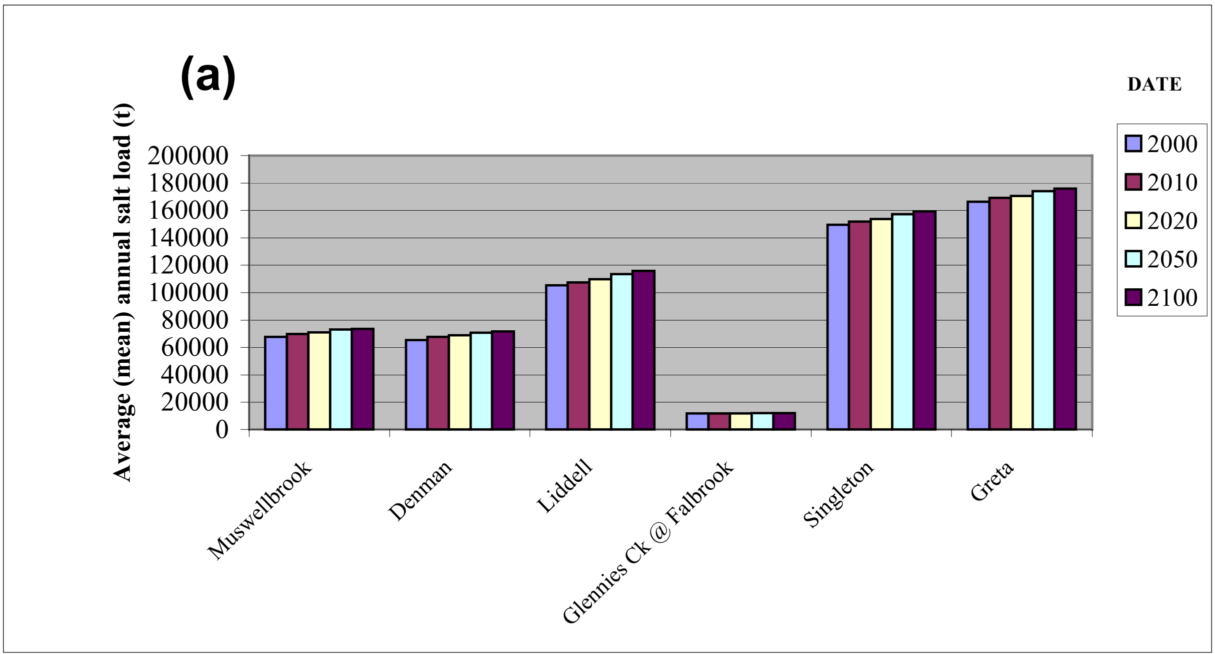
Table 2 summarises the overall groundwater potential salt flux for the whole catchment and the increment added to the stream for just the area above Greta.

Date	Annual groundwater salt flux (whole catchment) (t per year)	Annual in-stream added salt (whole catchment) (t per year)	Annual in-stream added salt (less Williams Patterson and Allyn Systems) (t per year)
2000	3350	Base level	('Current' annual in-stream load at Greta 166,500)
2010	8900	5550	4900
2020	12950	9550	8800
2050	21050	17650	16100
2100	25500	22100	20250

Table 2. Total potential annual salt load from groundwater at the target dates and the increment of additional salt entering the river system for the whole catchment and the catchment contributing to the Hunter River above Greta

Of this total input of salt from the tributaries including the additional salt coming from groundwater, approximately 60% passes out through the Hunter River at Greta, while approximately 20% is extracted in diversions, and a further 20% is accounted for in system losses. Some of this system loss recharges alluvial aquifers and would return to the system eventually although this has not been accounted for in this report.

Salt load increases progressively downstream as inputs from the tributaries accumulate in the mainstream as shown in Figure 1a. On the other hand cummulative salt load per unit area of catchment tends to decrease progressively downstream. Although this is primarily a result of differing scales i.e. area increases more rapidly downstream than salt load (salt load increases 246% from Muswellbrook to Greta, and the area increases 444%), it also emphasises the combined effect of the tributaries and extraction (Figure 2). The greatest level of extraction occurs between Denman and Liddell. Tributaries vary widely in both the amount of salt they export as well as in predicted salt load trend as shown in Figure 1b. This variation is partly due to differences in catchment area as well as flow. Differences can also be attributed to topography and geology as well as other factors such as vegetation.



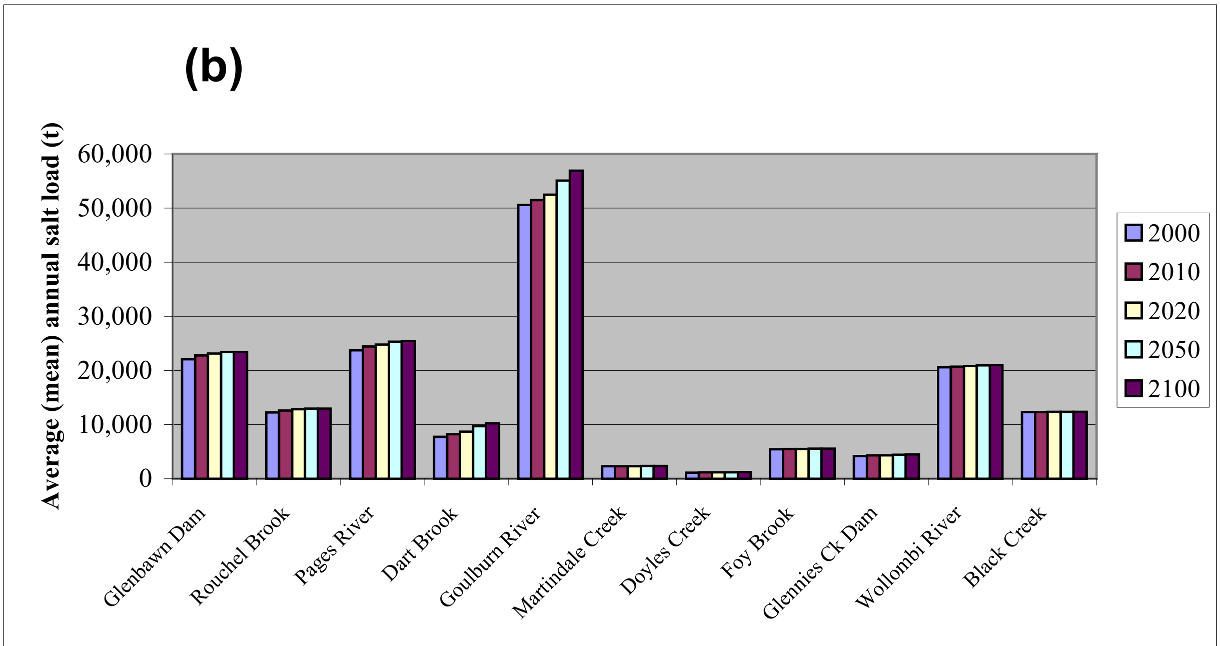
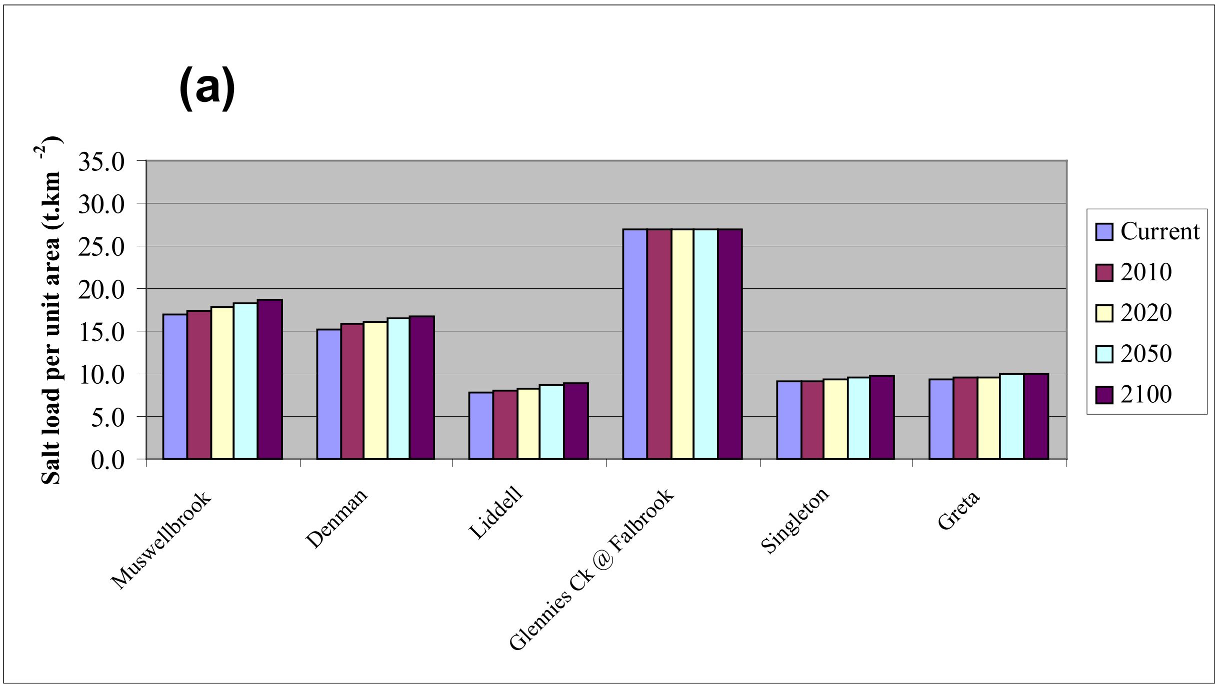


Figure 1. Increase in average annual in-stream salt load at target dates for (a) mainstream sites along the Hunter River including Glennies Creek at Falbrook and (b) for tributaries.



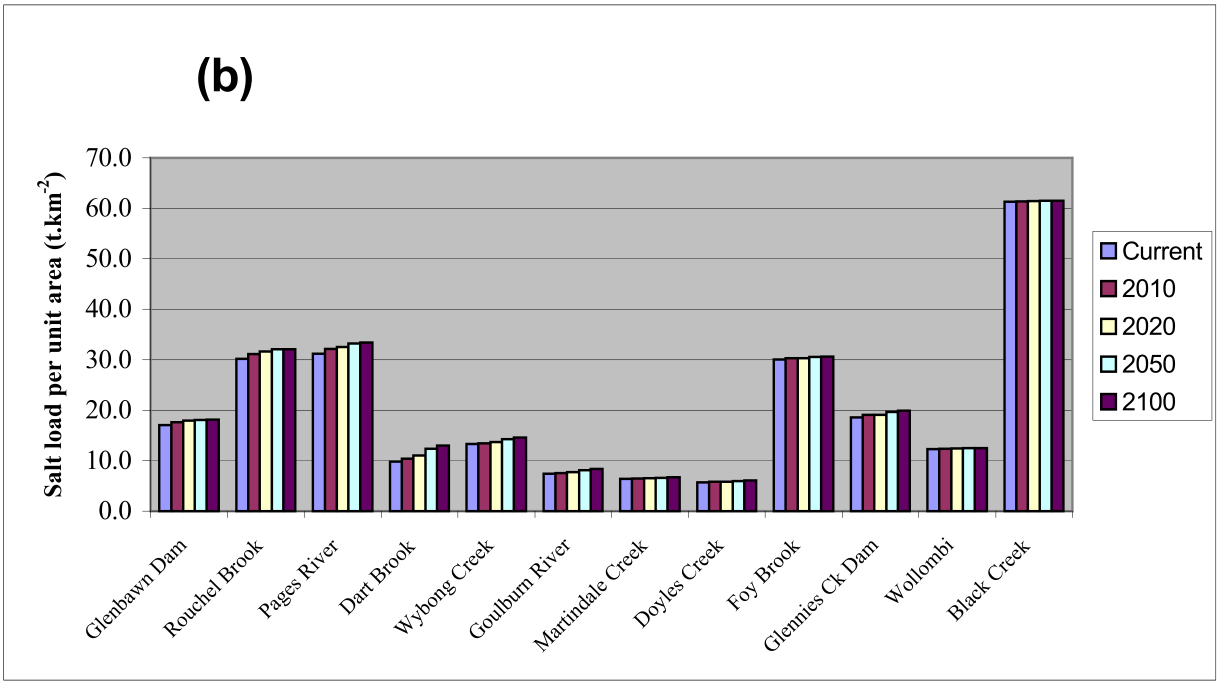


Figure 2. Trends in average annual salt load per unit area of catchment upstream of the gauge at (a) locations along the Hunter River mainstream as well as Glennies Ck at Falbrook and (b) for tributaries

The predicted increases in salt load are small relative to the ‘current’ salt loads already observed in-stream.

The overall salt load per unit area of catchment in the Hunter River at Greta is comparable with catchments of similar size in the MDB (see Table 3). The Hunter River is most similar to the Namoi River in size, salt load and depth of runoff.

Catchment	Location	Contributing area (km^2)	Annual salt load ($t.km^{-2}$ per year)	Runoff (mm)
Hunter River	Greta	17800	9.4	39
Namoi River	Gunnedah	17100	9	43
Lachlan River	Forbes	19000	15	60
Murrumbidgee River	Gundagai	21100	14.6	193
Macquarie River	Dubbo	19600	10.9	–

Table 3. Average annual salt load per unit area under ‘current’ conditions for the Hunter River and similar sized catchments in the Murray-Darling Basin

Over the full 100-year period of prediction between 2000 and 2100 the salt load at Greta is estimated to increase by 5.7 and 7.2 per cent for the constant loading and current distribution cases respectively. The only factor responsible for this simulated change is the predicted groundwater flux from the tributaries.

■ ‘Current’ and predicted in-stream salinity

Salinity in the mainstream river at any point in time is determined by the amount of flow and the source area contributing. That is; rainfall, runoff characteristics, and distance to the mainstream are not distributed evenly over the whole catchment; and thus tributaries vary in their contribution and timing with each event. In addition significant groundwater influx occurs in specific reaches where the river intersects major fault lines. These influxes have been accounted for as point source daily load inputs in the calibrated IQQM. During lower flows, that is when median to higher ECs are experienced, these groundwater fault zone interactions are the dominant influence on the salinity in the mainstream. During higher flow events salinity in the mainstream is dominated by wash off from the tributaries.

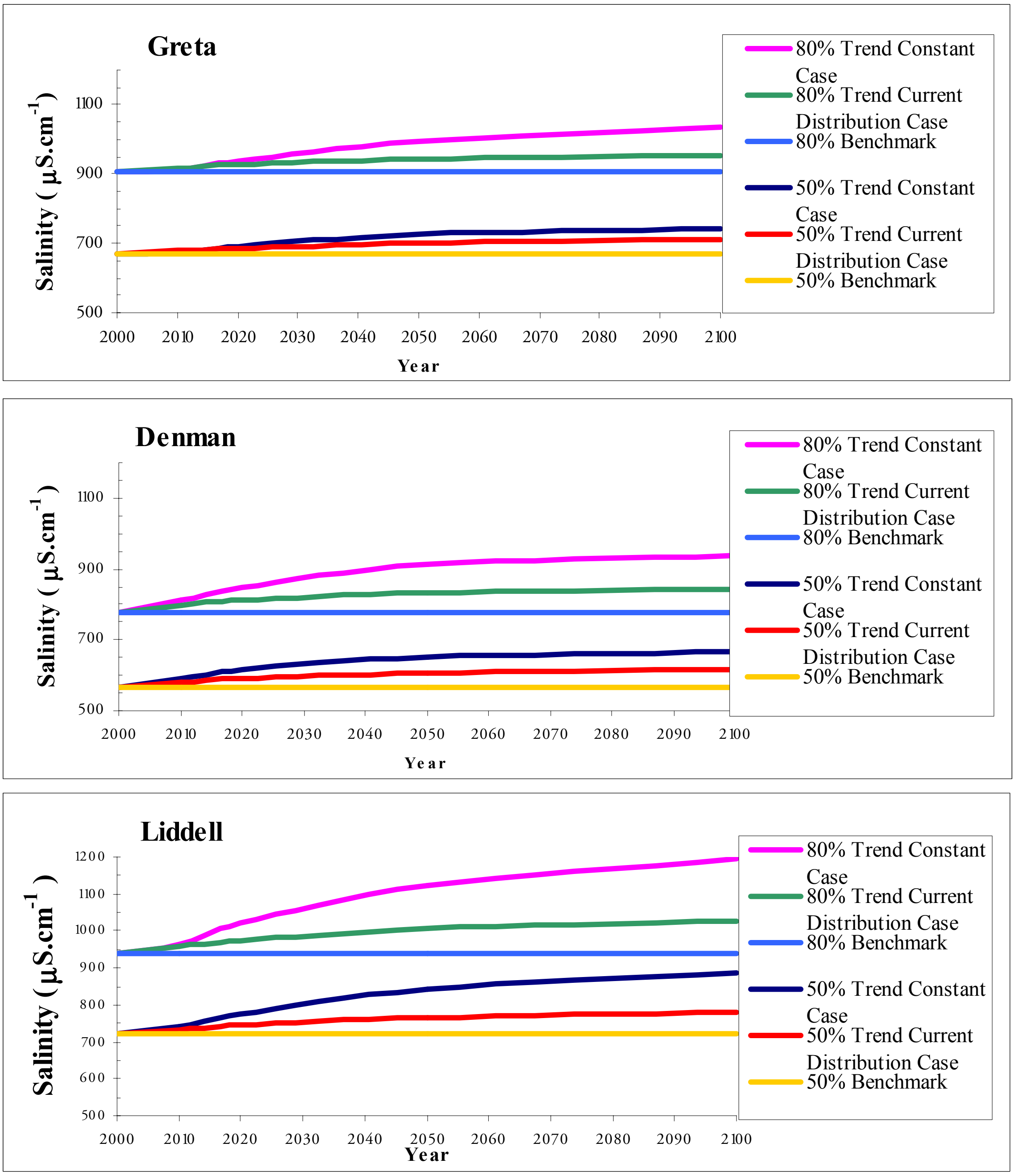


Figure 3. 'Current' benchmark median and 80th percentile salinities and predicted salinity trends for the current distribution case and the constant daily loading case

The mainstream groundwater fault zone interactions have not been modelled explicitly in this study. It was assumed that these systems would remain in a stable equilibrium condition throughout the prediction period. Therefore, the shifts in salinity reported for this study are due to the contributions made by the impact of dryland salinity processes operating in the tributaries. However, it is far from certain that the groundwater fault zone contribution will remain constant. In fact they would be likely to show some seasonal and climatic responses regardless of whether there is any trend. If rising groundwater levels throughout the catchment substantially increase salt contributions from major fault zones there could be some very definite changes in mainstream salinities as a consequence.

Salinity trends at Greta, Denman and Liddell are summarised in Figure 3. An increase of 10 $\mu S.cm^{-1}$ at 2010 is predicted at Greta for both the median and 80th percentile salinity rising to an increase of 40 $\mu S.cm^{-1}$ at 2100 for the most likely current distribution case. This represents only a 6% change over 100 years.

Salinity levels vary between tributaries and do not necessarily correspond directly with salt load per unit area. Ranking catchments according to salt load and salinity will result in a different order. Rouchel Brook, Pages River and Foy Brook all generate similar salt load per unit area, 30.2, 31 and 30 $t.km^{-2}$ a year under 'current' conditions but have corresponding median salinities of 470, 610 and 1870 $\mu S.cm^{-1}$ respectively. Dart Brook and Wybong Creek have similar median salinities of 1455 and 1465 $\mu S.cm^{-1}$, but quite different salt export rates of 9.8 and 13.3 $t.km^{-2}$ a year respectively. This difference makes it difficult to rank tributaries and prioritise remedial strategies across catchments.

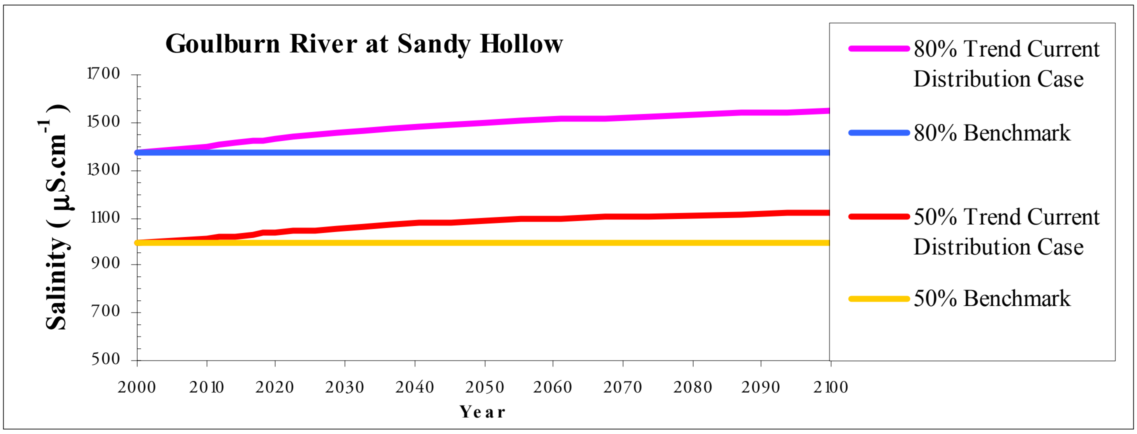


Figure 4. 'Current' benchmark median and 80th percentile salinities, and predicted salinity trends for the current distribution case in the Goulburn River

Although the groundwater analysis was undertaken on a majority of sub-catchments and extrapolated to all within the basin, sub-catchments had to be lumped together for the surface water analysis. In particular the Goulburn River system could only be analysed at the gauging station at Sandy Hollow representing the downstream outcome of processes operating in the twelve sub-catchments upstream. Average annual flow from the Goulburn River at Sandy Hollow is 150500 ML a year or approximately 40% of the flow in the Hunter River at Liddell. It currently exports 50,600 t of salt annually at a median salinity of 995 $\mu S.cm^{-1}$ and an 80th percentile salinity of 1375 $\mu S.cm^{-1}$. This is significantly higher than for the Hunter River at Denman, and is a significant determinant of both the higher salinity at Liddell as well as the higher trend in median and 80th percentile salinities. The estimated trend in salinity is shown in Figure 4 representing a 12.5% increase in median and 12.7% increase in 80th percentile salinity from a 12.5 % increase in annual salt load over the 100-year prediction time frame.

Reporting salinity distribution values for the tributaries is made difficult by the fact that most experience significant periods of zero flow. Median and 80th percentile salinities have been calculated using the current distribution case. During periods of zero flow salinity values have been held to a maximum observed value. Therefore the median and 80th percentile values represent the within tributary hazard, but not necessarily the distribution of salinities exported to the mainstream. During no-flow periods where water users continue to pump from pools, salinity values may be worse than the values reported here due to increasing concentration with evaporation. The tributaries vary in the degree to which they are ephemeral. The Goulburn River at Sandy Hollow only experiences zero flows for 3% of the time; while Rouchel Brook, the Pages River, Black Creek and Wybong Creek experience zero flows for 10%, 6%, 13% and 13% of the time respectively. Dart Brook, Martindale Creek and Wollombi Creeks have zero flow for 26%, 30% and 24% of the time respectively; while no flow was recorded in Foy Brook and Doyles Creek for 42% and 51% of the period from 1975 to 1998. Rising groundwater pressures are likely to result in increased flow duration mainly by increasing base flows with corresponding increases in high salinity flows.

■ Salinity impacts

Salt load per se is considered to be less valuable than salinity as an indicator of social or ecological problems in the Hunter Valley. The relative toxicity of a range of salinity levels is generally known for different end uses. Salinity may be assessed against social and environmental thresholds over time, and the probability of exceeding a threshold may be assessed as a basis for risk management. Load, on the other hand, gives an indication of the amount of environmental pollutant that has to be dealt with. For example, the salinity of water received by Macquarie Generation will determine whether or not water treatment is required. The salt load, however, will determine the amount of ameliorant required and the amount of waste product to dispose of. Salt load generally passes out to sea without being passed on to downstream users in the same way that, for example, the Macquarie River contributes to the Murray River. Salt may accumulate on irrigation areas, and although they are not huge areas when compared with those in the MDB, they represent significant economic resources for the Hunter. Therefore salt load was modelled and particular attention was paid to both accurately representing the salt load and salinity relationships.

Threshold salinity values of 800 and 1600 $\mu S.cm^{-1}$ have been chosen to represent risks associated with human consumption, irrigation of sensitive crops and ecosystem health. The World Health Organisation (WHO) recommends a desirable threshold limit for salinity of water for human consumption of 830 $\mu S.cm^{-1}$, although higher salinities can generally be consumed safely up to 1600 $\mu S.cm^{-1}$ and the absolute potable limit for drinking water is 2500 $\mu S.cm^{-1}$ (Taylor 1993). For irrigation, salinities of 280–800 $\mu S.cm^{-1}$ are capable of causing damage to sensitive crops, requiring moderate leaching and restricting the method of application. That is, even where low salinity irrigation is applied as a foliar spray to a sensitive crop, more damage is likely and salt can build up in the soil root zone unless flushed down to depth with drainage under the crop. Soils with poor drainage are generally unsuitable for irrigation with water salinity in the range 800 to 2300 $\mu S.cm^{-1}$, due to the requirement for high levels of leaching. Only tolerant crops can be grown with water salinities in this range. Additional leaching fractions applied have accelerated the formation of groundwater mounds and shallow water tables in the MDB. For the most part, irrigation is carried out on the alluvial flats in the Hunter Catchment where good drainage and high levels of groundwater extraction have led to falling trends in standing water levels, particularly in the southeast.

It is suggested that direct adverse biological effects are likely to occur in Australian river stream and wetland ecosystems when salinity levels reach 1560 $\mu S.cm^{-1}$ (ANZECC 1999). Water with salinity greater than 4690 $\mu S.cm^{-1}$ is considered distinctly saline by ecologists as it is typically inhabited by different biota, not found in waters of lower salinity. Although the Hunter River has no major wetlands of comparable size with those found in the MDB, riparian and phreatic wetlands are widespread, important ecosystems. Much of the mapping of dryland salinity in the Hunter Catchment has been done on the basis of erosion classes associated with salinity and vegetation indicators such as *Casuarina* and *Juncus* species typical of riparian and phreatic wetlands. The majority of dryland salinity discharge sites in NSW are in fact phreatic wetlands; that is, wetlands associated with high water tables. Severe erosion caused by damage to wetland vegetation in saline discharge sites was one of the primary reasons that dryland salinity was first recognised as a major environmental problem in Australia. Many small streams in the Hunter Catchment have saline flows in excess of 5000 $\mu S.cm^{-1}$.

For the end of system at Greta the median salinity is currently less than the WHO standard of 830 $\mu S.cm^{-1}$ and will not exceed it on the basis of these predictions. However for 20% of the time (i.e. 80th percentile) salinity already exceeds this threshold and is predicted to rise further. A summary of salinity distributions for the mainstream and tributaries is presented in Table 4.

Exceeds 800 $\mu S.cm^{-1}$ / Exceeds 1,600$\mu S.cm^{-1}$ / Exceeds 4,700 $\mu S.cm^{-1}$		'current' and predicted median and 80th percentile salinities for the Hunter River and Tributaries $\mu S.cm^{-1}$				
Location	Percentile	2000	2010	2020	2050	2100
Hunter River at Muswellbrook	50th	485	500	510	520	525
	80th	625	640	655	670	675
Hunter River at Denman	50th	565	580	590	605	615
	80th	775	795	810	830	840
Hunter River at Liddell	50th	720	730	745	765	780
	80th	940	960	975	1005	1025
Glennies Ck at Falbrook	50th	445	450	450	455	455
	80th	570	575	575	585	585
Hunter River at Singleton	50th	670	680	685	705	715
	80th	925	935	945	970	980
Hunter River at Greta	50th	670	680	685	700	710
	80th	905	915	925	945	955
Goulburn River at Sandy Hollow	50th	995	1015	1035	1085	1120
	80th	1375	1400	1430	1500	1550
Rouchel Brook	50th	470	485	495	500	500
	80th	650	675	685	695	695
Pages River	50th	610	630	640	650	655
	80th	765	790	800	815	820
Dart Brook	50th	1455	1545	1640	1825	1930
	80th	3915	4155	4415	4920	5190
Wollombi Brook	50th	705	710	715	715	720
	80th	1295	1300	1305	1315	1320
Wybong Creek	50th	1465	1480	1505	1565	1610
	80th	2460	2480	2525	2625	2695

Exceeds 800 µS.cm⁻¹ / Exceeds 1,600µS.cm⁻¹ / Exceeds 4,700 µS.cm⁻¹		'current' and predicted median and 80th percentile salinities for the Hunter River and Tributaries				
		µS.cm⁻¹				
Martindale Creek	50th	495	500	505	510	520
	80th	1815	1835	1845	1870	1895
Foy Brook	50th	1870	1885	1885	1900	1905
	80th	3370	3395	3400	3425	3440
Black Creek	50th	1220	1220	1220	1225	1225
	80th	1790	1790	1790	1795	1795

Table 4. Predicted 50th and 80th percentiles for salinity µS.cm^{-1}) in the major regulated river systems and tributaries of the Hunter Valley for 2010, 2020, 2050, and 2100 (shaded values exceed WHO drinking water standard and environmental thresholds).

Setting water quality targets at any point along the river is, in essence, designed to protect assets and values downstream of the target location. A series of within valley targets and strategies is required to address the problem at source and protect within-valley assets. Strategies to address dryland salinity primarily fall into four categories:

1. Vegetation strategies aimed at modifying the water and salt balance in recharge and discharge areas.
2. Engineering solutions such as streambed reclamation; groundwater pumping; storage and disposal, similar to the current operation of the HRSTS; and changes to river regulation to maximise the effectiveness of dilution flows.
3. Market mechanisms to expand the scope of environmental trading schemes such as the HRSTS, introducing a range of tradeable offset actions for development consent for a range of environmental outcomes, including salinity credits, biodiversity credits and carbon credits.
4. Monitoring and evaluation.

To undertake such a strategy in an integrated manner, further work will be required in prioritising catchments, prioritising interventions and establishing the currency and exchange rate for tradeable rights. Accounting for gains and losses is beyond doubt the most critical issue to the efficiency of this process. Adequate monitoring systems will be essential if the success of the salinity strategy is to be assessed.

1.2 Further work

Ultimately reducing the risks associated with dryland salinity in the tributaries to counteract the trends predicted in this study will involve the rehabilitation of recharge areas and discharge areas within the catchment as a whole. This will be expensive, and dollars need to be strategically targeted. This will require a methodology to rank catchments, recharge areas and discharge areas in an objective priority order.

Further work will be required in the areas of:

- **Salinity hazard mapping including assessing the spatial hazard associated with recharge risk.** Areas for intervention need to be prioritised on the weight of all the available evidence. Outputs of the current study such as the FLAG Wetness index, annual salt load and annual salinity statistics incorporated in a weights of evidence framework will add value to existing GIS layers used in this process.

- **Rapid stream survey of the stream network within the tributaries analysed in this study.** Not all recharge and discharge necessarily represents a salinity problem. Not all parts of a catchment contribute equally to the salt load coming from a tributary. Identifying which streams and geologies contribute saline discharge, and which contribute fresh water will add value to the hazard mapping process; and will allow priority recharge and discharge areas to be identified down to the property level. A one-off survey of stream EC during a low flow and a high flow event, coupled with detailed geology information, can provide information on the relative importance of geologies and geomorphological features such as paleo-channels and faults.
- **Evaluate scale of intervention required.** Hazard mapping and mapping of relative recharge risk associated with rainfall, soil type and landuse can be achieved as in the process advocated previously, without putting specific numbers on recharge and discharge. To evaluate the level of intervention necessary for a desirable level of salt load or salinity reduction will require realistic estimates of the impact of vegetation and management changes on the water and salt balances within the tributaries. Projects modelling recharge and salt mobilisation currently employed by DLWC Centre for Natural Resources in the MDB should be extended to selected tributaries in the Hunter Catchment. The recharge modelling project and the CATSALT modelling framework can provide information on the water and salt balance impacts of changed vegetation management; as well as evaluating the area treated against the in-stream salt load and salinity outcomes. Information about the scale of intervention required for a specific cost benefit, is essential to establishing the currency and exchange rate for environmental offset trading.
- **Mine rehabilitation study**—The importance of the mines and power generation industry as point source salt polluters is well recognised, and an efficient pollution licensing system has been put in place under the Salinity Trading Scheme to minimise the environmental impact. The coal seams exploited by the mining industry are found within the early and late Permian geologies within the catchment. These geologies were formed in marine environments, and contain large quantities of connate salt held within the consolidated rock matrix. The coal seams themselves are more permeable than the rest of the rock matrix, and form the aquifers contributing saline groundwater to the mine pits. The groundwater salinity is a result of the surface area of the rock matrix that the groundwater is in contact with, and its residence time. At present this groundwater seepage is intercepted and stored before discharge to the river. Questions arise as to the fate of this seepage following the back filling of the mine pits with the crushed over-burden as they are decommissioned. Seepage into these voids will bring groundwater into contact with an artificially very large surface area of crushed rock material with a very high salt store. Potential problems may occur where very high salinity groundwater from these voids escapes the site, contaminating surface runoff and fresher surrounding groundwater systems. A comprehensive study quantifying the seepage and salt dissolution processes, their likely effects on surface and groundwater flows and acceptable management protocols for decommissioning mines and the continued role of the Salinity Trading Scheme in this process must be carried out as soon as possible.
- **Groundwater monitoring network.** As stressed elsewhere in this report, the groundwater data available for analysis in this study has been gleaned from a small number of bores relative to the size of the catchment and the scope of the association with geology used to extrapolate the identified trends. Anecdotal evidence suggests that for large areas in the western part of the Hunter river catchment, particularly in the Goulburn River Catchments, groundwater has not been explored because most groundwater is known to be highly saline. A groundwater monitoring

network comprising existing bores and additional bores should be established and monitored regularly to specifically address the issues of standing water level trends and salinity. Particular emphasis should be given to filling knowledge gaps in the tributaries. Combining information from the rapid stream survey recommended above and the FLAG wetness index, would be a useful way of targeting the location of the bores.

- **Stream gauging network particularly in the Goulburn River catchments.** The region should consider extending its stream-gauging network to include continuous flow and salinity measurements in all the tributaries. In the past, flow gauging in many tributaries has been problematic due to the physical nature of the stream beds and difficulties in applying flow height to volume ratings as bed configuration in sandy streams continually shifts. In the Goulburn River sub-catchments rainfall runoff modelling using the Sacramento Model was attempted with the aim of producing simulated flows for the whole 1975 to 1998 period. This exercise had to be abandoned, as insufficient accurate flow data was available to calibrate the model. Considering the importance of salinity in the Goulburn River sub-catchments identified in this study, careful consideration should be given to overcoming some of these technical deficiencies.

CHAPTER TWO

INTRODUCTION

In response to the salinity audit of the Murray Darling Basin (MDB) which was completed in November 1999 (Beale et al. 2000), the New South Wales Government initiated the development of the NSW Salinity Strategy. There are known salinity issues outside the MDB including urban, dryland and irrigation induced salinity in the coastal catchments of NSW, that are not addressed in the audit. Therefore, to make the strategy a comprehensive policy initiative, an audit of dryland salinity impact on predicted river salinities was begun for the Coastal Catchments of NSW starting with the Hunter Valley. The Hunter Valley is somewhat unique in NSW in that major salinity issues associated with coal mining and the generation of electric power also exist alongside the more widely appreciated forms of salinity associated with agricultural and urban development.

The Hunter Valley has a long history of salinity with recorded river salinities far in excess of those measured for similar sized rivers in the MDB. Creek names such as Salt Water Creek aptly given by the early settlers attest to the fact that for the most part salinity is a naturally occurring phenomenon linked closely with the geological history of the Valley. Early explorers such as Dangar in 1828, wrote about the Liddell area and noted the suitability of land for grazing, but declined to recommend settlement due to the salinity of the available surface waters. Never-the-less owing to its proximity to Sydney in the early days of European colonisation, and its much greater agricultural potential, the Hunter Valley was cleared of its forest and woodland vegetation earlier than any other major catchment in Australia.

Land clearing is generally recognised as the major driver in the development of human-induced accelerated groundwater recharge leading to dryland salinity. A direct cause and effect relationship between rising water tables increasing dryland salinity and the salinisation of surface water resources by groundwater contamination is generally accepted and is used in this study. However, it is worthwhile to note that this is not the sole cause of salinity, and that waterlogging which may occur due to the same general process does not necessarily mean salinisation will occur. A number of conceptual models relating soil and geological structures to local intermediate and regional groundwater flow systems associated with land salinisation have been described by Coram in 1998. Regardless of which model is appropriate to individual situations, increased recharge is seen as the controllable factor in the hydrologic dis-equilibrium causing both land and surface water salinisation.

Various studies in the past have identified high levels of salinity in the Hunter Valley, but for the most part have assumed that the range of salinity levels observed in the Hunter River and its tributaries lie within the natural variability. Creelman in 1994 stated that: ‘The Hunter Valley has a salinity problem, but generally the water tables are stable neither rising nor falling, although on a limited local scale this may be occurring’. More recently, DeSilva et al. (1997) carried out reconnaissance bore surveys showing that rising groundwater pressure is more widespread than previously thought. High levels of groundwater pumping for irrigation and large scale de-watering of the many open cut coal mines in some geologies may be masking any background effects of increased recharge. In the present study the bores used in the previous reconnaissance survey were re-sampled to confirm the trends.

It is estimated that there are probably at least 20,000 bores located in the Hunter Valley. Of those only approximately 6,000 are listed on the NSW Department of land and Water Conservation

Groundwater Database. Of those, only 253 are listed with sufficient information regarding historic water levels to make an estimate of the rate of rising groundwater within the Valley. Whether this is a representative sample from which salinity prediction can be made, is a moot point; and care should be used when drawing conclusions from the results of this study.

Although much longer periods of river flow data are available for major sites within the valley salinity data has only been collected since the early 1970s. The period since salinity began to be recorded up until the present forms the basis of the analysis for tributary behaviour. The analysis is based on a statistical approach rather than a deterministic one, although groundwater trends have been linked to future surface water salinity trends as a causal factor. Process mechanisms of salt transport from groundwater to the stream have been evaluated qualitatively rather than quantitatively in any specific deterministic sense. Major changes affecting the water balance of the catchment have occurred during the base data period, requiring a cautious appraisal of the core data. The period itself has a unique climatic signature and has seen dramatic increases in the development of large-scale open cut coal mining and power generation as well as major changes in both river regulation, infrastructure and operation. During the period, the capacity of Glenbawn Dam was increased and the Glennies Creek Dam was constructed.

The catchment itself has unique features of physical geography, which distinguish it fundamentally from those of the MDB. The MDB can be understood as a large flat dish dominated by low slopes with only a very constricted single surface and groundwater outlet. Whereas, the Hunter Catchment, by contrast, is generally mountainous and rugged with slopes in excess of 15 degrees occupying approximately 42% of the catchment. Generally higher head gradients and a system driven by local to intermediate scale flow systems results. The geology is largely flat bedded, with groundwater flow dominated by faulting and bedding plane fractures resulting in highly anisotropic flow systems. Major fault lines contributing substantial amounts of saline groundwater, such as the Mt Ogilvie fault, are intersected by the course of the Hunter River. Little if any information is currently available on the location, extent and connectivity with the recharge intake zones feeding these fault lines. Creelman (1994) states that ‘water that is in equilibrium with the Wittingham coal measures appears to be discharging through the Mt Ogilvie fault, and there is some evidence that the Hunter River just above Jerrys Plains may be receiving part of this water through its alluvium.’ In this instance equilibrium refers to the species and concentration of salts in the groundwater. The connectivity of both aquifer systems is inferred, but the source of recharge is not identified.

The geology of the Hunter Catchment is recognised as being a significant determinant of the salt stores within the valley. Several authors give comprehensive descriptions of the geologies and their relative salt contributions (Creelman 1994, Bembric 1993 and Kellet et al. 1989). The marine and estuarine sediments of early and late Permian geologies contain significant amounts of connate salts. They also contain the major coal seams currently being developed by the mining industry which are also usually the most permeable strata acting as natural groundwater conduits. De-watering of these aquifers during mining operations produces large amounts of saline water that is disposed of in the river. Formalisation of this process led to the inauguration of the Hunter River Salinity Trading Scheme (HRSTS) in 1995 whereby the mines hold salinity credits allowing them to discharge saline water to the river during periods of high flow when EC threshold criteria are met. Some 11,000 t of salt currently enter the river this way each year.

Due to the proximity to the coast, oceanic cyclic salt inputs can be high, varying across the catchment. Creelman (1994) estimates rates of cyclic salt input ranging from 20 to 30 $t.km^{-2}$ a year in coastal areas, 9 to 19 $t.km^{-2}$ a year in the lower Hunter Catchment, 6 to 10 $t.km^{-2}$ a year in the mid Hunter Catchment and 3 to 8 $t.km^{-2}$ a year in the upper Hunter Catchment. By contrast cyclic salt input in the upland catchments of the MDB in NSW generally ranges from 1 to 4 $t.km^{-2}$ a year (Blackburn and McLeod 1983). Creelman (1994) attempted to modify salt release rates from the various geologies in the Hunter Catchment published by Bembric (1993) to account for the annual addition of cyclic salt. Catchments in equilibrium are catchments where salt input equals salt output, having input to output ratios of 1. Input to output ratios obtained from Creelman's figures suggest a catchment undergoing a period of salt imbalance rather than one in equilibrium. Ratios of approximately 1: 1.3 for Doyles Creek and Wollombi Creek and 1: 1.6 for Bowmans Creek are close to equilibrium.

However, most other catchments listed show considerably more imbalance. The ratio for the Pages River is 1: 5.25, for upstream of Glenbawn Dam 1: 6, Rouchel Brook 1: 4.25, Goulburn River 1: 2, Dart Brook 1: 3.25, Martindale Creek 1: 2.5, Bayswater Creek 1: 7.2 and Saltwater Creek is 1: 33.5. The concept of salt equilibrium in this case assumes a steady state in the longer term. That is, the change in the salt store in the landscape is determined by addition from cyclic salt plus addition from rock weathering minus discharge in stream and groundwater flow. For equilibrium to exist these processes must balance. Creelman attributes the additional salt predominantly to weathering processes or the salt bleed from regional groundwater systems via major fault lines. Saltwater Creek traverses the Saltwater Thrust for most of its length. Actual rates of salt accumulation due to weathering processes are generally considered to be very small due to the time frames involved, so salt imbalances such as those observed must be depleting the salt store in the catchment. Kellet et al. (1989) note that the fact that there is any marine solute left to leach since tertiary uplift is due to a process of entrapment within the coal and associated strata as compression reduced the porosity so that salt is now only released by molecular diffusion. 'Molecular diffusion is therefore the only hydro-chemical process which is sufficiently slow to explain the persistence, from tertiary uplift until present, of marine solutes in the active leaching regime of the upper Hunter Valley groundwater.' Yet a considerable salt imbalance exists today.

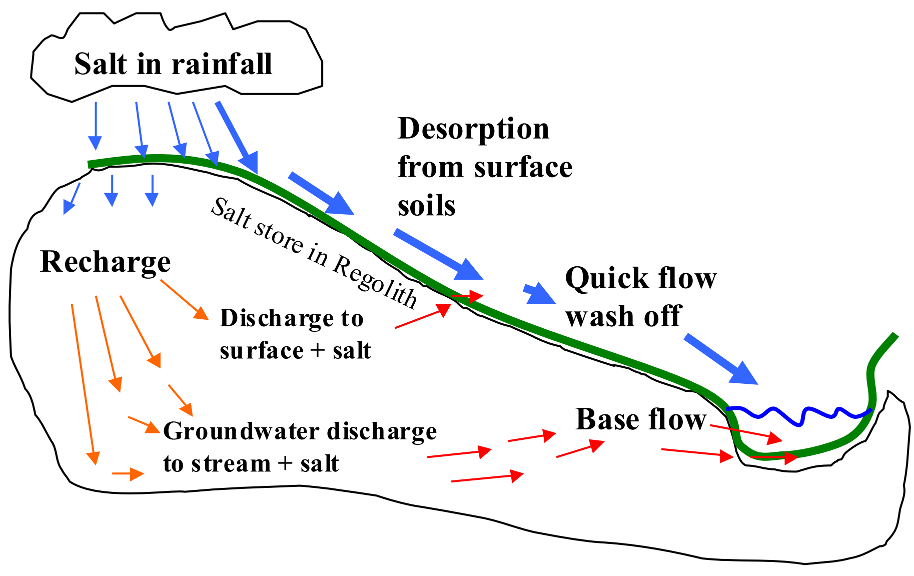


Figure 5. Sources of salt in stream flow

Salt is moved in the landscape with the movement of water. Hydrological equilibrium assumes that in the longer term all outputs via evapotranspiration, groundwater recharge and discharge, runoff, lateral drainage, and changes in the catchment moisture store directly balance rainfall input. This also assumes a steady state in the longer term, something not observed in nature in time frames relevant to human activity especially in Australia where extreme climatic variability is ubiquitous. In reality, the system is highly perturbed, primarily by the episodic nature of rainfall, its timing and amounts. Recharge is also episodic, and groundwater discharge either via base flow or to the land surface is lagged. The imbalance between recharge and discharge results in changes to the catchment moisture store particularly in the saturated zone, evidenced by fluctuations in bore hydrographs. Longer-term stresses in the system, due to climatic variability and altered evapotranspiration to recharge ratios due to land use change, cause rising or declining groundwater pressure trends. Discharge flow rates are directly proportional to the pressure head. When the pressure head is changed, the flow rate responds instantaneously. However, the rate of change in the pressure head is itself determined by recharge addition and the outflow rate. Outflow is a function of the aquifer transmissivity and the path length. A single recharge pulse may take 5–20 years to exit a local flow system and 50–100 years or more in larger intermediate systems although the rate of exit will vary over time.

A conceptual diagram illustrating sources of salt in stream flow is shown in Figure 5. This conceptual framework has been used to guide the approach to methodology as well as the interpretation of the patterns observed in the analysis.

The analysis assumes that the river itself is the integrator of all these processes; and therefore that the outcome of these processes is embodied in the patterns of stream flow and salt load, and stream flow and salt concentration, observed in the data.

As catchments wet up, phreatic pressures build up in higher elevation positions in the landscape and the discharge rate increases both via higher flow velocities as well as through a greater cross-sectional area. Salt mobilised from the regolith with this water tends to accumulate as an evaporite on the surface of discharge sites during drying phases, only to be washed off during the next wetting phase. Also, as a consequence of catchments wetting up, exhibiting rising groundwater trends, a much greater surface area of the regolith becomes saturated, and more of the salt store is accessed. Much of this additional salt store is only accessed during wet periods, and remains probably in greater concentration because it is leached less often than the more permanently saturated aquifers.

In a statistical analysis, only a simplified approach can be used to represent these processes. Therefore the driver for change is assumed to be only the change in area through which discharge emerges to the surface. The salinity of the groundwater and the rate of flow, equivalent to the rate of water level rise, are determined from the statistical analysis of the bores. Salinity and flow are assumed to remain constant over the prediction period. The volume of discharging water arriving at the surface, and therefore the accompanying mass of salt is assumed to change with only the area through which the water flows.

The location and extent of discharge areas is largely controlled by topography. The present day surface expression of topography is the result of all the climatic, geological, ecological, weathering, water-flow and soil formation processes that have been occurring for eons, and have produced today's salinity hazard. Therefore statistical patterns found within topographic data integrate all the above processes. Topography governs how pressure head will accumulate. However, groundwater will not necessarily discharge to the surface unless high pressure head accumulation also corresponds with low points in the landscape. The study uses the FLAG model (Dowling 2000) to identify the potential 'wetness area' through which discharge will occur. This area is assumed to be the maximum discharge area likely for the catchment.

Ultimately the question arising prior to any audit should be 'Is there a problem?'. That is, 'is there any evidence to suggest that salinity is increasing?'. Trends in groundwater pressures as well as in-stream salinity trends are examined to establish this. The role of the audit is then to quantify the size of the problem.

The current study assumes that the trends identified in the groundwater data represent a background increase in dryland salinity risk. The study addresses the question: 'If these trends were to continue unabated over the next century, what would be the size of the in-stream salinity problem at strategic locations within the Hunter River system?'.

CHAPTER THREE

DATA AVAILABILITY

Data used in the study fall into three functional categories:

1. Hydrogeology data used to determine the groundwater derived potential salt loads by catchment and geology;
2. Surface hydrology data used to determine the statistical structure of river flow and salt loads for tributaries, and as calibration points for the Hunter Integrated Quality and Quantity Model (IQQM) on the mainstream; and
3. GIS spatial data used in regionalising parameters, area weighting geology and sub-catchment contributions for future salt loads from tributaries, and preparation of attribute statistics for salinity hazard mapping and general presentation of results.

3.1 HYDROGEOLOGY DATA

All bore data used in the study were sourced from the DLWC Groundwater database. Approximately 6,000 bores in the Hunter Valley are listed in the database. Of these, a very much smaller data set, contains historical water level records suitable to the current analysis. Out of approximately 300 bores initially examined, 149 had only two recorded water levels, a further 30 had 3 to 4 recorded levels and the remainder contained multiple records. Some of these bores were excluded from the analysis due to the influence of pumping. The final number of bores used was 253.

Groundwater salinity data, however, was available for approximately 718 bores; although not all bores used in the analysis of water level rise also had corresponding salinity data.

Bore data was subdivided by geology, using bore lithology data to determine the strata associated with the aquifer intersected by the bore, and according to location on the 1:1,000,000 scale geology map. Six main geology units were used: Quaternary alluvium, Tertiary volcanic, Triassic sedimentary, Early Permian sediments, Late Permian sediments and Carboniferous sediments. Geologies were further subdivided into provinces depending on their location within the catchment as a whole.

3.2 SURFACE HYDROLOGY DATA

Stream gauging stations located within the Hunter Valley provide flow and salinity data representative of sub-catchment contributions to the total water and salt balance of the valley. The surface water sub-catchments fall into two categories: tributaries and mainstream points. Observed time series data for both are used as inputs and calibration sequences for the Hunter IQQM used in the study to model the routed contributions of water and salt to the end of system at Greta. The tributaries are further categorised by the type of salinity data available. In all cases electrical conductivity (EC) has been used as a convenient measure of salt concentration. Continuous monitoring using salinity probes has only been available since the early nineties for a limited number of sites. Where these have been installed, hourly time series data is available. Discrete EC measurements, varying in the frequency with which they were collected, are generally available for the remainder of the base investigation period from 1975 to 1998. Some tributaries have no recorded EC data. Tributary gauging stations are typically located upstream of the confluence with the main river and are representative only of the area above them in the catchment. The remaining ungauged areas that contribute, but have no representative flow or EC data, are referred to as residual catchments.

Figure 6 is a schematic diagram of inputs, calibration points, and the data types used in the Hunter Valley salinity audit.

The DLWC HYDSYS database was the primary source of continuous electrical conductivity (EC) and flow data. Discrete records of EC were sourced from the DLWC TRITON water quality database. Continuous EC data were used in preference to discrete EC data even though it was over a shorter period of time.

Continuous flow records exist for most of the Hunter Valley for the entire 1975 to 1998 period. Dart Brook and Martindale Creek are exceptions as monitoring at their stations was discontinued in the early 1980s. The Hunter River gauging station at Liddell was commissioned in 1993. The accuracy of observed flow volumes were poor for the Goulburn River at Sandy Hollow and for the Wollombi Brook due to the sandy nature of their streambeds (shifting bed geometry changes the rating calibration to convert flow height to flow volume). Calibration changes were estimated for these.

EC data available for the 18 tributaries were as follows: 7 sub-catchments had 3–8 years of continuous data (observed range 90–3500 flow weighted average daily EC), there were 4 sub-catchments where discrete data was used, 1 with no EC data, and 6 were residual catchments. The discrete EC data comprised 30 to 110 data points per site with the observed range of 60–4000 EC. There were 6 mainstream calibration points with 7–9 years of continuous EC data with an observed range of 90–1500 EC (flow weighted average daily EC).

Flow data without missing values were required for the tributaries as inputs into IQQM for the entire 24-year period. The missing flow data were filled using the Sacramento model or by correlation with another station. Sacramento is a model that simulates runoff from observed rainfall and pan evaporation.

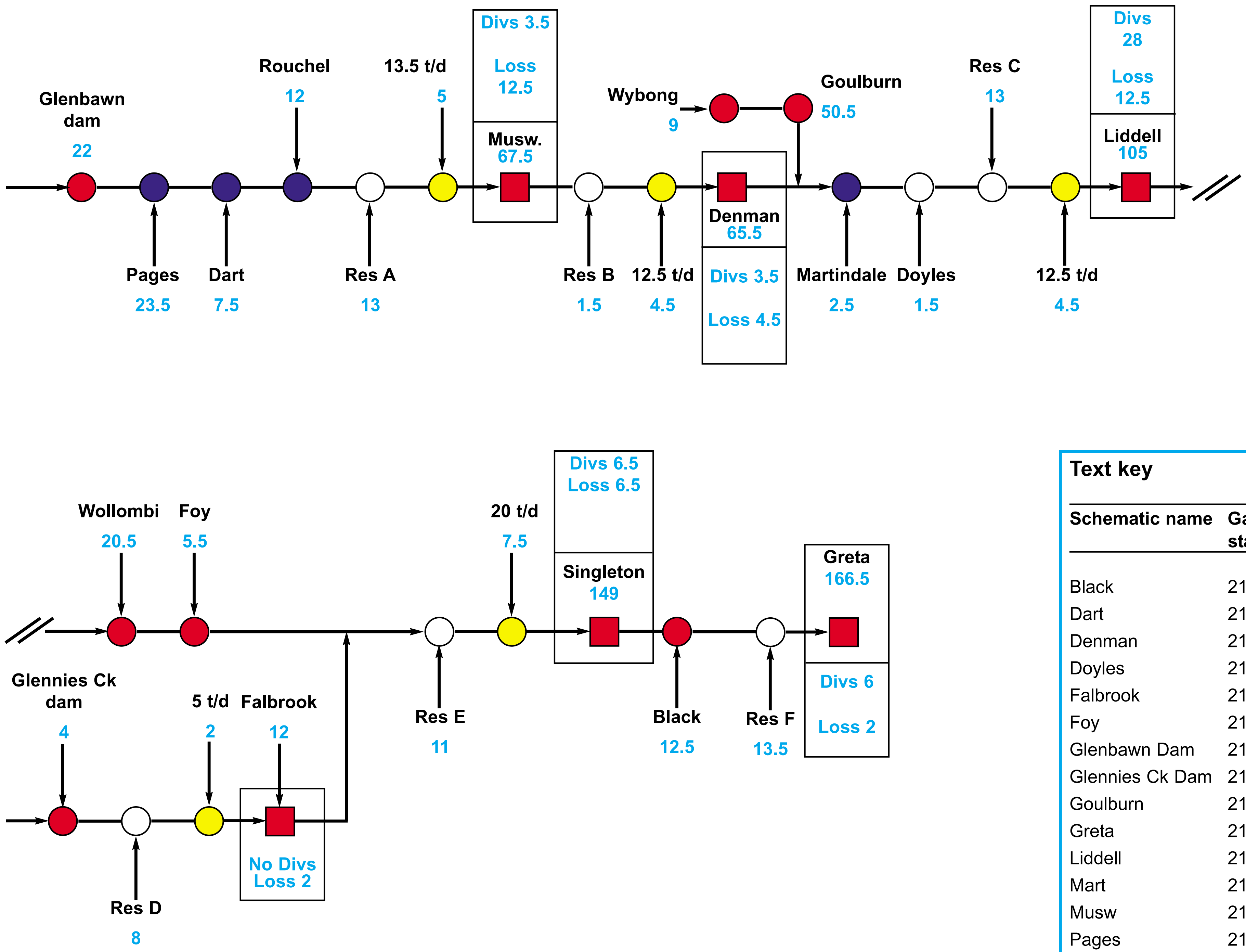
3.3 GIS SPATIAL DATA

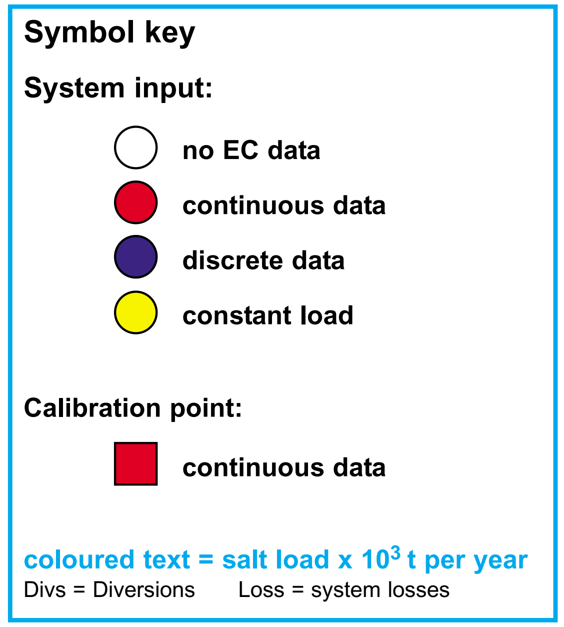
Geology and sub-catchment boundary data for the Hunter Valley is held in the DLWC Regional Office GIS database in Newcastle. Area statistics were calculated using Genamap.

A Digital Elevation Model (DEM) with a 25 x 25 metre pixel resolution for the Hunter Valley is available for topographic analysis. The DEM was analysed by the Centre for Natural Resources, Wagga Wagga, using the ArcInfo® platform.

A salinity map produced in ArcView® combines all salinity indicators that have been mapped at a scale of 1:25,000 for the Hunter Valley and are currently entered on the region's GIS. The salinity codes used include:

- Soil erosion class—saline indications
- Soil erosion class—sheet erosion, subclass salting
- Soil erosion class—rill erosion, subclass salting
- Salt—saline indications from other mapping projects
- No salt—no saline indications
- No data—area not mapped.





Text key

Schematic name	Gauging station no.	Gauging station name
Black	210089	Black Creek at Rothbury
Dart	210088	Dart Brook at Aberdeen
Denman	210055	Hunter River at Denman
Doyles	210087	Doyles Creek
Falbrook	210044	Glennies Creek at Middle Falbrook
Foy	210042	Foy Brook at Ravensworth
Glenbawn Dam	210015	Hunter River at Glenbawn
Glennies Ck Dam	210084	Glennies Creek at The Rocks
Goulburn	210031	Goulburn River at Sandy Hollow
Greta	210064	Hunter River at Greta
Liddell	210083	Hunter River at Liddell
Mart	210090	Martindale Creek near Martindale
Musw	210002	Hunter River at Muswellbrook
Pages	210052	Pages River at Gundy Recorder
Res A:F	N/A	Residual Catchments
Rouchel	210014	Rouchel Brook at The Vale
Singleton	210001	Hunter River at Singleton
Wollombi	210028	Wollombi Brook at Bulga
Wybong	210040	Wybong Creek at Wybong

Figure 6. Schematic diagram of the inputs and calibration points used in the Hunter Valley Salinity Audit showing the 'current' conditions salt load mass balance for 1975 to 1998

CHAPTER FOUR

METHODOLOGY

The methodology adopted for the Hunter Salinity Audit is adapted from that used to analyse the NSW rivers in the MDB (Beale et al. 2000). Salt load per se is not considered as good an indicator of social or ecological problems in the Hunter Valley as salinity, which provides some indication of the relative toxicity of the salt in solution for different end uses. Salinity may be assessed against social and environmental thresholds over time, and the probability of exceeding a threshold may be assessed as a basis for risk management. Load on the other hand gives an indication of the amount of environmental pollutant that has to be dealt with. For example the salinity of water received by Macquarie Generation will determine whether or not water treatment is required. The salt load, however, will determine the amount of ameliorant required and the amount of waste product to dispose of. Load, in general though, passes out to sea without being passed on to downstream users in the same way that, for example, the Macquarie River contributes to the Murray River. Salt may accumulate on irrigation areas and although they are not large areas as compared with those in the MDB, they represent significant economic resources for the Hunter Catchment. Therefore, salt load was modelled and particular attention was paid to accurately representing both the salt load and salinity relationships. The primary distinctions between the MDB analysis and the current study are:

- Inclusion of topographic analysis in the calculation of potential groundwater derived salt load using the Fuzzy Logic Analysis GIS (FLAG) model (Dowling 2000).
- Modification of the stochastic modelling component to utilise continuous data and improve EC prediction.
- Use of the Hunter IQQM to establish the salt and water balance for the 1993 to 1998 calibration period, for the 1975 to 1998 'current' conditions, and to route predicted groundwater salt contributions at target dates.
- There is no equivalent of the MDBC 1993/1994 development Cap in the Hunter Catchment. However, significant changes to river management such as the building of Glennies Creek Dam, the upgrading of Glenbawn Dam and significant diversions to Macquarie Generation were accounted for in the 'current' conditions IQQM.
- Accounting for significant point source salt contributions from fault zones.
- Addition of the predicted groundwater salt load contributions directly to the stream flow rather than the in-stream scaling approach used in the MDB analysis.
- Trend analysis of historic surface water EC data for 10 stations.

For a full description of the methodology used in the MDB with the governing equations for the calculation of potential groundwater derived salt loads and the quasi-observed stream salt load time series, see Beale et al. (2000) where they have been reported in detail. The schematic diagram in Figure 7 provides an overview of the method used in the Hunter salinity audit, and more fully explains details of the previously listed variations.

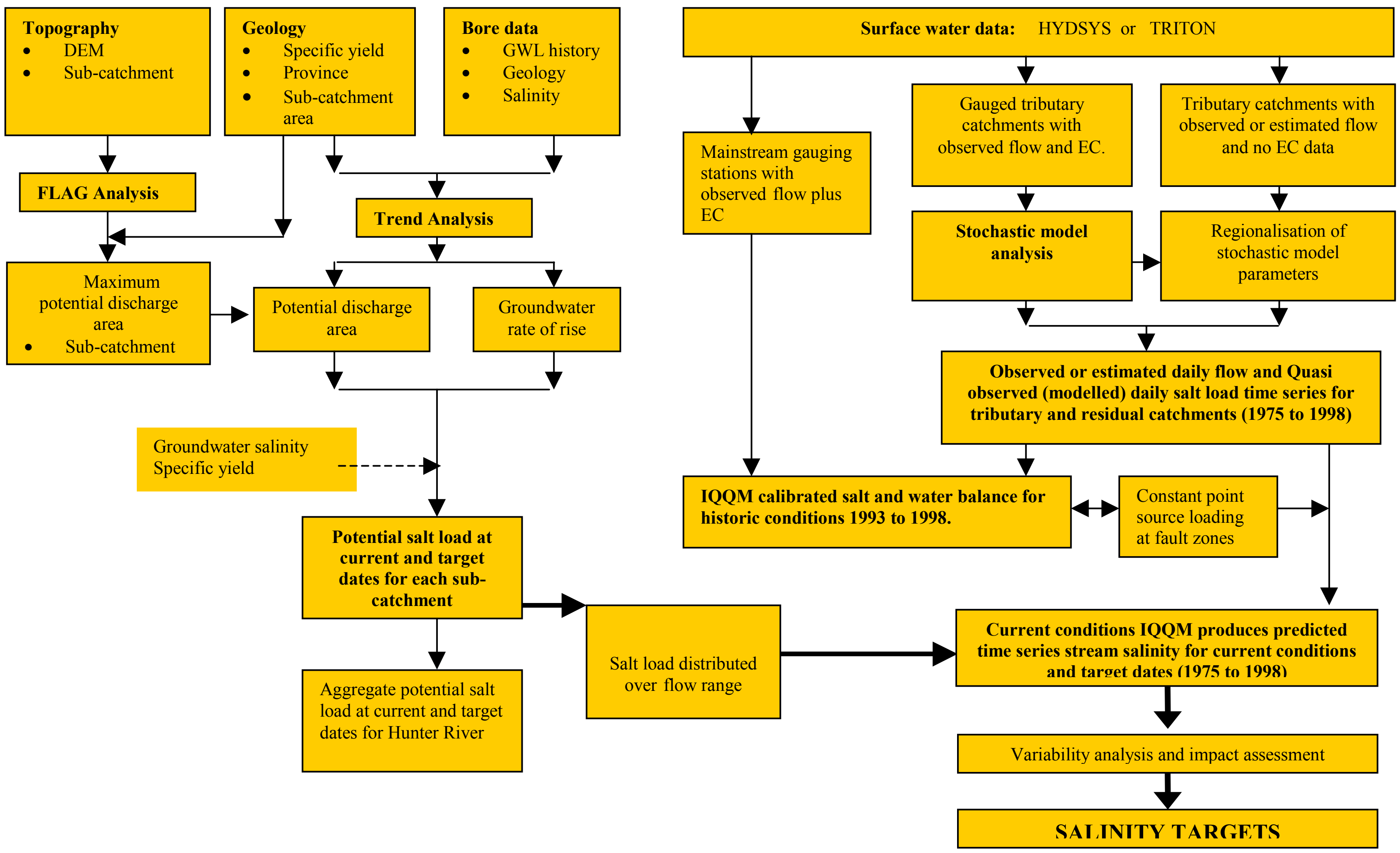


Figure 7. Schematic diagram of the Hunter Salinity Audit methodology

4.1 INCLUSION OF TOPOGRAPHIC ANALYSIS IN THE CALCULATION OF POTENTIAL GROUNDWATER DERIVED SALT LOAD

The Fuzzy Logic Analysis GIS or FLAG model was used to predict the influence of topography on the maximum potential area which is likely to contribute salt to the land surface with progressive rises in groundwater pressure.

A full technical description of the FLAG model with its governing equations is given in Dowling (2000) and also in Roberts et al. (1997). The model analyses the information contained in a digital elevation model (DEM) of the catchment. It uses a fuzzy logic approach where each point in the catchment is given a numerical weighting between zero and one for an attribute associated with dryland salinity. The indices derived are analysed statistically to produce a three-dimensional map representing distribution in the landscape of the index or scaled probability associated with the attribute.

Two primary indices of topography are combined to create a third compound index associated with dryland salinity known as the FLAG Wetness index. This differs from other commonly used GIS based wetness indexes in the way it is derived. The first of the primary indices is an index of pressure head accumulation called Upness. It differs from more commonly used flow accumulation indexes in that it looks beyond ridges to account for parts of the landscape contributing to the potential pressure head rather than just potential surface flow. The second of the primary indices called Lowness identifies locally low areas within the landscape in relation to a smoothed elevation surface or pseudo-water table. These lowness areas appear closely correlated with drainage lines at break of slope positions in the landscape. Although groundwater pressure may accumulate at a point in the landscape, it is unlikely to result in discharge to the surface unless it is also associated with a low point in the landscape.

A high wetness index indicates the statistical evidence that a point in the landscape has potentially both a high relative groundwater pressure and high level of opportunity to discharge through its relative lowness.

A cut off value for the index of relative wetness was chosen by comparison with mapped salinity in the Hunter Catchment to establish the maximum likely area of discharge. The area of maximum wetness for each sub-catchment was calculated and further subdivided on the basis of the mapped geology. A maximum area of potential discharge for the geologies in each sub-catchment was obtained.

The maximum discharge area was used to limit the area term A_{sal} in equation 4.1.

The salt load potentially delivered to the surface in each geological unit in each catchment is estimated by considering the potentially salinised area of each, the rate of water table rise, an assigned value for the specific yield of the geological unit and the salinity of the groundwater. Specific yield is essentially the drainable porosity, and describes the volume of water available in a unit volume of geological material at saturation. Values for specific yield were assigned from published estimates for each geological unit.

Using values determined as described previously, the salt loads delivered to the surface in each geological unit are calculated as follows:

$$Q_s^{pot} = A_{sal} \, C_g^s \, S_y \, \frac{dz_g}{dt} \qquad (4.1)$$

Where, Q_s^{pot} is the potential salt load, A_{sal} is the area potentially salinised, C_g^s is the salinity of the groundwater, S_y is the specific yield and dz_g / dt is the rate of groundwater level rise. Using an appropriate conversion factor Q_s^{pot} can be expressed in $t.year^{-1}$.

The potential salt load from Eq. (4.1), expressed as tonnes per year for the assessment period, provides an estimate of salt delivered from the groundwater system to the surface in each geological unit. The salt can potentially be transported to the stream through catchment scale runoff generation and salt wash off mechanisms including direct seepage into watercourses.

Potential salt load values are set to zero where the data indicate declining or steady water levels, i.e. a negative or zero rate of rise.

In the calculation of potential salt load using equation 4.1 the volume of water discharging to the surface is equal to the flow in $m.year^{-1}$ (the rate of rise) multiplied by the potential discharge area and the specific yield. The salt load is determined from the volume of water and its salt concentration (salinity of the water). For future predictions the rate of rise, the specific yield and the salinity are assumed to remain constant. The potential area salinised is assumed to vary with the number of bores with predicted water levels within 2 m from the ground surface. The number of bores within 2 m is determined by predicting the water levels at the target dates from the current water level and the rate of rise. The percentage number of bores in a geology predicted to have water levels within 2 m at each target date is assumed to correspond to (is assumed equal to) the percentage of the land area for each geology and province potentially salinised. That is, if water levels in twenty per cent of bores in the geology / province are predicted to lie within 2 m of the surface at the target date then twenty per cent of the geology / province is assumed to be potentially salinised. As the area salinised is the only term which varies over time in equation 4.1, very large over-estimates of potential salt load can be expected unless a topographic restriction is imposed to establish a maximum potential area that is salinised.

4.2 IN-STREAM DATA TREATMENT

4.2.1 Time step

Discrete EC samples were treated as instantaneous measurements of what the EC was at the time of sampling. Effort was made to attach an instantaneous flow to these readings as described in section 4.2.2 Quality.

Continuous EC data is read at a preset logging interval, depending on the site, and stored in Hydsys. Average hourly ECs and total hourly flows were extracted from Hydsys. These hourly numbers were aggregated to daily data by flow weighting to average daily ECs and using total daily flow.

4.2.2 Quality

The majority of discrete EC measurements have unknown quality. Where no continuous EC data were available for a site, all available discrete data were used. Where possible, the discrete data were matched to instantaneous flow measurements, if a flow gauging had been done on that day. Otherwise the measurement time was used to extract an instantaneous flow from Hydsys, and used regardless of its quality code. The majority of discrete EC readings were taken as spot samples at the time of flow gauging, so this method is an improvement on what was done for the MDB where the total daily flow was matched to the discrete EC measurements.

Continuous EC data is extracted from Hydsys with a quality code describing the reliability or accuracy of measurement. Observed continuous data has been excluded from this study if the EC or flow measurement has a poor quality code. Larger flow events that are always less reliable due to the nature of measurement, have still been included so that the data analysed are representative of the full range of events that occurred.

4.3 MODIFICATION OF STOCHASTIC MODELLING APPROACH TO STREAM FLOW AND SALT LOAD RELATIONSHIPS

Continuous EC data have not been collected in the Hunter Valley until fairly recently. The earliest records began in 1991 for the mainstream and much later for the tributaries. Discrete data were typically collected from the early 1970s up until the present, so there are two different types of data sets covering the period of interest from 1975 to 1998. This situation did not exist for the MDB, as only discrete data were available in most places. With this in mind, modelling was carried out on discrete data and continuous data separately at a site, and the modelled results were compared. In most cases the differences in the total estimated salt load between the two methods was small; however, the distributions were quite different. The additional detail has meant that a more rigorous approach to modelling the continuous data has been possible. The continuous data were a good representation of the range of flow events that occurred from 1975 to 1998, so the continuous models were chosen over the discrete models where both were available. This means a stochastic model fitted to the continuous observed EC and flow data was used to generate a daily salt load and salinity time series for the tributaries (1975–98) where possible. If only discrete data were available, a stochastic model fitted to the discrete data was used to generate the daily time series of salt load and salinity. Where no EC data were available, the salt load parameters were regionalised based on catchment characteristics.

4.3.1 Modelling continuous data

Automation of data collection has enabled the inclusion of salinity data for extreme events in the continuous data set. In the past, these were generally missed, due to practical problems for hydrographers visiting each site during large events. Analysis of the continuous data showed that it was not possible to fit just one salt load and flow relationship to the entire flow range. Each site's data were split into two groups so that two salt load and flow regression relationships were established at each site. This allowed different model types to be fitted to each data group to improve model performance for that data range. Generally the data were split using the 2 per cent flow exceedence limit, into a 'normal flow range', and an 'extreme flow range'. However, this splitting level was chosen individually for tributaries. The salt load and salinity time series for the 1975–1998 period were then generated by using one relationship below the chosen flow limit, and the other relationship above the flow limit.

Regression of salt load and flow is a simplified approach to salinity modelling. It predicts the median observed EC, and hence salt load, well; however, it does not necessarily reproduce a realistic EC distribution. In this case it is only a problem for reporting EC percentiles for the tributaries, which was not done on a daily basis for the MDB. Stochastic modelling of the mainstream points on the Hunter Catchment has been avoided since sufficient continuous data was available for calibration of the IQQM (see section 4.4). However, it was necessary to make an adjustment to the model regressions to reflect the daily EC distribution of the tributaries. This was achieved by adding the error in modelled versus observed salt loads to the regression model output giving it a random normal distribution. It was not appropriate to add the random error in all cases, either because the distribution was already well represented, or because the error was not normally distributed. This adjustment had an insignificant impact on the total estimated salt loads, and did reproduce the historical EC distribution. The addition of the random error for the tributaries did not significantly impact on estimates of mainstream salinities since EC variability in the mainstream Hunter River is primarily due to flow and flow source variability. The differences in modelled salinities produced by this method compared to that originally used in the MDB audit are illustrated in section 7.1.

4.3.2 Modelling discrete data

Discrete EC data were matched to instantaneous flow in the Hunter Catchment analysis. This is an improvement on what was done in the MDB where total daily flows were used. The adjustment of model regressions for fitting the observed salinity variability described previously, was also applied to the discrete data in addition to the original method used for the MDB.

4.4 THE SALT AND WATER BALANCE USING IQQM

The MDB salinity audit estimated tributary inputs of salt load on a daily basis. These were aggregated to monthly values and modelled in a spreadsheet to account for routing, diversions, losses, and cumulative effects. The Hunter Catchment salinity audit used the daily data as inputs into IQQM, and as calibration points on the mainstream. IQQM replaced the spreadsheet method, and allowed tributary contributions, mixing, routing, losses and water use to be accounted for on a daily basis. This is especially significant in determining salinity since large events can dominate monthly values. Daily data gives a much better representation of the percentage of time for salinities than do monthly values.

Prior to this audit, an IQQM flow balance model for recorded behaviour, and an IQQM flow model for 1998 conditions had already been developed. IQQM had also been used for predicting flow and salinity for the Hunter Valley's saline discharge scheme for points on the mainstream only, since 1995.

The Hunter Catchment salinity audit breaks the valley into sub-catchments, or tributaries, to model their cumulative impacts on the mainstream. The calibration period varies due to available observed continuous EC data, and is limited by the IQQM flow model only going up to 1998 at the time of the Audit. However, the calibration period was generally 1993 to 1998. Significant groundwater fluxes occur where the Hunter River intersects major fault lines such the Mt Ogilvie fault. These fluxes contribute additional salt to the river. The calibration process established the contributions of the tributaries and groundwater fluxes for 1993 to 1998, using flow and salt load relationships for the tributaries, which could then be extended to the 1975 to 1998 period. The groundwater contributions for the calibrated period were applied to the entire period in the absence of better information. The tributary and groundwater contributions were then used as inputs into the ‘current’ conditions IQQM to produce river flow and salinities that would occur if year 2000 development conditions and management rules had prevailed over the climatic period between 1975 and 1998. By definition, the unregulated tributary and groundwater contributions are unchanged by the 'current' conditions scenario. In the mainstream reaches ‘current’ conditions specifically refers to modelled flow and salt loads from the Hunter IQQM scenario. The 'current' conditions model results for the 1975 to 1998 climatic period were then used as a base case to which future increase scenarios could be compared.

Future scenarios were defined by using the ‘current’ conditions above, with the addition of predicted increases in salt load from the hydrogeology analysis.

The Hunter IQQM was used to establish the salt and water balance for the Hunter River for:

- the observed flow and salinity data where it existed (generally 1993 to 1998 calibration period);
- to establish ‘current’ conditions for 1975 to 1998; and
- to route predicted future salt contributions for the target dates over the 1975 to 1998 benchmark climatic period.

4.4.1 Prior to this audit

An Integrated Quantity Quality Model (IQQM) has been developed for the Hunter River System to investigate the impacts of various management scenarios on the availability of water for both human and environmental purposes. This ‘flow model’, was previously calibrated using recorded data for the period 1986–1991. The ‘flow model’ has been used since 1998 to investigate the impacts of a number of river operation changes, including the setting of environmental flow requirements, and implementing a sharing scheme for access to high flow water. An independent review of the model was undertaken (Perrins et al.. 1999) to investigate the suitability of the flow model for undertaking these studies. The flow model has been updated as a result of this review, and also to reflect changes in entitlement usage and management.

Mines and power generators release saline water into the Hunter River as part of a managed discharge scheme (EPA 1995). This scheme involves the real time monitoring and forecasting of flow and salinity, in order to identify ‘windows of opportunity’ for the discharge of saline waters. The Hunter IQQM has been used as a predictive tool to manage these saline point discharges (Simons et al., 1996). Transport of conservative solutes such as salt are modelled using short routing time steps, assuming that flows are fully mixed (Javam et al., 2000). Data in sufficient quantities to allow this modelling has only been available from 1991, and only on the mainstream from Muswellbrook down to Greta. In order to use the water quality capabilities for longer term scenario runs, it is necessary to extend this data. It is also necessary to break the valley into sub-catchments to assess the cumulative impacts of tributaries now and in the future.

4.4.2 IQQM salt calibration

The calibration was undertaken in stages, by doing a section of the river at a time. Each river section was defined as having observed salinities at both ends on the mainstream. The observed upstream data was fed into the model, and the observed downstream data was used as a check to see if other tributaries and groundwater contributions had been adequately represented in that section of the river. The tributary inputs were derived from observed data where it existed and from the salt load and flow relationships developed in the stochastic modelling. There was no explicit accounting for groundwater interactions in the flow part of the model. Addition of a constant daily salt load for groundwater and fault zone contributions was made at this stage to give a match at the downstream gauging station; more of this is discussed in section 4.4.4. The calibration reaches used for the Hunter River are from; Glenbawn Dam to Muswellbrook, Muswellbrook to Denman, Denman to Liddell, Liddell to Singleton, and Singleton to Greta. A reach was also calibrated on Glennies Creek from Glennies Creek Dam to Middle Falbrook.

After calibrating the reaches independently using observed data as input at the top of each section, the system was put together and run from the top down. The cumulative errors in the system were then assessed to check whether the calibration process had been adequate.

The calibration process established the contributions of tributaries and groundwater for 1993 to 1998.

4.4.3 IQQM 'current' conditions

The flow model used for 'current' conditions is not representative of actual conditions in the period 1975–1998. During this period, Glennies Creek Dam was constructed (1982) and Glenbawn Dam enlarged (1986). As a result, new licences have been issued, including one to a major power station. This has significantly altered the way water moves through the Hunter system. In addition, environmental flow rules have recently been introduced in the Hunter system by the Hunter River Management Committee. The two major rules include:

- The setting aside of 20 GL of stored water for environmental management purposes, including fish breeding/fish passage, flushing of algal blooms, and providing flushing flows downstream of dams.
- The requirement that all users must allow 50% of high flows to pass downstream.

A 100-year model of the Hunter Catchment regulated streams is used for water resource management planning. This has been calibrated for flow, dam behaviour and irrigation usage. A model of the power station water management system generates power station water requirements. Environmental rules have also been included in this model. The 100-year model was used in this study to provide storage release information, as well as extraction patterns for the industrial, town and irrigation requirements. As this model includes the storages as they are presently configured, with current levels of demand for water extraction, and current flow rules in place for the full simulation period, the data used for 'current' conditions is significantly different to the observed data for the 1975–1998 period.

The calibrated salinity inputs from tributaries and groundwater contributions were then used as inputs into the IQQM 'Current' Conditions model, producing daily time series of flow and salinity for the mainstream from 1975 to 1998.

4.4.4 Groundwater interactions

Groundwater interactions, including point source salt contributions from fault zones, are a significant contributor to in-stream salinities in the Hunter River.

There was no explicit accounting for groundwater interactions in the flow part of the model. Addition of a constant daily salt load for groundwater and fault zone contributions was done by choosing the value that best matched the observed salt loads and salinities at the downstream gauge. In particular, periods where dam flows could be traced through the system with no significant tributary inputs, guided the choice of groundwater loading for each reach. This procedure showed that surface and groundwater interactions are not constant over time.

4.4.5 IQQM future predictions

The tributary and groundwater contributions that were established in the IQQM calibration process were used as inputs into the 'current' conditions IQQM. This produced river flow and salinities that would occur if current river operation was applied over the 1975 to 1998 climatic period. Future scenarios were adopted by using the 'current' conditions model, with the addition of predicted increases in salt load from the hydrogeology analysis.

The predicted groundwater salt load contributions were added directly to the stream flow in this audit, rather than the in-stream scaling approach used in the MDB analysis. Two approaches were used to transfer potential salt loads from groundwater discharge to the river system and calculated river salinities were obtained from both.

The first method distributes the additional salt load from groundwater discharge over the full flow range of recorded river flows utilising the stochastic relationship between in-stream salt load and flow and the flow duration curve for the gauging station. This preserves the basic observed pattern of in-stream salt export; and in a physical sense, better approximates the observed processes of salt accumulation in the landscape and subsequent wash off. It also more realistically accounts for dilution processes, as groundwater feeding directly to the stream mixes with fresher in-stream water (groundwater salinities in fractured rock zones are generally higher than those found in-stream or in alluvial aquifers directly connected to the stream).

The second method was simply to add the annual potential salt load by sub-catchment to the river as a constant daily loading. This scenario, although not as well physically based as the first, is included here as a possible worst case. In a physical sense, this would very broadly approximate a situation where the groundwater discharge only entered the river in base flow. This is limited in that it cannot represent variations in base flow volume and salt load relationships. Where tributaries in particular cease to flow for substantial periods during the year, it is known in many cases that base flows continue beneath the sandy beds of the rivers, even although no surface flow is recorded. This second method, in some measure, accounts for this process.

4.5 TREND ANALYSIS OF HISTORIC SURFACE WATER EC DATA FOR 10 STATIONS

A salinity trend analysis at gauging stations with sufficient instantaneous flow and EC data available was carried out using the same methodology as that used for streams in the MDB. Ordinary Least Squares regression using generalised additive models and Auto-regressive Integrated Moving Average time series models were used in the analyses. Corrections for flow and seasonal effects are included in all models to provide the underlying EC trend. A fuller explanation of the methodology, the model equations and a description of the GENSTAT® program used in the calculation can be found in Williamson et al. (1997) and Jolly et al. (1997).

CHAPTER FIVE

POTENTIAL SALT LOAD IN GROUNDWATER DISCHARGE FROM DRYLAND SALINITY PROCESSES

A background of rising groundwater levels observed in the Hunter Valley suggests a probable increasing surface water quality problem for land managers and the community in general associated with an increasing incidence of dryland salinity throughout the catchment.

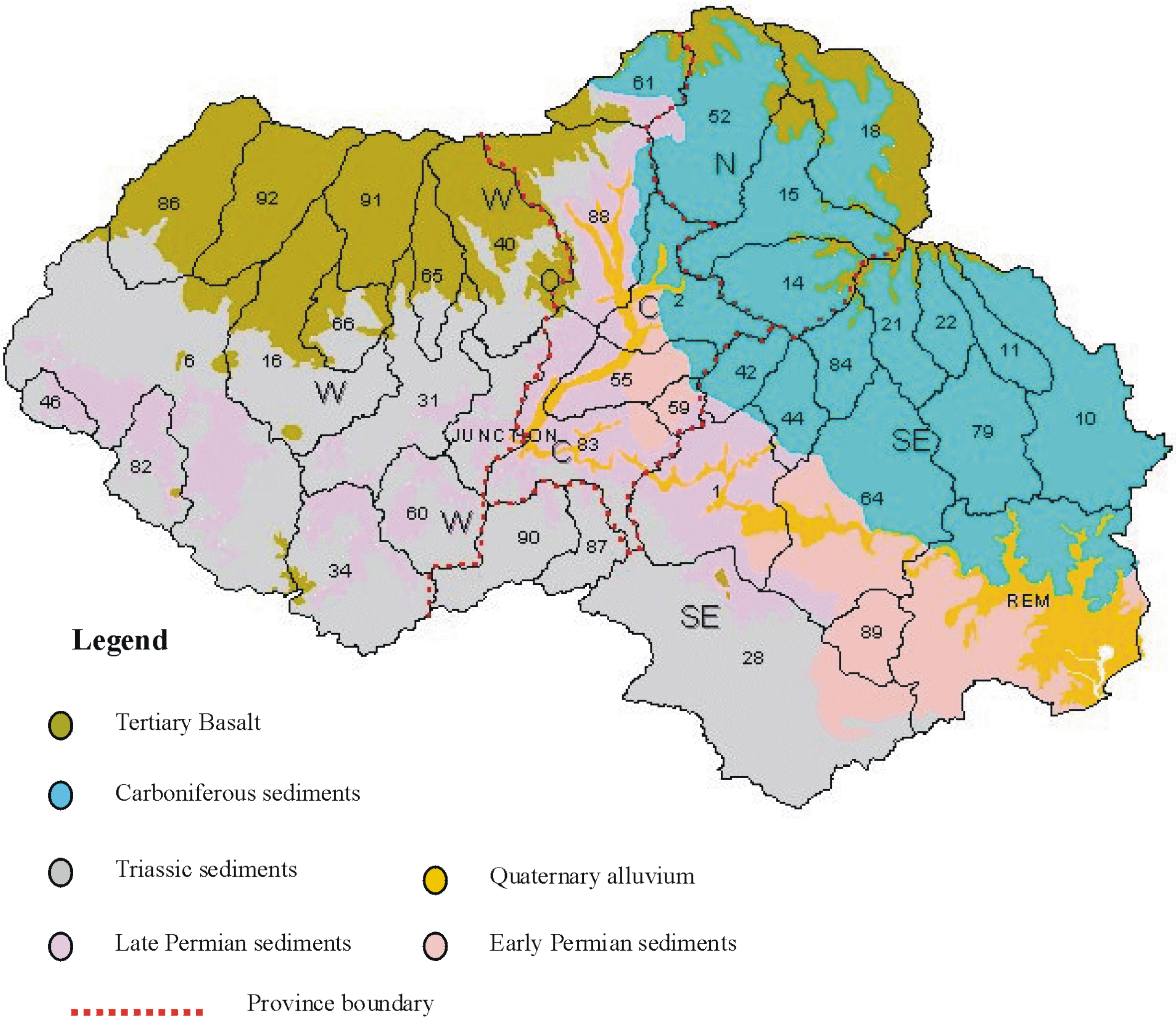


Figure 8. Geology map of the Hunter Valley showing province and sub-catchment boundaries

Groundwater trends were analysed first on a broad geology basis and then grouped on the basis of a geological sub-area or province. Province boundaries were set to correspond with sub-catchment boundaries. The quaternary alluvium was sub-divided into four provinces in the north, central, west and southeast of the catchment. Triassic sedimentary geologies were divided between those lying in the north-northwest of the catchment and those in the south-southwest. Late Permian sediments were divided into central, southeastern and western provinces and the Early Permian sediments into the central and southeast. Although initially the Tertiary basalts were separated into main and outlier provinces, their data were later combined because there were insufficient bore data to adequately analyse them separately. The Carboniferous sediments were sub-divided into northwestern and southeastern provinces. Figure 8 shows the geologies of the Hunter Valley and the province boundaries.

5.1 TOPOGRAPHIC ANALYSIS

Topography restricts the area through which groundwater discharge can occur. Water tables are generally thought of as following a smoothed elevation surface corresponding with the surface topography, but exhibiting overall lower slopes. As such, water tables will never rise high enough to intersect with the ground surface over most of the catchment. High relief precludes it. The slope of the water table determines the driving gradient for groundwater flow laterally out of a catchment. Highly incised catchments will tend to have higher gradients, and therefore drain more freely as well as having smaller areas through which discharge to the surface is likely to occur. Freeze et al. (1979) state: 'On an areal map discharge areas commonly constitute only five to thirty per cent of the surface area of a watershed.'

The Wetness index of the FLAG model was used to determine the maximum potential area through which groundwater discharge is likely to occur. The FLAG analysis produces a highly skewed distribution of pixel wetness because most of the catchment is relatively dry. The cut off point from the distribution singled out to represent the maximum likely wetness area contributing to discharge was ascertained by visual comparison with GIS overlays of mapped salinity. The area of wetness was then overlain with the geology 1: 1,000,000 map and the maximum potential discharge area for the geologies and sub-catchments was then calculated. Figure 9 shows the mapped wetness index colour-coded for geology. Figures 10 and 11 show selected sections of the map from the western and central parts of the catchment respectively, enlarged to show the match with mapped salinity.

Table 5 lists the sub-catchment areas and the proportion of FLAG wetness area determined for each. The average of all catchments represents a maximum discharge area of 11 per cent for the whole of the Hunter Valley. The proportion of catchment area occupied by the maximum Wetness area for each sub-catchment or tributary ranges from approximately 2.5 to 30 per cent. (Three digit catchment gauging station numbers listed correspond to the shorter catchment numbers in Figure 8).

The location and spatial distribution of predicted wetness area is in agreement with the mapped area of salinity in the Hunter Catchment and the proportion of the total area affected falls within an acceptable range. Salinity mapping in the Hunter has not been undertaken consistently enough to allow delineation of discharge areas. Much of the mapping represents erosion classes associated with salinity or vegetation indicators and is, in many instances, incomplete. These factors may overestimate the current extent of land salinisation. The wetness index is expected to overestimate current salinisation also. The maximum chosen provides a reasonable scope to the study in which potential land salinisation could expand if water tables are rising without using the mapped salinity to specifically define how much is already contributing.

Catchment / Tributary	Total catchment area (km²)	Wetness (%)	Catchment / Tributary	Total catchment area (km²)	Wetness (%)
001 Hunter R. at Singleton	733	6%	060 Baerami Ck at Baerami	387	12%
002 Hunter R. at Muswellbrook	458	22%	061 Pages Ck at Blandford	298	26%
006 Goulburn R. at Coggan	1874	4%	064 Hunter R at Greta	1117	4%
010 Williams R at Glen Martin	819	6%	065 Halls Ck at Gungal	244	28%
011 Williams R at Telligra	193	14%	066 Merriwa R. u/s Valences Ck	231	23%
014 Rouchel Brook at Rouchel	404	10%	079 Patterson R. at Gostwyck	487	8%
015 Hunter R. at Glenbawn	558	8%	082 Wollar Ck u/s Goulburn R.	284	2%
016 Goulburn R. at Kerrabee	801	5%	083 Hunter R. at Liddell	666	11%
018 Hunter R. at Moonan	735	6%	084 Glennies Ck at The Rocks No2	226	23%
021 Patterson R. at Lostock	291	21%	086 Munmurra R. at Tominbil	623	8%
022 Allyn R at Halton	189	21%	087 Doyles Ck at Doyles Ck	201	8%
028 Wollombi Brook at Bulga	1682	4%	088 Dart Brook at Aberdeen	788	25%
031 Goulburn R. at Sandy Hollow	674	9%	089 Black Ck at Rothbury	201	7%
034 Widden Brook at Widden	636	21%	090 Martindale Ck at Martindale	359	6%
040 Wybong Ck at Wybong	667	12%	091 Merriwa R. at Merriwa	449	26%
042 Foy Brook at Ravensworth	183	9%	092 Krui R. at Collaroy	505	16%
044 Glennies Ck at Falbrook	218	14%	junction	319	15%
046 Goulburn R. at Ulan	110	9%	REM	1633	14%
052 Pages R. at Gundy	761	6%	**TOTAL / AVERAGE**	21399	11%
055 Hunter R. at Denman	307	30%		**maximum**	30%
059 Bayswater Ck at Liddell	87	28%		**minimum**	2%

Table 5. Predicted maximum FLAG Wetness area as a percentage of total sub-catchment area

u/s upstream

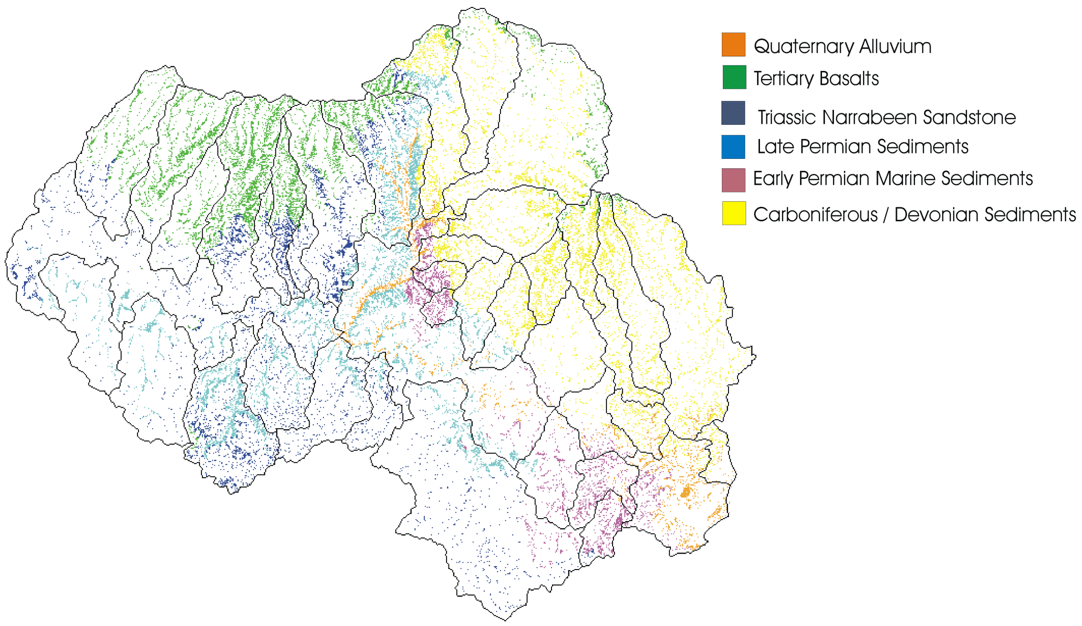


Figure 9. Area of maximum potential groundwater discharge by sub-catchment and geology using the FLAG Wetness Index, merged with 1:1,000,000 scale geology

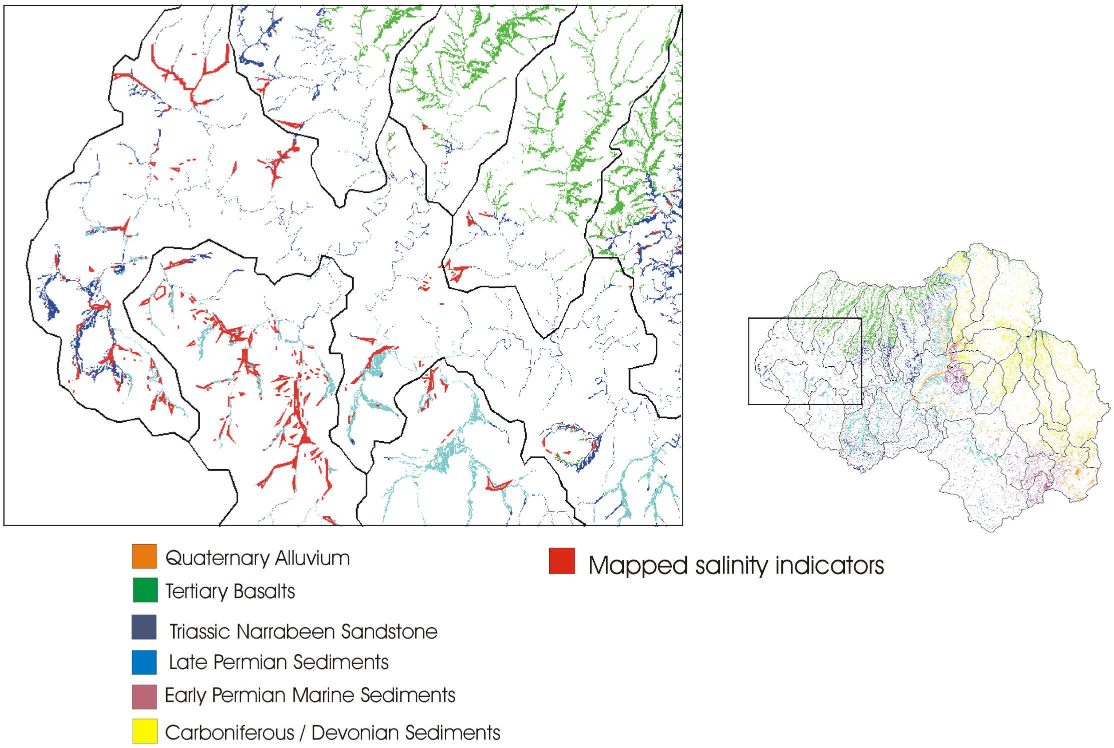


Figure 10. Comparison of maximum predicted Wetness area and mapped salinity in the western Hunter Valley

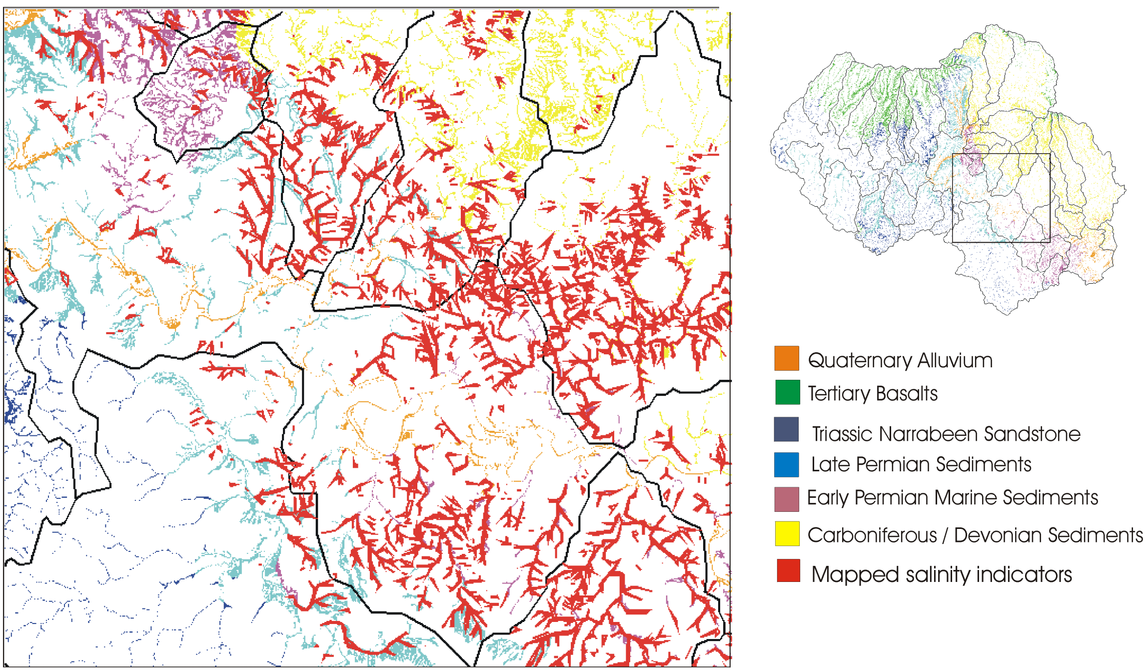


Figure 11. Comparison of mapped salinity and FLAG Wetness area in the central portion of the Hunter Valley

5.2 RATE OF GROUNDWATER LEVEL RISE

The results of the initial trend analysis on 253 bores are summarised in Table 6. All geologies and provinces contained bores with positive rates of standing water level rise except the south east province of the Late Permian sediments where only one bore was available for analysis. Most geologies and provinces also had bores for which the rate of rise was negative. However, it was not possible to separate negative trends from pumping and mine de-watering effects. Therefore only bores showing positive trends (Table 7) were included in the calculation of average and median rates of rise to be used in the calculation of potential salt loads. Approximately one third of the bores had a negative trend.

Geology	Group or province	Annual minimum SWL rise (m per year)	Annual maximum SWL rise (m per year)	Annual mean (m per year)	Annual median (m per year)	Annual STDEV (m per year)	n
Quaternary Sediments	Central	-0.001	0.434	0.079	0.043	0.138	69
	West	0.004	0.195	0.056	0.030	0.079	5
	South-east	-0.008	0.283	-0.040	-0.026	0.128	30
	All	-0.001	0.434	0.044	0.023	0.142	104
Tertiary Volcanic	All	-0.043	0.844	0.110	0.100	0.339	24
Triassic Sedimentary	West	-0.017	0.959	0.241	0.200	0.308	23
	South-east	-0.255	0.141	-0.057	-0.057	0.280	2
	All	-0.017	0.959	0.217	0.164	0.311	25
L. Permian Sedimentary	Central	-0.025	0.564	0.029	0.033	0.325	30
	West	-0.048	0.532	0.046	0.013	0.267	13
	South-east			-0.091	-0.091	0.000	1
	All	-0.048	0.532	0.031	0.020	0.302	44
E. Permian Sedimentary	Central	-0.004	0.639	0.054	-0.005	0.176	19
	South-east	-0.013	0.689	0.184	0.063	0.277	11
	All	-0.004	0.689	0.101	0.015	0.223	30
Carboniferous Sedimentary	North	-0.033	1.491	0.197	-0.033	0.541	9
	South-east	-0.001	0.298	0.033	0.041	0.142	17
	All	-0.001	1.491	0.089	0.022	0.336	26
TOTAL							**253**

Table 6. Summary of standing water level rates of rise for all available bores in each geology and province

Limited numbers of bores in some provinces make extrapolation problematic. This was particularly true in the case of the northern Carboniferous sediments where two out of the original four bores analysed showed unusually high rates of rise of 0.6 and 1.5 m a year. The average of the remaining two bores is somewhat less than for the central and the south-eastern provinces. Given that higher rates exist in the north, the average value of 0.107 m a year for all bores in this geology, was adopted in the potential salt load calculation (see Table 7).

Additional bores were included in the extrapolation of these trends. All bores with a water level recorded in 2000 were selected. The standing water level in each of these 345 bores was used as the base line from which the trend established for each province was projected to calculate the number of bores intersecting the zone 2 m from the surface at the target dates.

Geology	Group or province	Annual minimum SWL rise (m per year)	Annual Maximum SWL rise (m per year)	Annual mean (m per year)	Annual median (m per year)	Annual STDEV (m per year)	n
Quaternary Sediments	Central	0.004	0.434	0.130	0.103	0.113	51
	West	0.004	0.195	0.056	0.030	0.079	5
	South-east	0.004	0.283	0.065	0.023	0.089	10
	All	0.004	0.434	0.114	0.079	0.110	66
Tertiary Volcanic	All	0.015	0.844	0.243	0.100	0.339	18
Triassic Sedimentary	West	0.009	0.959	0.294	0.206	0.291	20
	South-east	0.141	0.141	0.141	0.141	0.000	1
	All	0.821	0.959	0.287	0.202	0.285	21
L. Permian Sedimentary	Central	0.017	0.564	0.182	0.111	0.174	19
	West	0.003	0.532	0.189	0.129	0.197	8
	South-east						0
	All	0.003	0.564	0.184	0.111	0.177	27
E. Permian Sedimentary	Central	0.013	0.639	0.182	0.119	0.215	8
	South-east	0.004	0.689	0.240	0.093	0.276	9
	All	0.004	0.689	0.213	0.093	0.243	17
Carboniferous Sedimentary	North	0.076	0.107	0.091	0.091	0.022	2
	South-east	0.003	0.298	0.110	0.078	0.095	11
	All	0.003	1.491	0.107	0.078	0.087	13
TOTAL							**162**

Table 7. Summary of standing water level trends for all bores displaying only positive trends

5.3 CHANGE IN POTENTIAL DISCHARGE AREA

The potential discharge area at each target date is calculated as a proportion of the maximum discharge area, (given by the FLAG wetness index). This proportion is equal to, the ratio of bores with predicted standing water levels within two metres of the ground surface, to the total number of bores in a province at the target date.

A summary of the percentage change for each geology and province is given in Table 8.

	Location	No. of Bores	2000	%	2010	%	2020	%	2050	%	2100	%
Quaternary	Central	68	5	7	15	22	35	51	60	88	67	99
Sediments	West	0	0	0	0	0	0	0	0	0	0	0
	South-east	24	0	0	0	0	0	0	0	0	0	0
Tertiary	Main	38	2	5	13	34	16	42	27	71	34	89
Volcanic	Outliers	1	0	0	1	100	1	100	1	100	1	100
Triassic	West	23	2	9	3	13	6	26	13	57	18	78
Sedimentary	South-east	24	2	8	4	17	5	21	10	42	19	79
L. Permian	Central	51	5	10	11	22	18	35	33	65	41	80
Sedimentary	West	45	13	29	23	51	26	58	34	76	41	91
	South-east	15	4	27	9	60	11	73	14	93	15	100
E. Permian	Central	15	0	0	3	20	6	40	9	60	15	100
Sedimentary	South-east	8	1	17	2	33	4	67	6	100	6	100
Carboniferous	North	16	2	13	9	56	13	81	16	100	16	100
Sedimentary	South-east	19	2	11	7	37	7	37	13	68	16	84
Total		347										

Table 8. Proportion of bores with predicted groundwater level within two metres of the surface at target dates

5.4 GROUNDWATER SALINITY

Groundwater salinity values were available for 718 bores across all geologies. Multiple salinity readings were available for most bores. Approximately 3000 data points were used to calculate the salt concentration statistics listed in Table 9. Salinity is recorded in EC units where 1 EC unit equals 1 $\mu S.cm^{-1}$ at 25^0 C. A conversion factor of 0.64 EC = 1 $mg.L^{-1}$ was used to convert EC to total dissolved salts (TDS) in the calculation of potential salt loads.

Average values for each geology and province were used in the calculation of potential salt loads. Adjustment was made before adopting these values in the calculation of potential salt loads from each geology and province. Due to the location of bores within the landscape in both recharge and discharge locations differences in salinity may be due to the influence of fresher meteoric water in bores. In light of this bores with salinities lower than 500 $\mu S.cm^{-1}$ were excluded from the analysis as these salinities indicate juvenile groundwater where the major component is still rainfall. Bores in the Quaternary alluvium were not adjusted in this way because of the inter-connections with the river. That is, alluvial aquifers exchange water with the river both as recharge and discharge and therefore more naturally have low salinities. Adopted values are shown in Table 9

Geology	Group or Province	Electrical conductivity ($\mu S.cm^{-1}$)				
		Min	Max	Average	Stdev	n
Quaternary	Central	355	5060	1377	835	250
	West	155	944	557	258	20
	South-east	542	6400	1614	1041	67
	All	155	6400	1375	886	337
Tertiary	Main	170	2760	1142	474	43
	Outliers	5380	6290	5835	643	2
	All	170	6290	1350	1086	45
Triassic	West	126	11800	1772	1886	48
	South-east	199	1100	568	358	7
	All	126	11800	1619	1809	55
L. Permian	Central	380	25800	3649	3716	74
	South-east	169	5730	1542	1540	25
	West	226	7600	1579	1320	88
	All	169	25800	2393	2753	187
E. Permian	Central	630	9500	3387	2874	11
	South-east	373	9350	2280	2222	22
	All	373	9500	2649	2471	33
Carboniferous	South-east	777	11050	3431	2626	27
	West	260	3130	1055	544	34
	All	260	11050	1600	2137	61
Total no. of bores						718

Table 9. Salinity of groundwater in 718 bores in the Hunter Valley

5.5 POTENTIAL SALT LOAD

Potential salt loads discharged from groundwater were calculated for all sub-catchments using equation 4.1. Included in this assessment were the Williams, Patterson and Allyn River systems although they do not contribute to the Hunter River above Greta that is the primary focus of the audit. Dryland salinity processes identified in these systems could be significant to water supplies for Newcastle.

Potential loads at the target dates of 2000, 2010, 2020, 2050 and 2100 were calculated by first establishing the potential salt load per unit area of each geology and province. Each tributary or sub-catchment lies within a particular province. A specific rate of change for each tributary or sub-catchment was calculated from the area-weighted change in potential discharge area for all geologies in each. The proportion of bores with projected standing water level within 2 m of the surface (Table 8) was adopted as a surrogate for the predicted proportion of the maximum potential discharge area in each province established in the topographic analysis.

Values for specific yield were obtained initially from the literature (published reports for the Hunter region). However, for most geologies the published values were very low, representing the solid rock matrix rather than unconsolidated materials in the fractured rock aquifers that the methodology attempts to describe. Values were, therefore, adjusted after consultation with local experts and departmental hydrogeologists. The values adopted along with the rates of rise and salinity values used are listed in Table 10.

Geology	Location	Ave. EC (µS.cm^{-1})	Ave. Salinity (mg.L^{-1})	Specific Yield	Annual mean SWL Rise (m per year)	Annual unit salt load t.km^{-2} per year)
Quaternary Sediments	Central	1377	882	0.20	0.130	22.9
	West	557	357	0.20	0.056	4.0
	South-east	1614	1033	0.15	0.065	10.1
Tertiary Volcanic	All	1165	746	1.00E-02	0.243	1.8
Triassic Sedimentary	West	2346	1502	7.00E-02	0.294	30.9
	Central		1014	*	*	15.4
	South-east	821	525	7.00E-02	0.141	5.2
L. Permian Sedimentary	Central	3879	2483	5.00E-02	0.182	22.6
	West	1786	1143	5.00E-02	0.189	10.8
	South-east	2010	1286	5.00E-02	0.184	11.8
E. Permian Sedimentary	Central	4933	3157	1.00E-02	0.182	5.7
	South-east	2788	1784	1.00E-02	0.240	4.3
Carboniferous Sedimentary	North	3431	2196	1.00E-01	0.107	23.5
	South-east	1102	705	1.00E-01	0.110	7.8
	Central		2196	1.00E-01	0.107	23.5

Table 10. Values of average salinity, specific yield and average rate of rise used to calculate salt load per unit area of each geology and province

Multiplying the load per unit area for each geology and province by the per cent area affected at the target dates gave a load factor that was used to calculate the load from the maximum wetness area. This FLAG factor for each geology and province is given in Table 11. Although a salt delivery rate of 10 t.km^{-2} a year was obtained for the Quaternary alluviums in the south-eastern province (Table 10) the actual potential rate was set to zero (Table 11) as water levels were not predicted to intersect the surface in the forecast period.

The calculated areas of FLAG wetness for each geology sub-catchment and province are listed in Table 12 and the calculated potential salt load for each sub-catchment at the target dates is listed in Table 13. Values from Table 13 were used as inputs into the prediction of future stream salinities and routed in IQQM.

		Annual salt load per unit area	Percent area affected (%)					Annual FLAG factor ($t.km^{-2}$ per year)				
Geology	Location	($t.km^{-2}$ per year)	2000	2010	2020	2050	2100	2000	2010	2020	2050	2100
Quaternary Sediments	Central	22.921	7	22	51	88	99	1.69	5.06	11.80	20.22	22.58
	West	3.993	7	22	51	88	99	0.29	0.88	2.06	3.52	3.93
	South-east	0.000	0	0	0	0	0	0.00	0.00	0.00	0.00	0.00
Tertiary volcanic	All	1.812	5	36	44	72	90	0.09	0.65	0.79	1.30	1.63
Triassic Sedimentary	West	30.901	9	13	26	57	78	2.69	4.03	8.06	17.47	24.18
	Central	15.431	9	15	23	49	79	1.31	2.30	3.61	7.55	12.15
	South-east	5.186	8	17	21	42	79	0.43	0.86	1.08	2.16	4.11
L. Permian Sedimentary	Central	22.592	10	22	35	65	80	2.21	4.87	7.97	14.62	18.16
	West	10.804	29	51	58	76	91	3.12	5.52	6.24	8.16	9.84
	South-east	11.835	27	60	73	93	100	3.16	7.10	8.68	11.05	11.84
E. Permian Sedimentary	Central	5.746	0	20	40	60	100	0.00	1.15	2.30	3.45	5.75
	South-east	4.282	17	33	67	100	100	0.71	1.43	2.85	4.28	4.28
Carboniferous Sedimentary	North	23.496	13	56	81	100	100	2.94	13.22	19.09	23.50	23.50
	South-east	7.755	11	37	37	68	84	0.82	2.86	2.86	5.31	6.53
	Central	23.496	11	46	57	83	91	2.69	10.74	13.43	19.47	21.48

Table 11. Salt load per unit area, percentage area affected and FLAG maximum wetness area conversion factor for each geology and province

NB in Quaternary sediments, the small area in the west has assumed the same % area affected as for the central province.

NB for Carboniferous in central province, use values from the North province, and combine all bores to obtain % salinised.

NB for the Triassic sediments within the central province, values for each catchment were allotted using values from the western province for those in the north central province; and values from the southeast province for those in the south central province.

Geology	1. **Early Permian Sediments** 2. **Tertiary Basalt** 3. **Late Permian Sediments** 4. **Carboniferous sediments** 5. **Triassic Narrabeen Sandstone** 6. **Quaternary Alluvium**	**1**	**2**	**3**	**4**	**5**	**6**	**total**
Catchment	STATION	Total area Wetness (ha)						
1	001 Hunter R. at Singleton	206	0	3204	17	131	1005	4563
2	002 Hunter R. at Muswellbrook	1660	0	868	5800	0	1607	9936
6	006 Goulburn R. at Coggan	0	219	3679	0	2683	0	6581
10	010 Williams R at Glen Martin	0	44	0	4974	0	0	5018
11	011 Williams R at Telligra	0	296	0	2402	0	0	2698
14	014 Rouchel Brook at Rouchel	0	297	0	3731	0	0	4027
15	015 Hunter R. at Glenbawn	0	310	0	4431	0	0	4741
16	016 Goulburn R. at Kerrabee	0	2530	18	0	1272	0	3820
18	018 Hunter R. at Moonan	0	2551	0	2051	0	0	4602
21	021 Patterson R. at Lostock	0	624	0	5533	0	0	6157
22	022 Allyn R at Halton	0	311	0	3638	0	0	3949
28	028 Wollombi Brook at Bulga	1420	0	2592	0	3056	0	7067
31	031 Goulburn R. at Sandy Hollow	0	706	1884	0	3250	0	5840
34	034 Widden Brook at Widden	0	296	6411	0	6367	0	13074
40	040 Wybong Ck at Wybong	0	4687	0	0	3599	0	8286
42	042 Foy Brook at Ravensworth	0	0	287	1446	0	0	1733
44	044 Glennies Ck at Falbrook	0	0	331	2799	0	19	3150
46	046 Goulburn R. at Ulan	0	0	290	0	683	0	974
52	052 Pages R. at Gundy	0	766	382	3644	0	0	4791
55	055 Hunter R. at Denman	3199	0	3591	881	0	1513	9184
59	059 Bayswater Ck at Liddell	1701	0	550	211	0	0	2462
60	060 Baerami Ck at Baerami	0	0	2415	0	2229	0	4644
61	061 Pages Ck at Blandford	0	2902	1328	2989	635	0	7853
64	064 Hunter R at Greta	1537	0	879	1656	4	566	4641
65	065 Halls Ck at Gungal	0	4652	0	0	2135	0	6788
66	066 Merriwa R. u/s Valences Ck	0	2868	0	0	2563	0	5430
79	079 Patterson R.at Gostwyck	0	0	0	3888	0	0	3888
82	082 Wollar Ck u/s Goulburn R.	0	20	571	0	110	0	701
83	083 Hunter R. at Liddell	378	6	5093	0	450	1434	7360
84	084 Glennies Ck at The Rocks No2	0	99	0	5160	0	0	5259
86	086 Munmurra R. at Tominbil	0	3960	0	0	922	0	4882
87	087 Doyles Ck at Doyles Ck	0	0	320	0	1197	0	1517
88	088 Dart Brook at Aberdeen	0	4659	8794	1341	2835	2356	19986
89	089 Black Ck at Rothbury	1413	0	0	0	0	0	1413
90	090 Martindale Ck at Martindale	0	0	579	0	1502	0	2081
91	091 Merriwa R. at Merriwa	0	11526	0	0	0	0	11526
92	092 Krui R. at Collaroy	0	7933	0	0	0	0	7933
junction		0	0	2256	0	2278	107	4640
REM		9080	0	0	6368	155	7903	23507
	TOTAL	20593	52261	46320	62959	38056	16512	236701

Table 12. Maximum FLAG Wetness area for each sub-catchment by geology

u/s upstream

		Annual salt load (t per year)				
Sub-catchment	**STATION**	**2000**	**2010**	**2020**	**2050**	**2100**
1	001 Hunter R. at Singleton	103	232	286	366	394
2	002 Hunter R. at Muswellbrook	202	766	1076	1638	1862
6	006 Goulburn R. at Coggan	187	313	448	772	1015
10	010 Williams R at Glen Martin	41	142	142	265	326
11	011 Williams R at Telligra	20	71	71	131	162
14	014 Rouchel Brook at Rouchel	110	495	715	880	881
15	015 Hunter R. at Glenbawn	130	588	848	1045	1046
16	016 Goulburn R. at Kerrabee	37	69	124	257	351
18	018 Hunter R. at Moonan	63	288	412	515	523
21	021 Patterson R. at Lostock	46	162	163	302	371
22	022 Allyn R at Halton	30	106	106	197	243
28	028 Wollombi Brook at Bulga	105	231	298	413	493
31	031 Goulburn R. at Sandy Hollow	147	240	385	731	983
34	034 Widden Brook at Widden	371	613	916	1639	2176
40	040 Wybong Ck at Wybong	101	176	327	690	947
42	042 Foy Brook at Ravensworth	21	62	66	108	128
44	044 Glennies Ck at Falbrook	33	104	109	185	222
46	046 Goulburn R. at Ulan	27	44	73	143	194
52	052 Pages R. at Gundy	116	505	732	922	938
55	055 Hunter R. at Denman	129	383	657	1113	1367
59	059 Bayswater Ck at Liddell	18	69	111	180	243
60	060 Baerami Ck at Baerami	135	223	330	586	777
61	061 Pages Ck at Blandford	121	419	553	862	1007
64	064 Hunter R at Greta	52	132	168	251	278
65	065 Halls Ck at Gungal	62	116	209	433	592
66	066 Merriwa R. u/s Valences Ck	72	122	229	485	666
79	079 Patterson R.at Gostwyck	32	111	111	206	254
82	082 Wollar Ck u/s Goulburn R.	21	36	45	66	83
83	083 Hunter R. at Liddell	143	335	600	1081	1325
84	084 Glennies Ck at The Rocks No2	42	148	148	275	339
86	086 Munmurra R. at Tominbil	28	63	106	213	287
87	087 Doyles Ck at Doyles Ck	15	33	41	61	87
88	088 Dart Brook at Aberdeen	312	787	1298	2298	2837
89	089 Black Ck at Rothbury	10	20	40	60	60
90	090 Martindale Ck at Martindale	25	54	67	96	130
91	091 Merriwa R. at Merriwa	11	75	91	150	187
92	092 Krui R. at Collaroy	7	52	63	103	129
junction		132	217	327	586	777
REM		117	313	443	730	811
	Total	**3375**	**8912**	**12933**	**21036**	**25493**

Table 13. Predicted potential groundwater salt load for current conditions and target dates 2010, 2020, 2050 and 2100 by sub- catchment

u/s upstream

CHAPTER SIX

TREND ANALYSIS

Ten sites within the Hunter River system were analysed to determine whether there was any strong evidence for rising salinity trends in mainstream reaches or in tributaries. The analysis utilised both the long term discrete data as well as more recent continuous flow and EC data. Seasonal effects were accounted for; however, it was impossible to separate the effects of changes to river regulation, infrastructure development and the advent of the Salinity Trading Scheme. Therefore the results of the analysis are inconclusive with respect to a background increase in dryland salinity in the catchment.

	Linear time trend in EC units per year*	
Station number	**Long term (1972–1999)**	**Short term (1995–1999)**
210083 Hunter River at Liddell	**-16.5**	29
	(1972–1999)	(1995–1999)
210004 Wollombi Brook at Warkworth	**3.2**	Nil
	(1972–1999)	(1996–1999)
210006 Goulburn River at Coggan	Nil	Not Available
	(1972–1990)	
210022 Allyn River at Halton	Nil	Not Available
	(1972–1989)	
210031 Goulburn River at Sandy Hollow	**-6.5**	**-34**
	(1976–1999)	(1995–1999)
210040 Wybong Creek at Wybong	Nil	Nil
	(1972–1999)	(1997–1999)
210044 Glennies Creek at Falbrook	Nil	Nil
	(1972–1999)	(1995–1999)
210052 Pages River at Gundy	Nil	Not Available
	(1972–1990)	
210064 Hunter River at Greta	**-50.6**	Nil
	(1972–1999)	(1995–1999)
210002 Hunter River at Muswellbrook	Nil	**23.5**
	(1972–1999)	(1995–1999)

* Values in parenthesis shows the period analysed

*Trend values in bold are significant at the 5% level otherwise significant at the 10% level

Table 14. Results of salinity trend analysis for tributaries and mainstream reaches of the Hunter River

Table 14 summarises the results of the trend analysis. Overall, the analysis showed no trend or decreasing trends in the longer-term data with the exception of station 210004 (Wollombi Brook at

Warkworth). The Goulburn River system represented by 210031at Sandy Hollow is unregulated and negative trends both in the short and long term data are at odds with the groundwater trends. This is possibly an artefact of the data but may be the result of interactions between fresh flow from National Parks and extraction of more saline sources for agriculture.

In most cases for the longer term analysis the number of discrete data points was low (< 150 data points). Although the results have been reported at the five and ten per cent confidence level, the small sample size further limits the confidence that can be placed on these results.

CHAPTER SEVEN

RESULTS FOR THE TRIBUTARIES

Details of the stochastic models used in the MDB audit are presented in Beale (2000). These were used in this study to characterise salt contributions from tributaries in the Hunter River system. In summary, they provide options for examining relationships between flow and salt load, or flow and salinity using linear or non-linear regressions. The models provide additional options for examining seasonal and time dependant effects. All models were tested with the data available. Inclusion of the time dependence and seasonality options did not provide additional accuracy to that obtained from simpler regression models, and so were not used for salt load or salinity generation. For this reason, only models IIA to IID were examined for each catchment in detail.

In summary:

- Model IIA is a (linear regression of [{observed flow – seasonal mean flow} versus {observed salt load – seasonal mean salt load}]); + seasonal mean salt load.
- Model IIB is a (non-linear regression of [{observed flow – seasonal mean flow} versus {observed salt load – seasonal mean salt load}]); + seasonal mean salt load.
- Model IIC is a simple linear regression between flow and salt load.
- Model IID is a non-linear regression between flow and salt load.

Model choices IIA-IID were made by visual inspection of associated plots for the following:

a) Whether the data needed to be transformed (linear or non-linear model forms).
b) The ability of the model to represent the seasonality in salt load.
c) The ability of the model to reproduce the cumulative probability distribution function (cdf) of the daily salt load time series, (and salinity where there is continuous data) via per cent exceedence probability plots.
d) Scatter about the 1:1 line and R^2 of observed versus estimated salt loads.

7.1 STOCHASTIC MODELLING RESULTS

In the majority of cases, the model that was chosen performed the best in all the selection criteria. This was the non-linear and non-seasonal model IID, which transforms the data by the natural logarithm. The linear and non-seasonal model IIC was only used for some continuous '*extreme events*' data, where there were few data points and less significant variations in salt wash off response.

Seasonality was accounted for by fitting a Fourier series of flow and EC to the observed data. In the process of fitting Fourier series to flows in the Hunter sub-catchments, it was necessary to exclude extreme events as these skew the flow distribution over the time period. A 2% exceedence limit was chosen for this after experimentation in choosing different limits and observing the effect on the seasonal means produced. The two percentile limit was chosen as it excluded the smallest amount of data to smoothen the seasonal means derived, without biasing them. This exclusion was only done in fitting the Fourier series to the data to explain seasonality more adequately. It was not excluded from the data for the rest of the model fitting, (note: the seasonal models have a seasonal component and a non-seasonal component).

Seasonality could not be explained adequately in the Hunter system using this method, and so no seasonal models were chosen for use. Tributaries, exhibit highly variable flows and in-stream salinities, and are not expected to exhibit strong seasonality.

A summary of the observed data used, and the results of the stochastic analysis, including model forms chosen, is given in Table 15.

Station	EC data type	Observed period used	n	Observed data range	Observed data range	Model chosen	η	λ	R^2	Standard deviation of errors
				EC ($\mu S.cm^{-1}$)	Flow ($ML.d^{-1}$)	High & low			x or ln(x)*	x or ln(x)*
210014	D	1972–1990	80	200–1100	0.3–2350	IID	3.15	0.923	0.74	0.27
Glenbawn Dam	D	1978–96	494	310–740	Regulated	see note 2	na	na	na	na
210028	C(004Data)	Feb 1992	3	100–150	9300–13000	Hi- IIC	-106	7.240	0.43	133.31
		1992–1998	1034	100–3300	1–9300	Lo- IID	3.46	0.818	0.36	0.54
210031	C	1992–1999	38	200–600	2000–105600	Hi- IIC	492	10.200	0.99	328.77
			1684	200–2850	1–2000	Lo- IID	4	0.860	0.823	0.25
210040	C	1993–1999	18	100–550	600–4200	Hi- IIC	94.1	9.790	0.55	104.10
			1369	200–4300	1–600	Lo- IID	3.88	0.759	0.88	0.18
210042	C from 210130	1993–1999	39	100–500	500–32000	Hi- IID	3.68	0.676	0.91	0.24
			1911	250–2800	2–500	Lo- IID	3.8	0.786	0.96	0.14
210052	D	1972–1990	107	250–960	0.4–23800	IID	3.44	0.915	0.84	0.18
210084	C	1997–1999	765	130–500	regulated	see note 1	na	na	na	na
210087	None	210090 Data	na	na	na	IID	2.54	0.721	0.95	0.29
210088	D	1972–1981	42	60–4000	0.2–1590	IID	3.55	0.737	0.97	0.20
210089	C	1996–1999	24	450–2000	80–5700	Hi- IID	3.75	0.980	0.78	0.42
			1064	300–2700	1–80	Lo- IID	3.98	0.920	0.81	0.30
210090	D	1973–1981	27	90–1800	0.1–667	IID	2.54	0.721	0.95	0.29
210114	D(w total daily flows)	1978–1990	65	120–780	1–467	IID	2.3	0.899	0.92	0.27
Residual upstream of Denman	None	Mass balance at Denman 1993–98	466	na	na	IID	3.63	0.600	na	na
Residual upstream of	None	None	na	na	<=1100	IID	3.24	0.60	na	na

Station	EC data type	Observed period used	n	Observed data range	Observed data range	Model chosen	η	λ	R^2	Standard deviation of errors
				EC ($\mu S.cm^{-1}$)	Flow ($ML.d^{-1}$)	High & low			x or ln(x)*	x or ln(x)*
Singleton										
Residual upstream of Singleton	None	None	na	na	>1100	IID	3.9	0.614	na	na

Table 15. Summary of the tributary data used in, and results of the stochastic analysis

*NB.η & λ are regression coefficients of the flow and salt load relationships. The R^2 and standard deviation of errors is in either log or real space depending on the model type chosen for that data set, (e.g. model IIC is linear (untransformed), and model IID is transformed using the natural logarithm).

Notes:

1. 210084 was not modelled. Observed data was merged with an average value for 1997–98 (167 $kg.ML^{-1}$).
2. The gauge readings of salinity downstream of Glenbawn dam at station 210015 are the combination of dam outflows of low salinity and small amounts of seepage of higher salinities. This seepage is not significant for flow and hence is not measured accurately; however, it was taken into account to explain the variation in observed ECs at 210015. Seepage volumes were estimated by taking the minimum of flow at 210015, and a randomly generated seepage as a natural logarithm with a mean of 1.94 and a standard deviation of 0.9. Observed continuous data at 210015 was considered to be seepage when the flow was less than $50ML.d^{-1}$, and gave an average salinity of $600\mu S.cm^{-1}$ with a standard deviation of 9.77. The dam concentrations used were a mean of $323\mu S.cm^{-1}$, and 3 standard deviations. The salinities at 210015 for 1975 to 1998 were then estimated by breaking the observed flow at 210015 into seepage and dam components, applying the above salinity values to each water component, and then mixing them. This method does not accurately estimate the seepage; however, it is sufficient for estimating it's average effect on the salinity at 210015 for the recorded data 1996–1999. No attempt has been made in this study, to assess the differences in seepage for 1975 to 1996, or for the future cases even though it would most certainly vary. The impacts of this on downstream salinities are infrequent, occurring only when flows released from the dam are insignificant. Those impacts are likely to be negligible in any case, as the estimated mean seepage salinity of 600 $\mu S.cm^{-1}$ is well within the range of observed salinities for other tributaries.
3. At gauge 210130 continuous observed salinities were regressed with flows gauged at 210042 for Foy Brook estimation. This assumes that there is no concentration change between 042 and 130 gauges. Although this may not be the case, 130 provided the best information for the upper reaches of Foy Brook since it is the major part of the contributing catchment to 130.
4. Modelling for Wollombi Brook was a very rough first cut. The quality of gauged flow data at the end is extremely low, so flows were estimated using a Sacramento model simulation at Bulga. Observed EC at the outlet was still used, though the quality is hard to assess. Anecdotally the system has a significant groundwater store that gets flushed out in big events. This is a significant process that couldn't be modelled explicitly.
5. Flow measurements for the Goulburn River at Sandy Hollow (210031) are unreliable due riverbed instabilities, which result in changes to measured flow height and volume relationships. A flow ratio

factor relating Sacramento modelled flows at 210016 with flows at Sandy Hollow was used to estimate flows at 210031 and these were regressed with continuous observed salinities at 210031.

6. A fault zone contributes saline water upstream of The Wybong Creek gauge at Wybong (210040). The regression for this site is difficult as there are two major processes contributing to in-stream salinities here with different behaviours. The regression is sufficient for identifying simple washoff characteristics of Wybong catchment, but not it's relationship to the timing and duration of fault zone seeps, or the combination of fault zone seeps and washoff events on salinities.

The R^2 regression criterion was used in obtaining the regression coefficients or salt parameters to be used for each tributary. The R^2 statistic of salt load versus flow alone, however, does not give a good indication of how well the model has been fitted to the observed data. This point is illustrated by Figures 12 to 15. Discrete and continuous data have been fitted successfully for salt loads (Figures 12 and 14); however, the uncorrected model fits give typically poor concentration distributions (Figures 13 and 15). The model was updated using the method outlined in section 4.3.1 of this report, to give a corrected model fit for EC. Figures 13 and 15 also show the corrected model fits for concentration as 'Est_Corrected'. These figures illustrate the need for correction for salinity variability in the reporting of percentile salinities for the tributaries, and to show it is adequate as a correction method for the data analysed. This method is limited by the variability observed, and hence the representativeness of the observed data. Note that the corrected salinity model has negligible impact on the predicted salt loads (Figures 12 and 14).

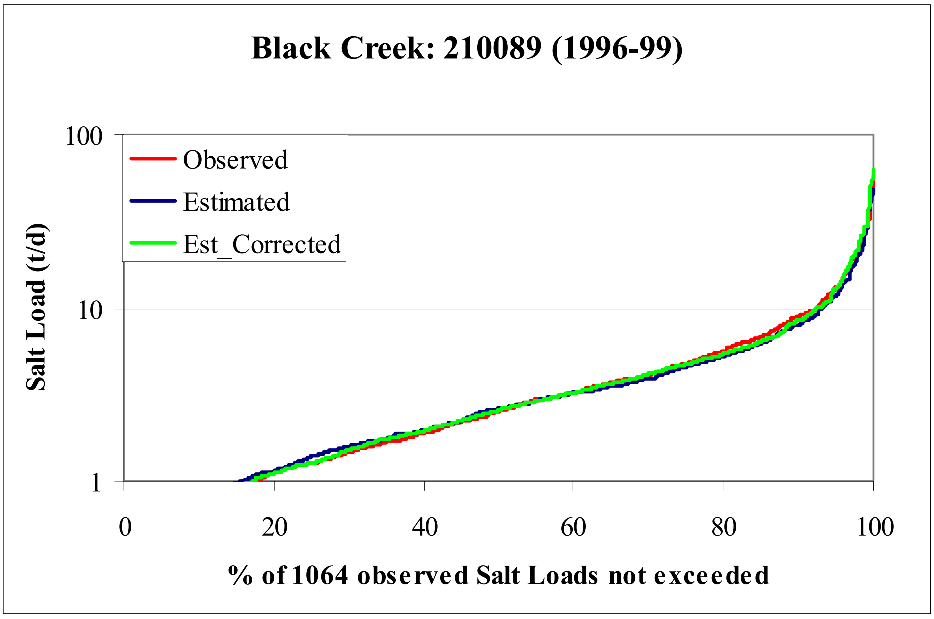


Figure 12. Example of Observed versus Modelled Salt Load Distributions for continuous data for Black Creek ('normal events dataset')

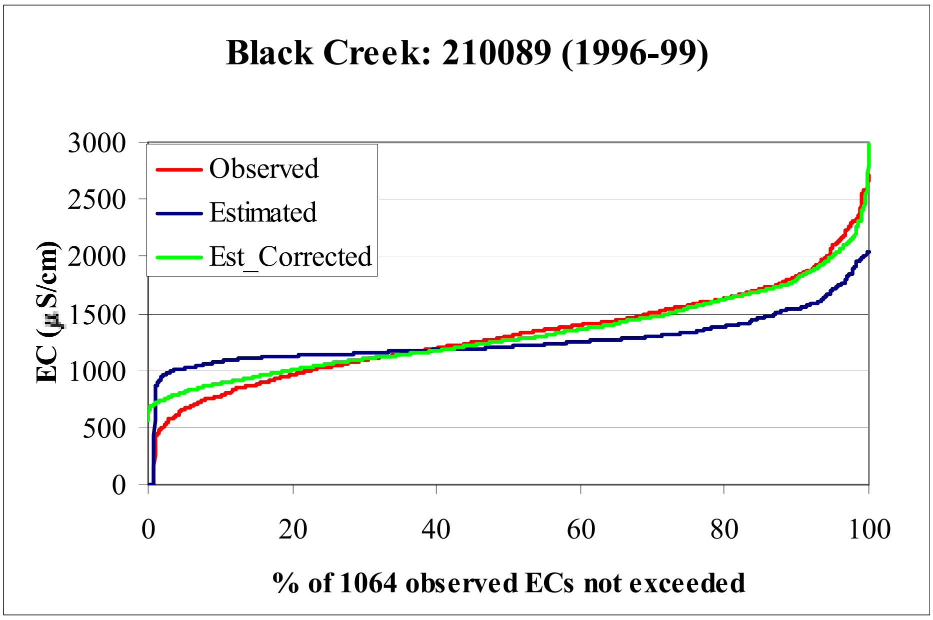


Figure 13. Example of Observed versus Modelled Salinity Distributions for continuous data for Black Creek ('normal events dataset')

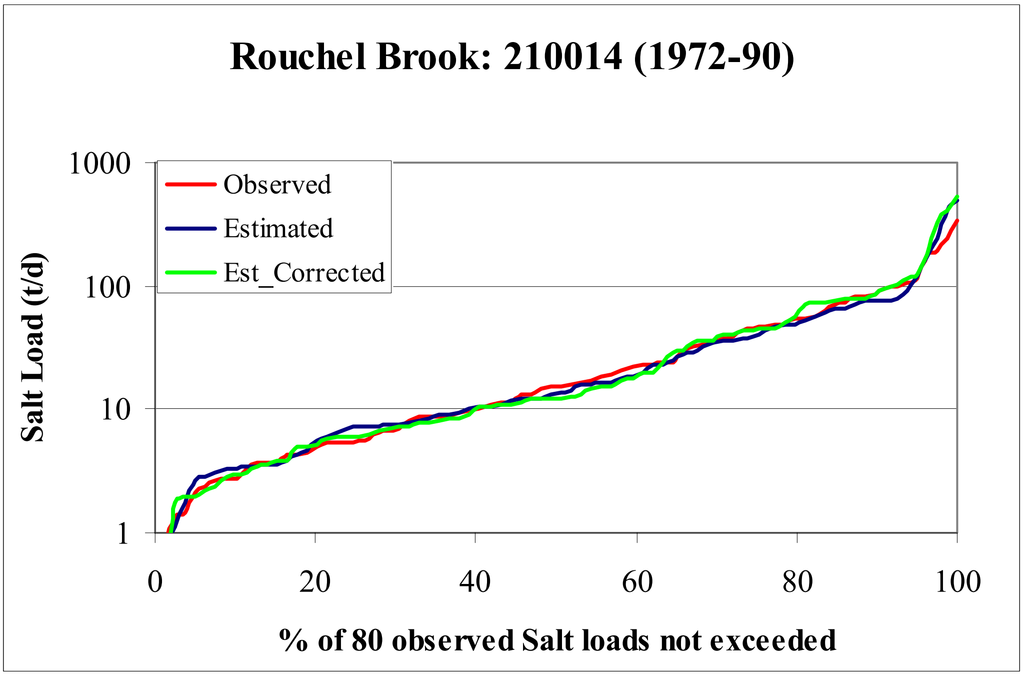


Figure 14. Example of Observed versus Modelled Salt Load Distributions for discrete data for Rouchel Brook

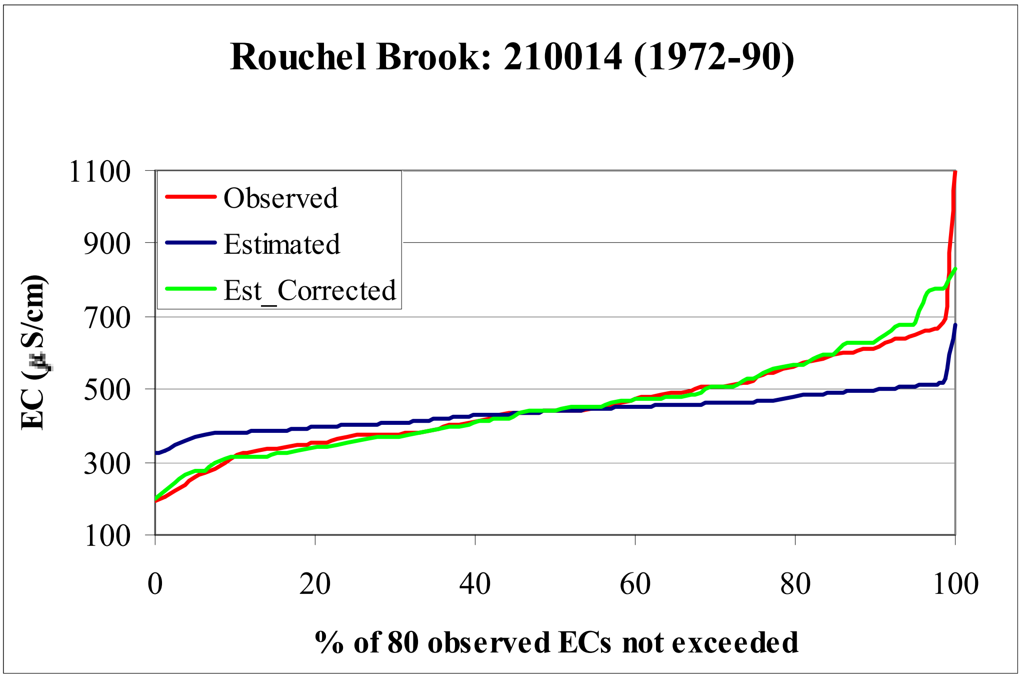


Figure 15. Example of Observed versus Modelled Salinity Distributions for discrete data for Rouchel Brook

7.2 REGIONALISATION

All catchments with no observed salinity data were regionalised using model IID since it was the major model type chosen for the tributaries with observed data. That is, the salt parameters η & λ, which are regression coefficients of the flow and salt load relationship, were taken from catchments with observed salinity data having similar physical features and used to predict the salt load associated with the observed flow.

Doyles Creek (210087) is the only tributary where regionalised parameters were applied to flows. The salt parameters were taken directly from Martindale Creek (210090), an adjacent catchment of similar size, rainfall, evaporation, and landuse characteristics.

Salt parameters for the residual catchments were derived as follows:

1. The residual catchment upstream of Muswellbrook, (catchment from Glenbawn Dam to Muswellbrook). The residual flow is estimated as (210052 + 210088 + 210014) * 0.3. This does not correspond for salinity since the residual catchment is physically made up of Pages River and Rouchel Brook. The resulting flow distribution of the residual flow is consistent with that of Pages river and Rouchel brook so a combination of their salt parameters is sufficient for regionalisation. This gives results similar to those obtained by simply applying the same concentrations from each of the tributaries, as they contribute to the residual. This last method was adopted for its simplicity.
2. The residual salt parameters of the catchment upstream of Denman were calculated to supply the additional salt load required by mass balance between Muswellbrook and Denman after a constant load had been added to account for groundwater contributions. This technique produced a poor R^2 on a daily basis (0.26) showing that upstream tributaries and/or groundwater contributions in the reach are more dominant in determining Hunter River salinities at Denman.

3. For the residual catchment upstream of Liddell, flows were combined with the salt parameters for Wybong Creek (210040) as shown in Table 15, section 7.1.
4. For the residual catchment upstream of Falbrook, flows were combined with the salt parameters for Carrow Creek and Foy Brook.
5. For the residual catchment upstream of Singleton, regionalised parameters are shown in table 15, section 7.1. They were taken from calculations of the residual upstream of Middle Falbrook (044–084), an adjacent catchment.
6. For the residual catchment upstream of Greta the discrete salt parameters for 210028 were used, (Model IID, $\eta = 3.28$, $\lambda = 0.788$).

7.3 OUTPUT

Table 16 is a summary of stochastic outputs for all tributaries for the 1975 to 1998 period.

Station	Name	Catchment area	Annual mean runoff	Annual mean salt load	Annual unit salt load	Zero flow	EC 50 percentile	EC 80 percentile
		(km^2)	(ML per year)	(t per year)	($t.km^{-2}$ per year)	(%)	($\mu S.cm^{-1}$)	($\mu S.cm^{-1}$)
210014	Rouchel Brook at The Vale	404	52,000	12,192	30.2	10	470	650
210015	Hunter River at Glenbawn	1,293	103,500	22,055	17.1	0	na	na
210028	Wollombi Brook at Bulga	1,682	107,000	20,599	12.2	24	705	1295
210031	Goulburn River at Sandy Hollow	6,817	150,500	50,601	7.4	3	995	1375
210040	Wybong Creek at Wybong	667	25,000	8,884	13.3	13	1465	2460
210042	Foy Brook at Ravensworth	183	17,000	5,484	30.0	42	1870	3370
210052	Pages River at Gundy Recorder	761	84,000	23,747	31.2	6	610	765
210084	Glennies Creek at The Rocks	226	25,000	4,203	18.6	0	na	na
210087	Doyles Creek	201	10,000	1,148	5.7	51	na	na
210088	Dart Brook at Aberdeen	788	31,000	7,716	9.8	26	1455	3915
210089	Black Creek	201	24,000	12,324	61.3	13	1220	1790

Station	Name	Catchment area	Annual mean runoff	Annual mean salt load	Annual unit salt load	Zero flow	EC 50 percentile	EC 80 percentile
		(km^2)	(ML per year)	(t per year)	($t.km^{-2}$ per year)	(%)	($\mu S.cm^{-1}$)	($\mu S.cm^{-1}$)
	at Rothbury							
210090	Martindale Creek near Martindale	359	20,500	2,290	6.4	30	495	1815
ResA	Residual use Muswellbrook	458	50,000	13,099	28.6	4	na	na
ResB	Residual use Denman	307	3,000	1,531	5.0	60	na	na
ResC	Residual use Liddell	985	43,000	13,029	13.2	0	na	na
ResD	Residual use Falbrook	218	34,500	7,981	36.5	12	na	na
ResE	Residual use Singleton	733	68,000	11,169	15.2	15	na	na
ResF	Residual use Greta	1,117	87,000	13,489	12.1	4	na	na

NB. Doyles Ck has 51% zero flows and no observed salinity data, so no 50 or 80 percentile ECs are reported.

Table 16. Summary of salinity and salt load statistics for tributaries, obtained from stochastic modelling for the 1975 to 1998 period

These results are further discussed in section 9.2 in relation to predicted future salt loads.

CHAPTER EIGHT

IN-STREAM SALT BALANCE FOR IQQM CALIBRATION

Calibration of the mainstream Hunter River IQQM was achieved reach-by-reach by:

- inputting the observed upstream flow and salinities;
- adding and routing tributary and groundwater inputs; and
- comparing IQQM simulated salinities to those observed at the downstream gauge.

This validated the size of tributary inputs and groundwater contributions at each stage. The IQQM system was then run from the top down as a check on the cumulative errors in the system. The calibration periods and statistics for each river section are given in Table 17. The results for the top-down calibration check are shown in Table 18. As explained in section 4.4, the flow calibration was not made specifically for the period of salt calibration, so flow statistics for the same period are given for comparison. Deviations for the top-down calibration check begin to appear at Greta; however, this occurs in the 0 to 10 per cent and 90 to 100 per cent non-exceedence ranges and so is not likely to impact on 50 & 80 percentile ECs reported for 'current' and future conditions.

The flow calibration was not adequate for salinity calibration for Liddell and Greta without modification, as significantly more base flow was modelled than was observed. This is an artefact of different calibration periods, and differing groundwater interaction behaviours over those periods. Since groundwater interactions are not modelled explicitly, an adjustment to the flow balance was done in the calibration of these reaches by mass balance, excluding differences due to timing problems. These adjustments did not affect the in-stream concentration as they were taken out in a similar manner to diversions, and were included in the salinity calibration only. They represent less than 10% of the total flow over the calibration period, for both Liddell and Greta. The flow adjustments were not included in the 1975 to 1995 'current' conditions run or future scenarios as they are period specific. This behaviour highlights the need for groundwater and surface water interactions to be modelled explicitly in the Hunter IQQM.

Despite the lack of continuous observed data to input into the model for the tributaries, good results for the mainstream calibration are still obtained. Whilst individual events could not be modelled well when tributary contributions were not measured, their contribution to mainstream behaviour was represented well. This is shown by the per cent exceedence plots of salt load and salinity for the calibration periods for each reach in Figures 18 to 29. Where the mass balance and related statistics can be strongly influenced by one or two events, the per cent exceedence plots give a better indication of how the model performs overall. The figures show results for the reach by reach calibration only.

A summary of the constant loadings representing groundwater and fault zone contributions chosen during calibration, and their location within the modelled flow network is given in Figure 6 in section 3.2.

Calibration point	River reach	Period	No. points	Catchment Area (km^{-2})	Flow			River load			Concentration	
					CD	CE	Mass balance (%)	CD	CE	Mass balance (%)	CD	CE
210002	Glenbawn Dam to Muswellbrook	1992–98	2341	4220	0.72	0.56	111	0.71	0.71	103	0.56	0.55
210055	Muswellbrook to Denman	1993–98	1824	4530	0.97	0.91	87	0.93	0.79	101	0.77	0.75
210083	Denman to Liddell	1991–98	2843	13400	0.87	0.87	102	0.84	0.84	101	0.6	0.59
210044	Glennies Dam to Middle Falbrook	1993–98	1859	466	0.48	0.42	93	0.47	0.4	102	0.43	0.38
210001/129/134	Liddell to Singleton*	1993–98	1942	16400	0.93	0.93	98	0.83	0.64	81	0.66	0.49
210064	Singleton to Greta	1/9/1995–98	1198	17320	0.96	0.96	110	0.81	0.45	117	0.65	0.64

-- Mass Bal. % is the mass balance per cent, where the total modelled mass is divided by the total observed mass for a period expressed as a per cent.

** Observed salinities for Singleton were taken mainly from 210129, although where this was judged unreliable, 210134 was used (4/1994 – 12/1995).*

Table 17. Mainstream Hunter River reach-by-reach calibration results

Station	Station Name	Period	No. points	Catchment Area (km^2)	Flow			River load			Concentration	
					CD	CE	Mass balance (%)	CD	CE	Mass balance (%)	CD	CE
210055	Denman	1993–98	1824	4530	0.71	0.64	88	0.68	0.53	103	0.47	0.34
210083	Liddell	1991–98	2843	13400	0.83	0.83	106	0.77	0.69	107	0.6	0.59
210001/129/134	Singleton	1993–98	1942	16400	0.91	0.83	108	0.84	0.73	84	0.5	0.26
210064	Greta	1/9/1995–98	1198	17320	0.86	0.86	112	0.76	0.75	94	0.5	0.31

Table 18. Mainstream Hunter River check of top-down calibration results

8.1 Representativeness of the calibration period

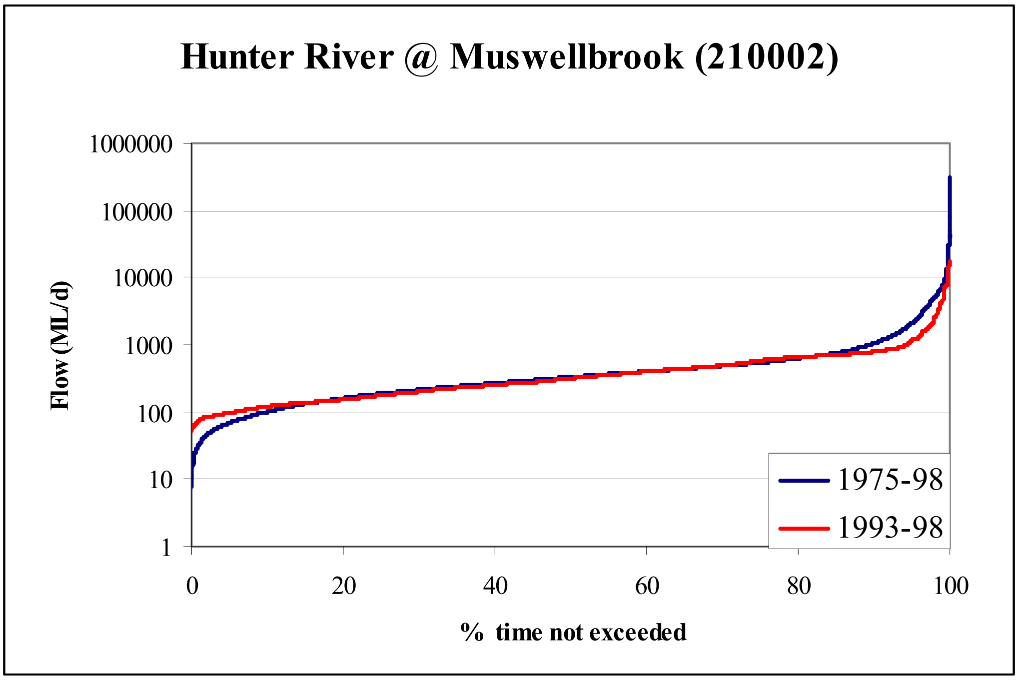


Figure 16. Flow duration plot of observed flows for the Hunter River at Muswellbrook for the calibration period (1993–98) and the 'current' conditions period (1975–98)

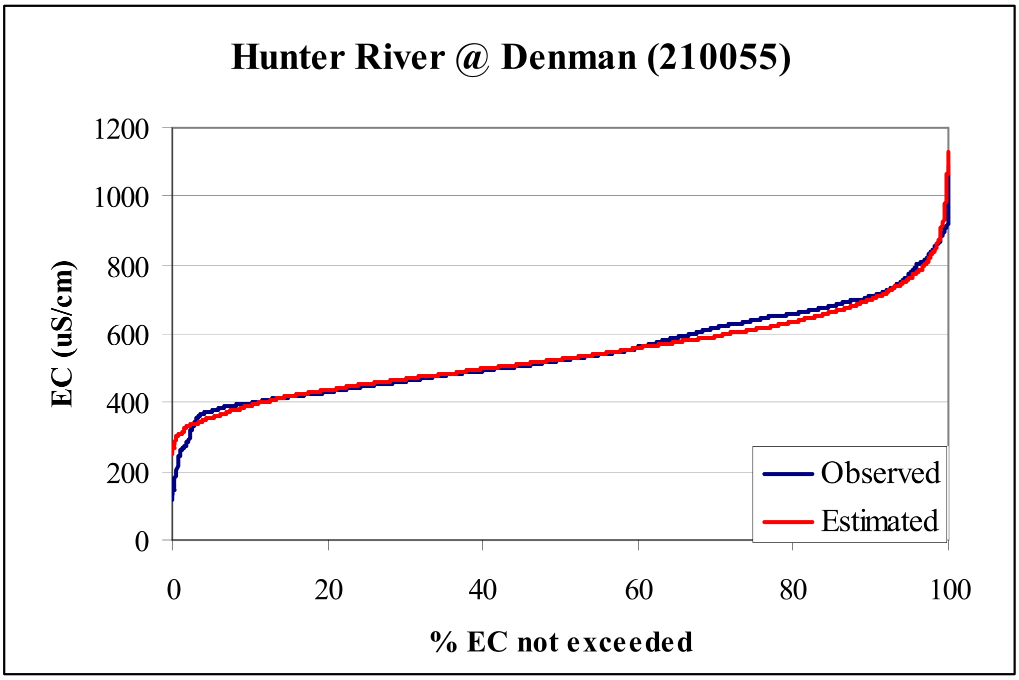


Figure 17. Salinity distribution for the Hunter River at Denman, Observed and Estimated (1993—98)

To address the issue of whether the chosen calibration period (1993–98) using continuous salinity data, is representative of the 'current' conditions period (1975–98), flows and salinities were assessed. Only discrete salinity information is available prior to the 1990s, so an assessment of how similar the flow sequences are provides intuitive information about how similar the salinity characteristics may be. The objective is not necessarily to explain what specifically happened from 1975; but rather to evaluated whether enough information is gleaned from the calibration period to explain the present salinity characteristics, if they are applied over the 1975–98 climatic period. Flows in the 1993–98 period are representative of flows in the 1975–98 period in the 10–85 percentile exceedence range (Figure 16). The 1993–98 period had a lower frequency of large events, and a higher frequency of low flows. The low flow difference is affected by both regulation and groundwater, recharge and/or discharge processes, both of which have significantly different associated salinities. A check to eliminate the flow impact on salinity for the different periods was done by comparing the stochastic model output fitted to the discrete data from the early period, to the continuous observed salinity data for the later period. Model output for the Hunter River at Muswellbrook, Denman, and Liddell, gave good fits to the observed salinity distribution. An example is shown in Figure 17.

Although the build up and wash off processes for the larger events in the early period will differ, it is not known by how much since they were not sampled for salinity. The limited salinity data suggests that for most of the time, the 1993–98 period is representative of the 1975–98 period on the mainstream.

8.2 Glenbawn Dam to Muswellbrook

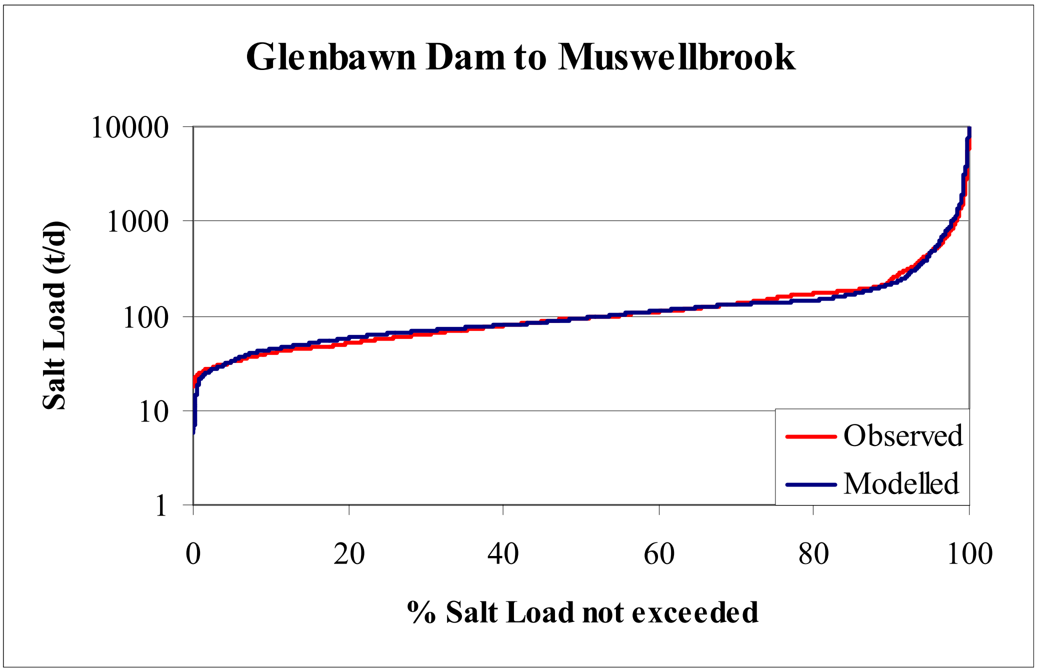


Figure 18. IQQM Reach by Reach Salt Load Calibration for the Hunter River from Glenbawn Dam to Muswellbrook, 1992 to 1998

Simulation of the Glenbawn Dam to Muswellbrook reach of the Hunter River begins at the gauge downstream of Glenbawn Dam (210015), with tributaries of Pages River, Dart Brook, Rouchel Brook, and Residual catchment A. The constant load chosen to represent groundwater or fault zone contributions to the mainstream is 13.5 t a day. 210015 is the only gauging station with continuous EC data beginning in 1996. There is some discrete data for the Pages River, Dart Brook, and Rouchel Brook . Given the lack of measured continuous data for this reach, the calibration at Muswellbrook is surprisingly good (Figure 18). This is due to the significant groundwater contributions of salt, and the tendency for regulated water from the Dam to dominate the observed salinities at Muswellbrook.

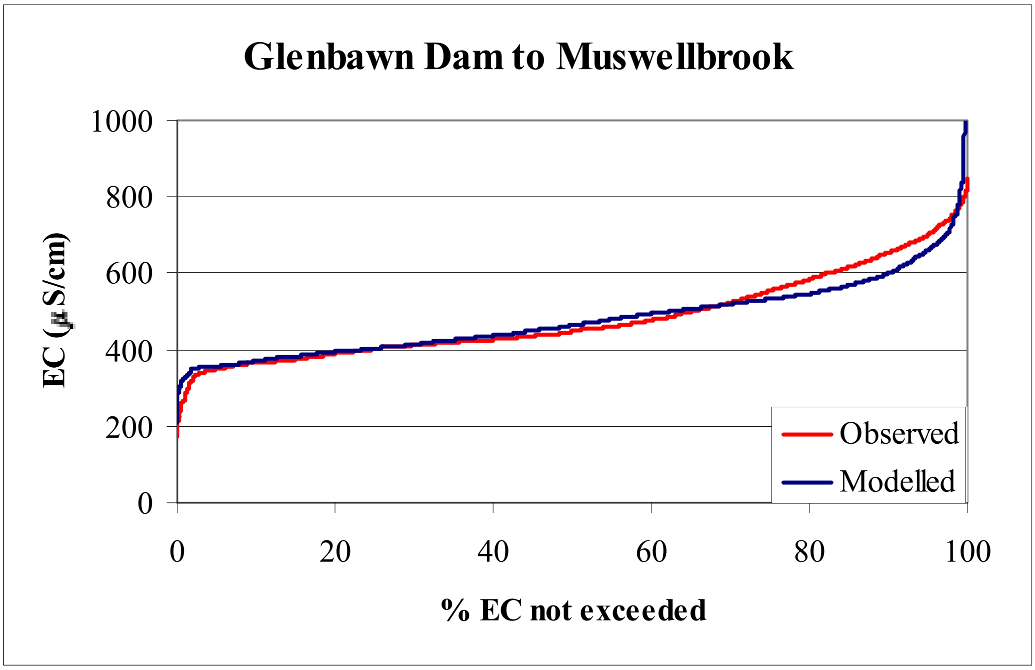


Figure 19. IQQM Reach- by-Reach Salinity Calibration for the Hunter River from Glenbawn Dam to Muswellbrook, 1992 to 1998

The deviation between observed and modelled EC in the range of the 70 to 100 per cent EC not exceeded at Muswellbrook shown in Figure 19 is predominantly the effect of poor representation of the data for 1992. If data for 1992 is taken out, the plotted lines show a good fit. There was no upstream or downstream data in 1992 to verify the observed data against. It is not justifiable to adjust the calibration for 1993 to 1998, on the basis of this 1992 deviation. It is observed data, however, and this problem may be due to measurement errors or failure of the present audit model to represent all dominant processes contributing to the salinity of the river at Muswellbrook. Further work on groundwater and surface water interactions may shed light on this apparent anomaly.

8.3 Muswellbrook to Denman

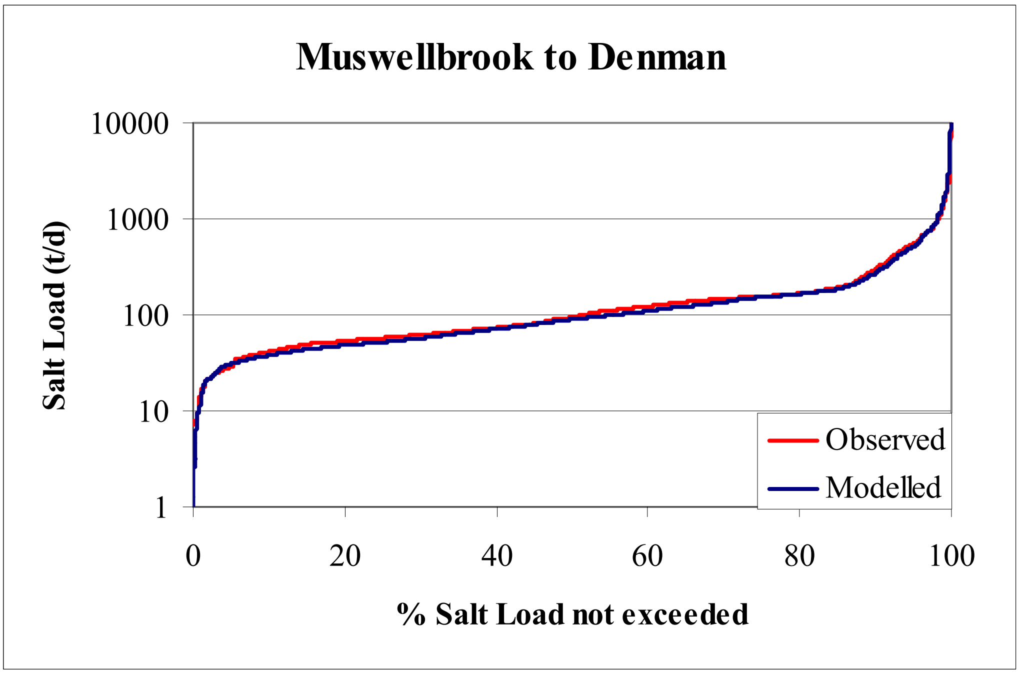


Figure 20. IQQM Reach by Reach Salt Load Calibration for the Hunter River from Muswellbrook to Denman, 1993 to 1998

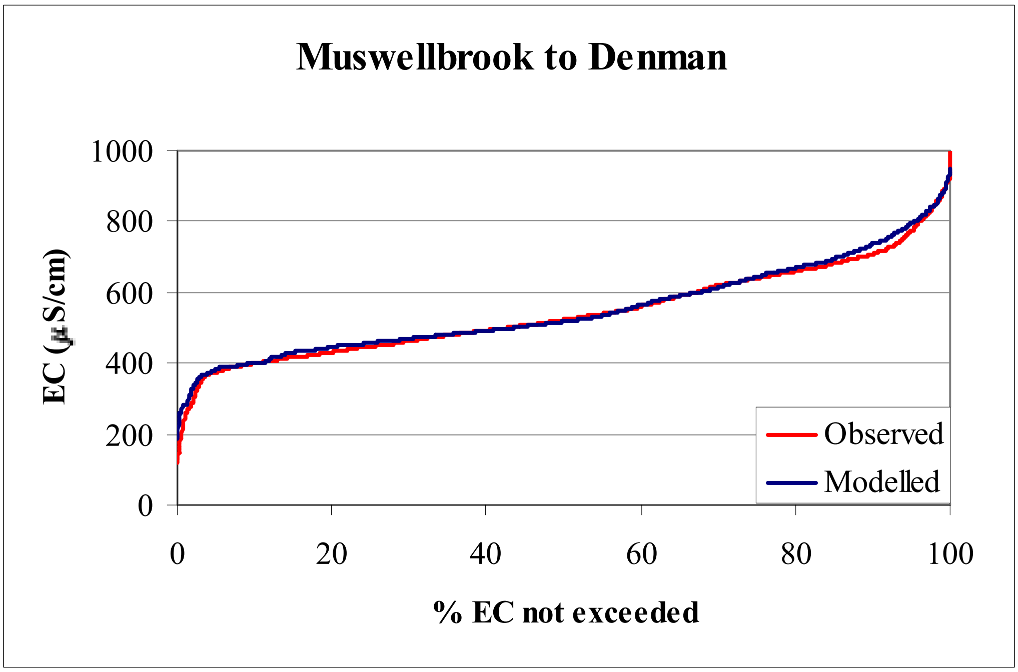


Figure 21. IQQM Reach by Reach Salinity Calibration for the Hunter River from Muswellbrook to Denman, 1993 to 1998

There is very little tributary contribution downstream of the Muswellbrook to Denman reach of the Hunter River. Residual catchment B, and a constant load of 12.5 t a day was added to match the observed salinities at Denman well (Figures 20 and 21). The groundwater contributions of salt represent those that are sourced from the Mount Ogilvie fault line, which is crossed by the Hunter River between Muswellbrook and Denman.

8.4 Denman to Liddell

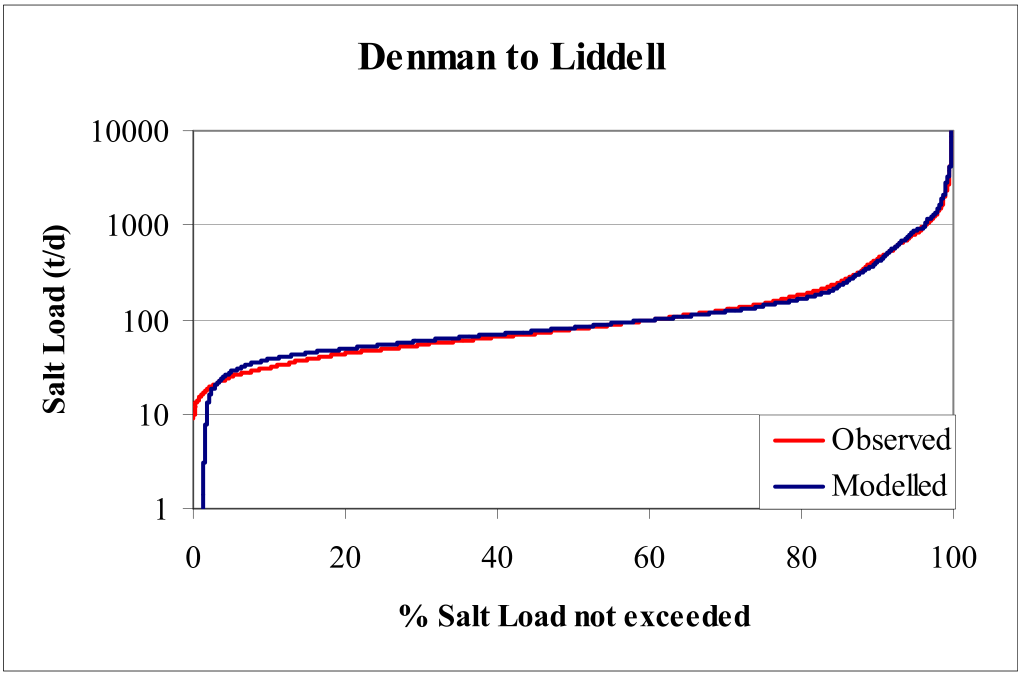


Figure 22. IQQM Reach by Reach Salt Load Calibration for the Hunter River from Denman to Liddell, 1991 to 1998

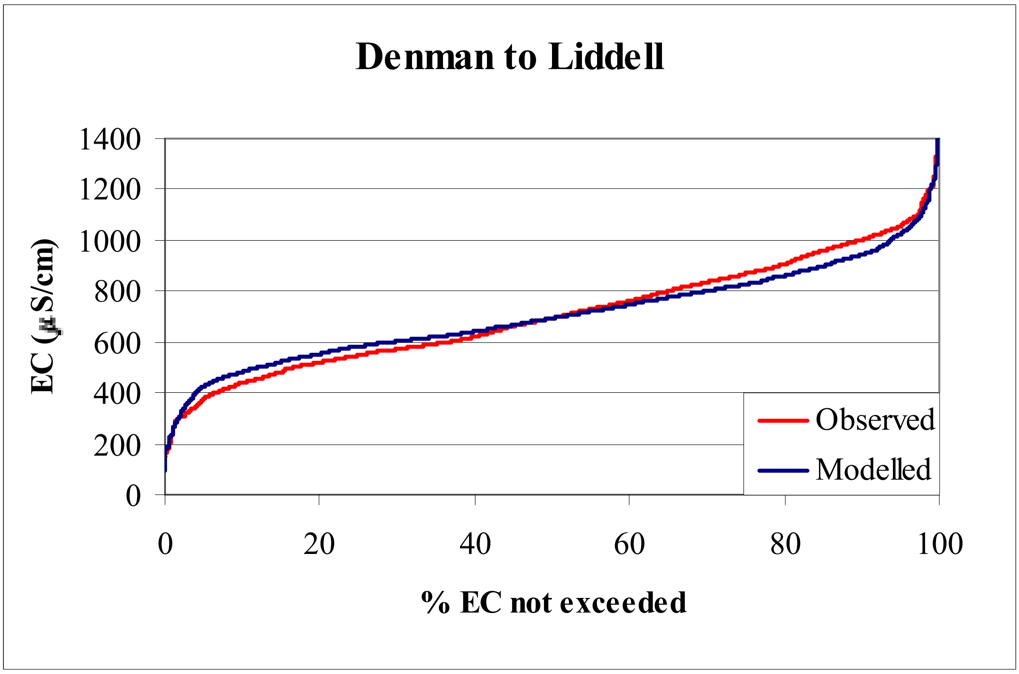


Figure 23. IQQM Reach by Reach Salinity Calibration for the Hunter River from Denman to Liddell, 1991 to 1998

The Denman to Liddell section of the Hunter River includes the large catchment area of the Goulburn River as well as Wybong, Martindale, and Doyles Creeks, and Residual catchment C. The groundwater loading constant was set at 12.5 t a day for this reach. The Goulburn River outlet has a very sandy riverbed, which makes accurate flow and salinity measurements difficult due to the changing nature of the streambed. Figure 22 shows a good model fit for intermediate and high salt loads, with some error in very low salt loads. This is due to the difficulty in modelling the large daily extractions for the power station upstream of Liddell accurately. This problem is not significant for the salinity calibration since power station extractions are regulated water from Glenbawn Dam, which has low salinity. Figure 23 shows some over-estimation of low salinities for significant events, which is compensated by under-estimation of higher salinities.

8.5 Glennies Creek Dam to Middle Falbrook

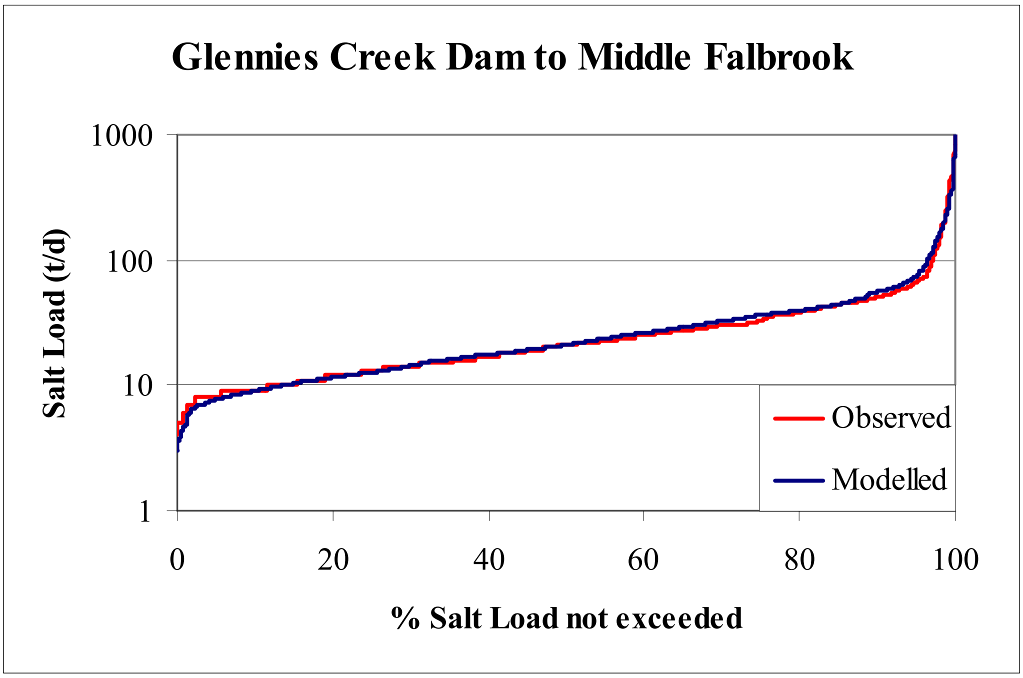


Figure 24. IQQM Reach by Reach Salt Load Calibration for Glennies Creek from Glennies Creek Dam to Middle Falbrook, 1993 to 1998

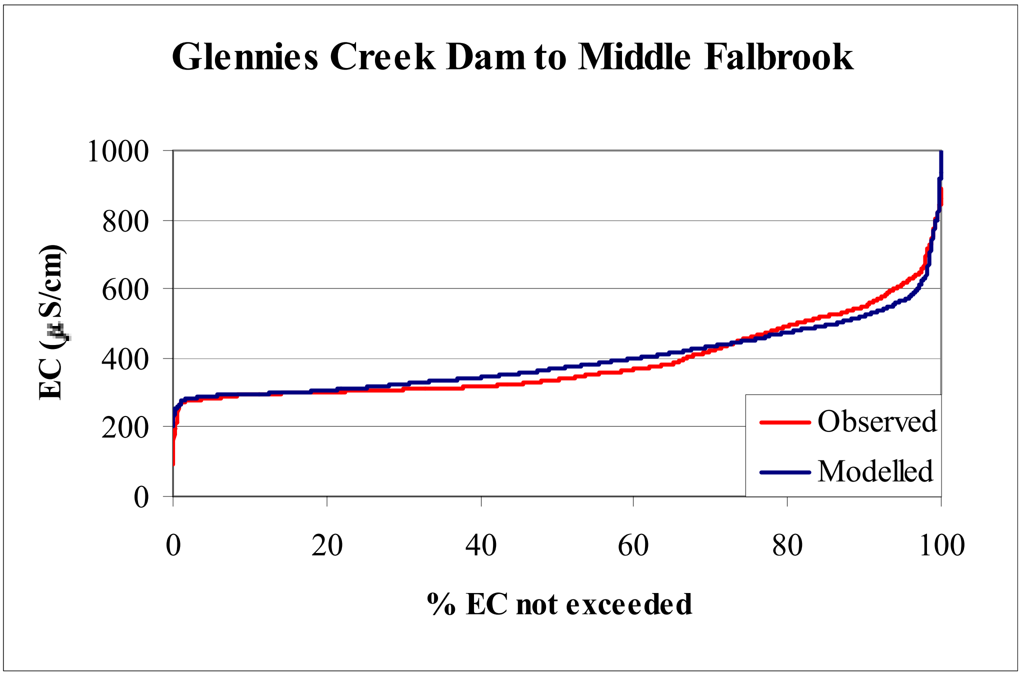


Figure 25. IQQM Reach by Reach Salinity Calibration for Glennies Creek from Glennies Creek Dam to Middle Falbrook, 1993 to 1998

Certain issues affect the accuracy of the flow calibration for Glennies Creek from downstream of Glennies Creek Dam to Middle Falbrook. Modelled flow over-estimates intermediate flows by approximately 10%, and underestimate high flows by up to 50%. This is because the residual flow was estimated using a correlation with Carrow Brook gauge (210114), which has since been found to be unreliable in measuring high flow events. These high flows only occur for two or less per cent of the time, and so whilst they impact the model fit statistics, they do not affect the salinities modelled at 210044 for the majority of the time.

Figure 24 shows a good correlation between modelled and observed salt load distribution. Discrepancies in modelled salinities are shown in Figure 25, where some compensatory over- and under-estimation is noted. The Glennies Creek catchment to Middle Falbrook is somewhat smaller than the mainstream Hunter River, and so is more sensitive to changes in recharge / discharge characteristics, and to the assumption of constant groundwater additions we have adopted for this study. The overestimation of 300–400 ECs for 1993–96 reflects the inability of this technique to model the 400–700 ECs observed from May to October 1998 in response to wetter climatic conditions. The constant load of 5 t a day represents the average condition over the calibration period; however, assuming this average over another climatic period appears to be problematic. Future salinity percentiles for Middle Falbrook will be significantly influenced by dam operation behaviour.

8.6 Liddell to Singleton

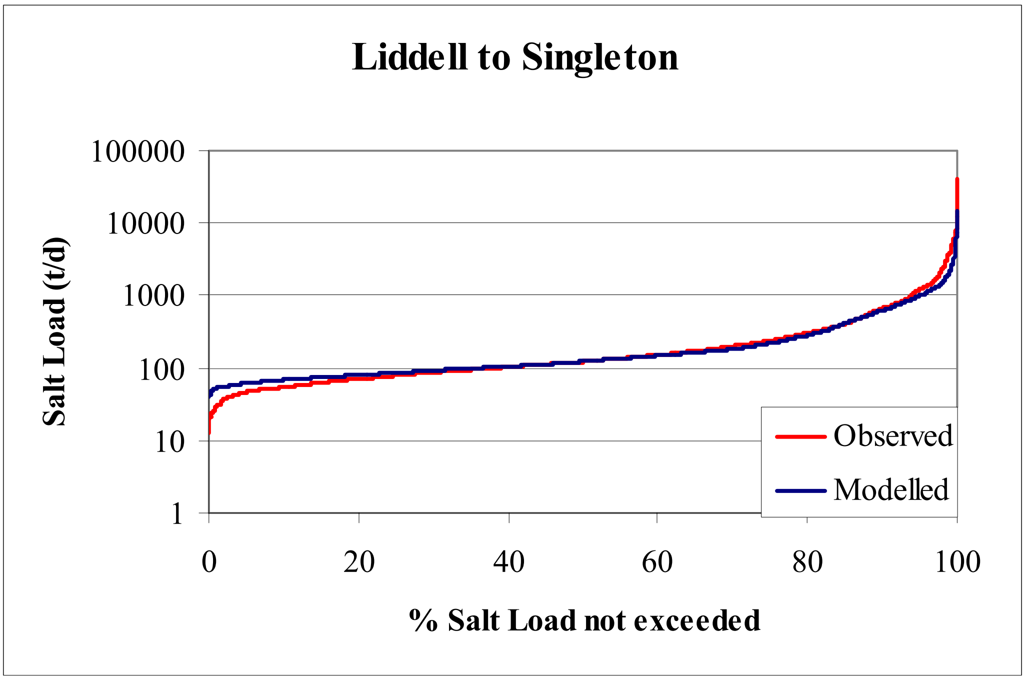


Figure 26. IQQM Reach by Reach Salt Load Calibration for the Hunter River from Liddell to Singleton, 1993 to 1998

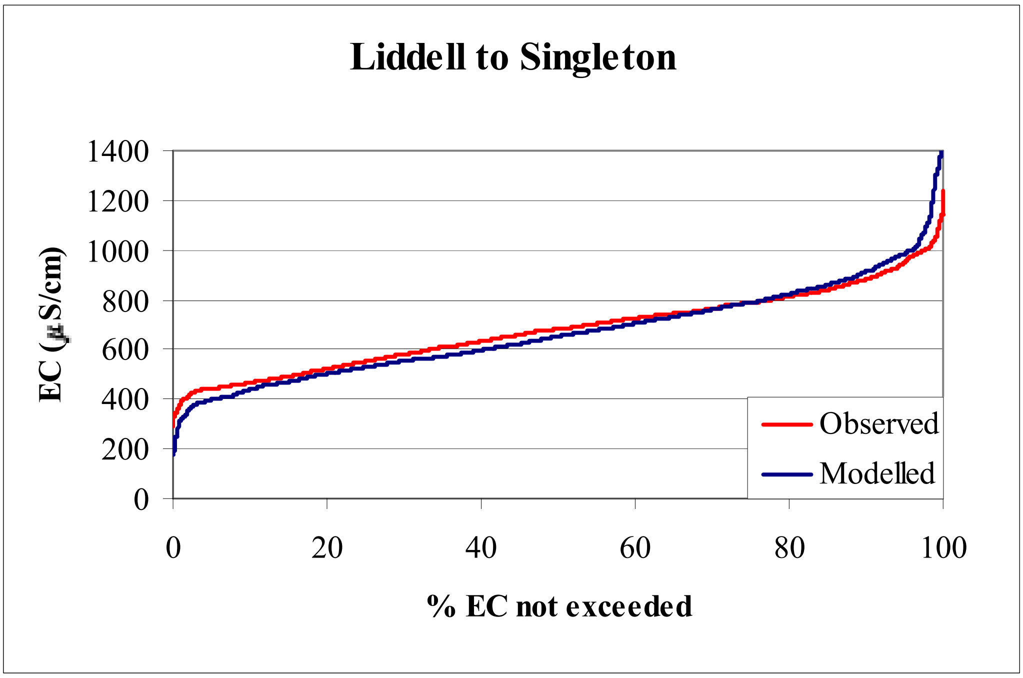


Figure 27. IQQM Reach by Reach Salinity Calibration for the Hunter River from Liddell to Singleton, 1993 to 1998

There are no continuous observed salinities at the Singleton flow gauge 210001. However, there are several nearby continuous probes in the mainstream river, which were used to approximate the salinities at Singleton. The primary gauge used for this purpose was 210129, the Hunter River upstream of Singleton; although where this was judged unreliable, 210134 (Hunter River at Long Point) was used (4/1994 – 12/1995). The choice of which gauging station to use for Singleton salinities was subjective, and comparison of the probe readings progressively downstream showed calibration problems with all of the probes at some point in time. This did not give greater confidence to one probe or another, and more work could be done in tracing which data is reliable.

The section of the Hunter River from Liddell to Singleton includes the Wollombi and Foy Brook tributaries, Glennies Creek, and Residual catchment E. A constant groundwater loading of 20 t a day was chosen for this reach. Whilst the modelling of Wollombi Brook is considered poor, due to data problems with flow and salinity, contributions did not significantly affect the modelled concentrations at Singleton. This was tested by artificially doubling the Wollombi concentrations to observe the impact on modelled concentrations at Singleton. The test had very little effect on modelled concentrations at Singleton, and Wollombi concentrations were returned to the original stochastic estimates. This shows that Singleton is now far enough down the system for individual tributary contributions to be much less significant for determining mainstream concentrations. Low salinity water released regularly from Glennies Creek Dam is significant for observed salinities at Singleton. Where tributaries do not have a significant impact on mainstream salinities, the calibration process can not validate the stochastic modelling of contributions for those tributaries.

Modelling of observed salinities for large events at Singleton proved difficult. Observed salinities and flows for Glennies Creek at Middle Falbrook, and Liddell were input in the calibration. Lake Liddell does not contribute significant amounts to the mainstream. Both Foy Brook and Wollombi Creek have observed data that could be used, although the Wollombi data has significant problems. The underestimation of some events at Singleton in the model, is due to the concentrations from Liddell dominating the salinities routed to Singleton. 1996 and 1997 are the only years where observed Liddell event concentrations match Singleton event concentrations. In all other years the observed concentrations of events at Liddell are much less than those observed at Singleton. The opposite is true for high concentrations and low flows. Liddell concentrations are frequently higher than those at Singleton. The event behaviour is only partially attributed to the tributaries currently in the model, and tests in artificially increasing tributary concentrations failed to account for the discrepancy. Groundwater contributions from tributaries may be confusing the picture since any transmissions under the surface are not measured at the gauge, and hence are not attached with an appropriate salinity. Sub-surface contributions are likely in events from the Wollombi catchment, although this has not been studied. The gauge at Liddell is the most reliable for both flow and salinity as it is measuring fully mixed flow. There are other continuous salinity probes in the section of river between Liddell and Singleton, which may give a much better indication of the sources of salt and dilution flows. Data was not available from these during the audit.

Despite these considerations Figures 26 and 27 show good correlations between observed and modelled, salt loads and salinity.

8.7 Singleton to Greta

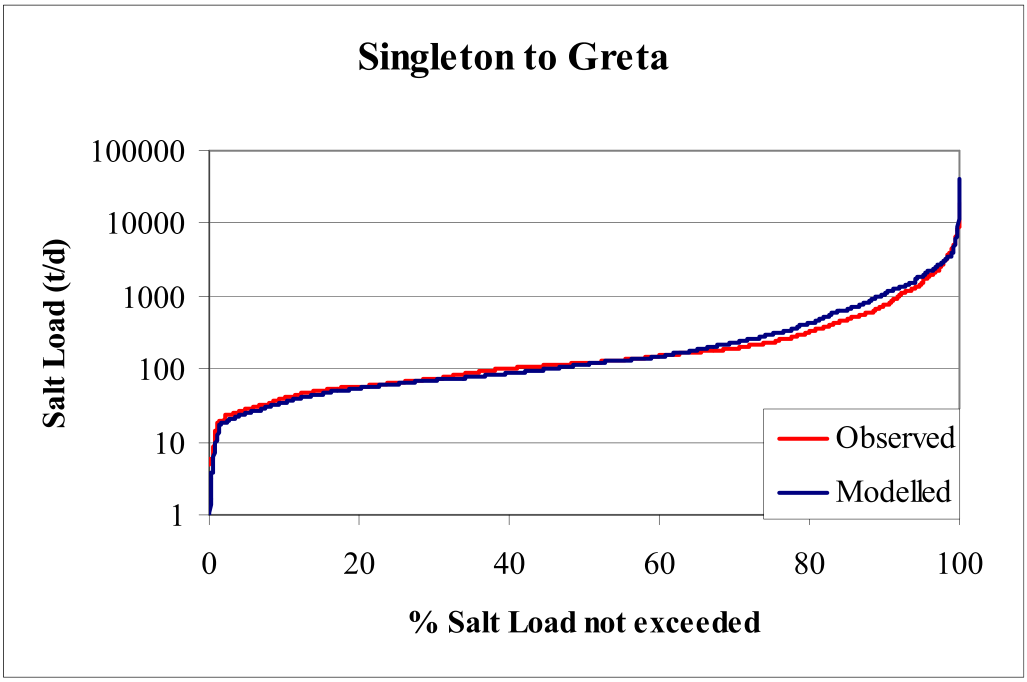


Figure 28. IQQM Reach by Reach Salt Load Calibration for the Hunter River from Singleton to Greta, 9/1995 to 1998

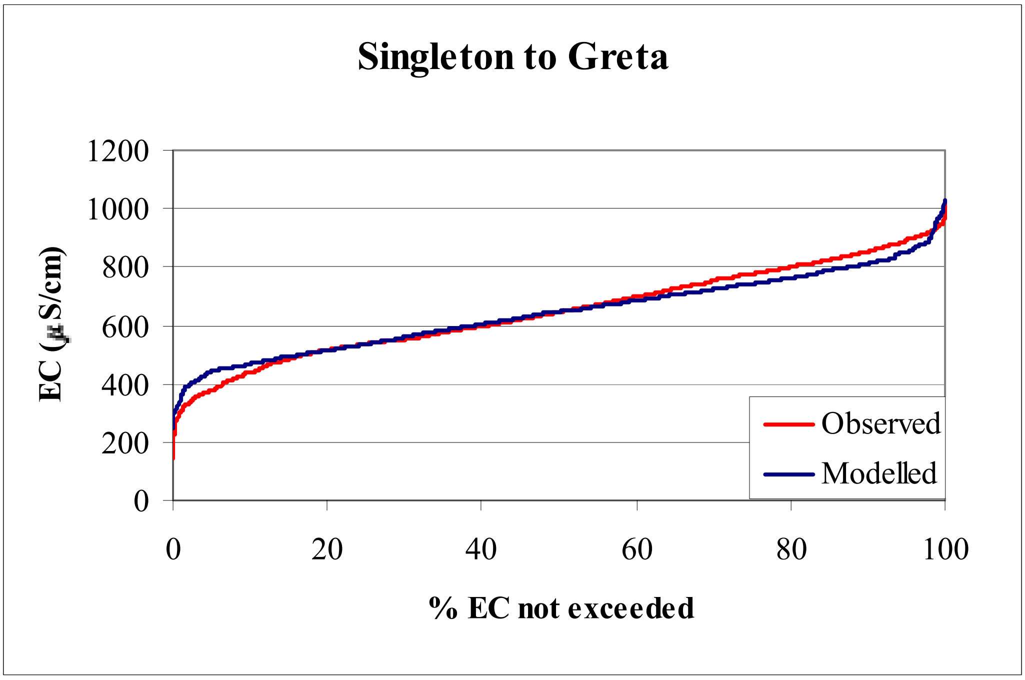


Figure 29. IQQM Reach by Reach Salinity Calibration for the Hunter River from Singleton to Greta, 9/1995 to 1998

Data quality issues limit the usefulness of the Greta salinity probe (210064). Continuous salinity data for the period 1993 to September 1995 was discarded from the analysis due to data quality considerations. Therefore, the period September 1995 to 1998 was chosen for calibration of this reach.

The reach of the Hunter River from Singleton to Greta includes contributions from Black Creek and Residual catchment F only. No constant groundwater loading was added to the mainstream in this river section. Observed flows for Singleton are slightly less than those for Greta for large events, although events less than 600 $ML.d^{-1}$ at Singleton are reduced by approximately 15 per cent, by the time they reach the Greta gauge. The tributary contributions are not significant compared to the flow in the mainstream, and so simulated salinities at Greta are similar to those modelled for Singleton. The plots of salt load and salinity distributions for modelled versus observed in Figures 28 and 29, are similar to those for the Liddell to Singleton calibration.

C H A P T E R N I N E

'CURRENT' AND PREDICTED FUTURE SALT LOAD AND SALINITY

9.1 'CURRENT' AND PREDICTED SALT LOADS

Salt from the potential groundwater flux at future target dates was added to that already observed in-stream for each tributary and contributing residual area. These additional inputs were routed using the Hunter IQQM to establish the salt load and flow relationships for the future scenarios determined by the potential groundwater salt load analysis. Values of potential salt load from groundwater sources estimated for 'current' conditions (that is at 2000), were assumed to already be accounted for within the calibrated in-stream salt balance. Only the predicted increment of new salt between 2000 and the target date was incorporated as additional salt load.

'Current' conditions for the in-stream analysis was defined in section 4.4.

9.1.1 Mainstream

Average annual salt loads for 'current' conditions and at target dates at major locations on the Hunter River mainstream are reported in Table 19 (note: all values are rounded to the nearest 500 t). Glennies Creek at Falbrook is included in the table as it is considered to be a primary indicator location representing the health of the regulated system. The two methods of salt addition used are discussed in section 4.4.5.

	Annual mean salt load (t per year)									
	Annual 'current' conditions		Future case using current distribution				Future case using constant daily loading			
Mainstream	**Flow (ML per year)**	**Salt load (t per year)**	**2010**	**2020**	**2050**	**2100**	**2010**	**2020**	**2050**	**2100**
Muswellbrook	262,500	67,500	70,000	71,500	73,500	74,500	70,000	71,000	73,000	73,500
Denman	239,000	65,500	68,000	69,500	71,500	72,500	67,500	69,000	71,000	72,000
Liddell	385,000	105,500	108,000	110,000	115,000	117,500	107,500	109,500	113,500	116,000
Glennies Crk at Falbrook	52,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000
Singleton	601,500	149,500	152,000	154,500	159,000	162,000	152,000	153,500	157,500	159,500
Greta	688,500	166,500	169,500	171,500	176,000	178,500	169,000	170,500	174,000	176,000

Table 19. Predicted in-stream average annual salt loads for indicative locations within the regulated river system

The average annual predicted salt load per unit area of catchment is presented in Table 20. Salt load per unit area of contributing catchment generally decreases progressively downstream. This pattern is consistent with rivers in the MDB and the values are also similar. Although this is primarily a result of differing scales i.e. area increases more rapidly downstream than salt load (salt load increases 246% from Muswellbrook to Greta and area increases 444%), it also emphasises the combined effect of the tributaries and extraction.

There is little apparent difference in the calculated salt load between the methods of salt addition. The method, although having little effect on the salt load calculation, does result in significant differences in EC distribution.

River regulation has a significant impact on the source of water in the mainstream at any time. Fresh releases from the dams affect the salt load to some extent but have a much more profound effect on stream salinity.

The calculated current salt loads per unit area for mainstream locations are generally much less than those reported by Creelman (1994) and Bembric (1993). Annual salt yield estimated by Bembric (1993) for the Hunter River at Muswellbrook, Singleton and Liddell was 26, 18 and 25 $t.km^{-2}$ a year. Creelman estimated that 6 $t.km^{-2}$ a year was the result of oceanic cyclic salt at Muswellbrook and 12 $t.km^{-2}$ a year was contributed by rainfall in Glennies Creek. Salt loads under current conditions calculated for the mainstream and tributaries in this study are generally lower than estimates made by Croft and Associates (1983). The differences between the previous estimates and those presented here are mainly due to methodology and differences in data availability. Calibration of the model used in this study has been shown to be accurate in section 8 of this report. Although these estimates are more conservative than those of the earlier studies, these loads represent the 'current' conditions as defined in section 4.4 which simulates the behaviour of the river system for the 1975 to 1998 climatic period, had the 2000 flow management rules applied. The imposition of the 2000 flow rules ensures that the predictions are also based on the latest management rules.

		Average Annual River load ($t.km^{-2}$ per year)								
	Area		Future case using the current distribution				Future case using constant daily loading			
Mainstream	(km^2)	'Current'	2010	2020	2050	2100	2010	2020	2050	2100
Muswellbrook	4003	16.9	17.5	17.9	18.4	18.6	17.5	17.7	18.2	18.4
Denman	4310	15.2	15.8	16.1	16.6	16.8	15.7	16.0	16.5	16.7
Liddell	13338	7.9	8.1	8.2	8.6	8.8	8.1	8.2	8.5	8.7
Glennies Ck at Falbrook	445	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0
Singleton	16468	9.1	9.2	9.4	9.7	9.8	9.2	9.3	9.6	9.7
Greta	17786	9.4	9.5	9.6	9.9	10.0	9.5	9.6	9.8	9.9

Table 20. Predicted in-stream salt load per unit area of catchment for indicative locations within the regulated river system

9.1.2 Tributaries and residual catchments

The estimated current annual salt load and annual flow for the tributaries and residual catchments together with the predicted additional annual salt load at the target dates are listed in Table 21. Both salt load and flow vary considerably between sub-catchments. In general annual salt load exports from sub-catchments increase with flow. However, sub-catchments with similar flow may vary by more than 100% differences in salt load. Geology, topography, climate and salt in rainfall are the major factors likely to explain these differences.

Table 22 lists the estimates of annual salt load by unit area for the tributaries and residual catchments for current conditions and at the predicted target dates.

		Annual mean salt load (t per year)				
			Annual additional salt load (t per year)			
Tributary	**Annual flow**	**Current**	**2010**	**2020**	**2050**	**2100**
Glenbawn Dam	103,500	22050	680	1070	1370	1380
Rouchel Brook	52,000	12200	390	610	770	770
Pages River	84,000	23750	690	1050	1550	1710
Dart Brook	31,000	7700	480	990	1990	2530
Residual u/s Muswellbrook	50,000	13100	560	870	1440	1660
Residual u/s Denman	3,000	1550	250	530	980	1240
Residual u/s Liddell	43,000	13050	280	650	1390	1830
Wybong Creek	25,000	8900	70	230	590	850
Goulburn River	150,500	50600	860	1910	4470	6330
Martindale Creek	20,500	2300	30	40	70	110
Doyles Creek	10,000	1150	20	30	50	70
Foy Brook	17,000	5500	40	50	90	110
Glennies Ck Dam	25,000	4200	110	110	230	300
Residual u/s Falbrook	34,500	8000	70	80	150	190
Wollombi	107,000	20600	130	190	310	390
Residual u/s Singleton	68,000	11150	180	280	430	520
Black Creek	24,000	12300	10	30	50	50
Residual u/s Greta	87,000	13500	80	120	200	230

Table 21. Average annual salt load and flow for Hunter River tributaries and residual catchments for ‘current’ conditions and predicted additional salt load from dryland salinity processes at 2010, 2020, 2050 and 2100

u/s upstream

	Area (km^2)	Annual total salt load ($t.km^{-2}$ per year)					
Tributary		**Current**	**2010**	**2020**	**2050**	**2100**	**%Zero Flow**
Glenbawn Dam	1293	17.1	17.6	17.9	18.1	18.1	0
Rouchel Brook	404	30.2	31.1	31.7	32.1	32.1	10
Pages River	761	31.2	32.1	32.6	33.2	33.4	6
Dart Brook	788	9.8	10.4	11.0	12.3	13.0	26
Residual u/s Muswellbrook	458	28.6	29.8	30.5	31.8	32.2	4
Residual u/s Denman	307	5.0	5.8	6.7	8.2	9.0	60
Residual u/s Liddell	985	13.2	13.5	13.9	14.6	15.1	0
Wybong Creek	667	13.3	13.4	13.7	14.2	14.6	13
Goulburn River	6817	7.4	7.5	7.7	8.1	8.4	3
Martindale Creek	359	6.4	6.5	6.5	6.6	6.7	30
Doyles Creek	201	5.7	5.8	5.8	5.9	6.1	51
Foy Brook	183	30.0	30.3	30.3	30.5	30.6	42
Glennies Ck Dam	226	18.6	19.1	19.1	19.6	19.9	0
Residual u/s Falbrook	218	36.5	36.8	36.9	37.2	37.4	12
Wollombi	1682	12.2	12.3	12.4	12.4	12.5	24
Residual u/s Singleton	733	15.2	15.5	15.6	15.8	15.9	15
Black Creek	201	61.3	61.4	61.5	61.6	61.6	13
Residual u/s Greta	1117	12.1	12.1	12.2	12.3	12.3	4

Table 22. Catchment area, current and predicted salt loads per unit area and percentage zero flow for Hunter River Tributaries and Residual Catchments

u/s upstream

9.2 'CURRENT' AND PREDICTED SALINITIES

9.2.1 Mainstream

Salinity in the mainstream river at any point in time is determined by the amount of flow and the source area contributing. That is, rainfall, runoff characteristics, salt stores, and distance to the mainstream, are not distributed evenly over the whole catchment, and thus tributaries vary in their contribution and timing with each event. In addition, significant groundwater influx occurs in specific reaches where the river intersects major fault lines. These influxes have been accounted for as point source daily load inputs in the calibrated IQQM. During lower flows, that is when median to higher ECs are experienced, these influxes are the dominant influence on the salinity in the mainstream although small dam releases may moderate this. During flow events salinity in the mainstream is dominated by wash off from the tributaries. Which sub-catchment is contributing influx and when it is contributing, is significant. However, even in major events the significance of influx from any particular sub-catchment to the mainstream salinity reduces progressively downstream, because there are so many contributing sub-catchments.

These mainstream groundwater fault zone interactions have not been modelled explicitly in this study. It was assumed that these systems would remain in a stable equilibrium condition throughout the prediction period. Therefore, the shifts in salinity reported for this study are due to the contributions made by the impact of dryland salinity processes operating in the tributaries. However, it is far from certain that the groundwater fault zone contribution will remain constant. In fact, they would be likely to show some seasonal and climatic responses regardless of whether there is any trend. If rising groundwater levels throughout the catchment substantially increase salt contributions from major fault zones, there could be some very definite changes in mainstream salinities as a consequence.

Salinity trends in the mainstream are summarised in Table 23. An increase of 10 $\mu S.cm^{-1}$ at 2010 is predicted at Greta for both the median and 80th percentile salinity rising to an increase of 40 $\mu S.cm^{-1}$ at (current distribution case). This represents only a 6% change over 100 years.

		Median and 80th percentile salinity ($\mu S.cm^{-1}$)									
Location	**Percentile**	**Future case using current distribution**					**Future case using constant daily loading**				
		2000	**2010**	**2020**	**2050**	**2100**	**2000**	**2010**	**2020**	**2050**	**2100**
Muswellbrook	50th	485	500	510	520	525	490	515	530	560	575
	80th	625	640	655	670	675	625	660	695	745	765
Denman	50th	565	580	590	605	615	565	590	615	650	665
	80th	775	795	810	830	840	775	810	850	915	940
Liddell	50th	720	730	745	765	780	715	740	775	845	885
	80th	940	960	975	1005	1025	940	965	1020	1125	1195
Glennies Ck at Falbrook	50th	445	450	450	455	455	445	450	450	455	460
	80th	570	575	575	585	585	570	590	590	605	610
Singleton	50th	670	680	685	705	715	665	680	695	730	750
	80th	925	935	945	970	980	920	930	960	1025	1065
Greta	50th	670	680	685	700	710	665	675	690	725	740
	80th	905	915	925	945	955	905	910	935	995	1035

Table 23. Summary of stream salinity statistics for mainstream locations on the Hunter River

9.2.2 Tributaries

Salinity levels vary between tributaries and do not necessarily correspond directly with salt load per unit area. That is, ranking catchments according to salt load and salinity will result in a different order. Rouchel Brook, Pages River and Foy Brook all generate similar salt load per unit area, 30.2, 31 and 30 $t.km^{-2}$ a year under current conditions, but they have corresponding median salinities of 470, 610 and 1870 $\mu S.cm^{-1}$ respectively. Dart Brook and Wybong Creek have similar median salinities of 1455 and 1465 µS.cm^{-1} but quite different salt export rates of 9.8 and 13.3 t.km^{-2} a year respectively. This anomaly makes it difficult to rank tributaries and to prioritise remedial strategies across catchments.

Tributary	Percentile	Median and 80th Percentile Salinity (µS.cm^{-1})				
	Date	2000	2010	2020	2050	2100
Goulburn River	50th	995	1015	1035	1085	1120
	80th	1375	1400	1430	1500	1550
Rouchel Brook	50th	470	485	495	500	500
	80th	650	675	685	695	695
Pages River	50th	610	630	640	650	655
	80th	765	790	800	815	820
Dart Brook	50th	1455	1545	1640	1825	1930
	80th	3915	4155	4415	4920	5190
Wollombi Creek	50th	705	710	715	715	720
	80th	1295	1300	1305	1315	1320
Wybong Creek	50th	1465	1480	1505	1565	1610
	80th	2460	2480	2525	2625	2695
Martindale Creek	50th	495	500	505	510	520
	80th	1815	1835	1845	1870	1895
Foy Brook	50th	1870	1885	1885	1900	1905
	80th	3370	3395	3400	3425	3440
Black Creek	50th	1220	1220	1220	1225	1225
	80th	1790	1790	1790	1795	1795

Table 24. Summary of in-stream salinity statistics for tributaries

Although the groundwater analysis was undertaken on a majority of sub-catchments and extrapolated to all within the basin, it was necessary to combine data for sub-catchments, for the surface water analysis. In particular the Goulburn River system could only be analysed at the gauging station at Sandy Hollow representing the downstream outcome of processes operating in the twelve sub-catchments upstream. Average annual flow from the Goulburn River at Sandy Hollow is 150500 ML a year, or approximately 40% of the flow in the Hunter River at Liddell. It currently exports 50,600 t of salt annually at a median salinity of 995 µS.cm^{-1}, and an 80th percentile salinity of 1375 µS.cm^{-1}. This salinity concentration is significantly higher than for the Hunter River at Denman, and is a significant determinant of the higher salinity at Liddell. The estimated trend in salinity for the Goulburn River, represents a 12.5% increase in median and 12.7% increase in 80th percentile salinity, from a 12.5 % increase in annual salt load over the 100-year prediction time frame.

Reporting salinity distribution values for the tributaries is made difficult by the fact that most experience significant periods of zero flow. Median and 80th percentile salinities have been calculated using the current distribution case. During periods of zero flow salinity values have been held to a maximum value. Therefore the median and 80^{th} percentile values represent the within tributary hazard, but not necessarily the distribution of salinities exported to the mainstream. Rising groundwater pressures are likely to result in increased flow duration mainly by increasing base flows with corresponding increases in high salinity flows.

Median and 80^{th} percentile salinities are listed for the tributaries for the target dates in Table 24. Values for Doyles Creek have not been included as flow occurs less than 50% of the time, and both the median and 80^{th} percentile would simply reflect a maximum salinity. Salinity values are not applicable for residual catchments as their salt loads are factored in to salinities reported for the mainstream reaches.

Salinity percentiles are not reported for tributaries for the future scenario where a constant load is added. Salinities obtained would simply be an artefact of the method. There is insufficient information to assume a 'groundwater addition scenario' for tributaries in contrast to the ‘salt wash-off scenario’.

CHAPTER TEN

DISCUSSION

10.1 STRENGTHS AND WEAKNESSES OF THE STUDY

The method used by Beale et al. 2000 in the Murray Darling Basin has been modified for the Hunter analysis.

Two methods of transferring the salt were used, a simple addition of a constant daily loading for each tributary and contributing sub-catchment, and a more complex matching of the salt delivery to the flow and salt load distribution currently observed in-stream. The choice of method had only a small impact on the calculated in-stream salt load in the Hunter mainstream, but made a considerable difference to the predicted distribution of the salinity. The latter method results in slightly higher estimates of salt load export, but returns lower median and 80th percentile salinities. Although the latter method is considered to give a more realistic result, the former constant loading method is also reported as a possible worst-case scenario.

10.1.1 Conceptual framework

The results of this study are predicated on a conceptual model that assumes that groundwater can and will continue to rise at a linear rate indefinitely. Although the area through which it can flow, and therefore the volume of flow, has been constricted by the topographic analysis, this assumption is a purely statistical projection. It is unlikely, from a process point of view.

The topographic constriction although entirely justified, when coupled with the rates of rise governing the proportion of the contributing area ensures that an ultimate steady state must eventually be reached. There is no reason to believe that a new steady state equilibrium resulting from higher recharge rates associated with land use change will match that enforced by this method. None-the-less a new equilibrium could be expected. Therefore, the study is best viewed as a scenario. Confidence in the realism of the scenario is probably acceptable in the short term, but perhaps dubious for longer-term predictions.

10.1.2 Data limitations and factors not considered

■ Data scarcity

The rates of rise governing the predictions of potential salt load contributed by groundwater to the land surface have been assessed from a very small number of bores in relation to the area they are used to represent. They tend to be clustered rather than evenly spaced across the landscape. They have been extrapolated uniformly across all sub-catchments by association with geology, despite the fact that catchments vary in land use, vegetation and climate—and therefore in recharge and discharge potential. For example Widden Brook and Martindale Creek are almost completely contained within a National Park, and therefore are unlikely to be affected by anthropogenic salinity. Both are treated in the same as any other tributary.

For most bores, assessed rates of rise were calculated from two to three points over time. It is likely that rates of rise or fall will depend on the period in which the first reading was taken, together with the climatic sequence that followed. For example, if the first reading was taken during a particularly dry climatic sequence where bore levels were generally low, a greater level of change could be indicated than if the initial reading was obtained during a wet climatic period.

Data scarcity also affected the ability to model surface water relationships. Spot sample EC data was often infrequent, and where continuous data existed for the tributaries it was only available for a short period of time.

In the Goulburn River system there was insufficient flow data from the tributaries to model the salt loads. Rainfall runoff modelling using the Sacramento model was attempted with the aim of producing simulated flows for the whole 1975 to 1998 period. This exercise had to be abandoned, as insufficient accurate flow data was available to calibrate the model.

Modelling for Wollombi Brook was a very rough first cut. The quality of gauged flow data at the outlet is extremely low, so flows were estimated using a Sacramento simulation at Bulga. Observed EC at the catchment outlet gauge was still used, though the quality of the data is hard to assess. Anecdotally, the system has a significant groundwater store that is flushed out during large flow events. This is a significant process that couldn't be modelled explicitly.

■ Measurement accuracy

Salinity values reported here have been rounded to the nearest five ECs to enable the trends to be clearly perceived relative to the benchmark 'current' conditions. They are not accurate to this level, in the sense that the original observed data is not accurate to this level. The Hunter IQQM has been calibrated to observed data measured using continuous flow and EC meters. These meters typically have a measurement accuracy of plus or minus one per cent of the measurement range. For a meter with a zero to 5000 EC measurement range this represents an accuracy of plus or minus 50 ECs. However, the observed data has been quality checked and accepted as it is for use in this study, and the values reported do not present a problem for interpreting the trends or accepting the appropriate benchmarks for use in target setting for the salinity strategy. Rather, problems may arise following the setting of catchment targets, as the outcomes are monitored using this same technology. Stringent adherence to the department’s calibration, maintenance and monitoring protocols must ensure the highest possible quality assurance continuing into the future.

■ Groundwater influx from fault lines intersecting the stream

Significant groundwater influx occurs in specific reaches where the river intersects major fault lines. These influxes have been accounted for as point source daily load inputs in the calibrated IQQM. During lower flows, that is when median to higher ECs are experienced, these groundwater fault zone interactions are the dominant influence on the salinity in the mainstream. Dam releases have a dilution effect. During flow events induced by rainfall, salinity in the mainstream is dominated by wash off from the tributaries. Which sub-catchment is contributing influx and when it is contributing, is significant. However, even in major events the significance of influx from any particular sub-catchment to the mainstream salinity reduces progressively downstream, because there are so many contributing sub-catchments.

These mainstream groundwater fault zone interactions have not been modelled explicitly in this study. It was assumed that these systems would remain in a stable equilibrium condition throughout the prediction period. Therefore, the shifts in salinity reported for this study are due to the contributions made by the impact of the dryland salinity scenario operating in the tributaries. However, it is far from certain that the groundwater fault zone contribution will remain constant. In fact, they would be likely to show some seasonal and climatic responses regardless of whether there is any trend. If rising groundwater levels throughout the catchment substantially increase salt contributions from major fault zones there could be some very definite changes in mainstream salinities as a consequence.

■ Groundwater flow system response

Coram et al. (2000) have coarsely mapped the groundwater flow systems for the whole of Australia. The Hunter is primarily mapped as local flow systems or mixed local and intermediate flow systems. Local flow systems are generally defined as shallow with a flow length of 1−3 km with recharge and discharge occurring in close proximity. These systems can be expected to relatively quickly establish a new equilibrium following a shift in recharge due to landuse change.

'Local flow systems respond rapidly to increased groundwater recharge. Water tables rise rapidly and saline discharge typically occurs within 20–30 years of agricultural development. These systems can also respond relatively rapidly to salinity management practices, and afford opportunities for dryland salinity mitigation through alternative land management practices.

Intermediate flow systems have a greater storage capacity and permeability than local systems and take longer to 'fill' in response to increased recharge. Saline discharge typically occurs within 50 to 100 years after agricultural development. The extent and responsiveness of these groundwater systems offer much greater challenges for dryland salinity control.' Coram et al. 2000. The fault zone systems discussed above are likely to be fed by these systems

The major landuse changes usually associated with dryland salinity processes occurred in some cases more than a century ago. Anecdotally, the current extent of perennial forest type vegetation in parts of the Hunter Valley is now greater than it was a century ago. Therefore it is likely, given the nature of the flow systems, that a new dynamic equilibrium between land use and the water balance has been established already. This may be true overall, but will vary from one sub-catchment to another.

■ Recharge potential

Rainfall and evapotranspiration are by far the largest terms in the annual water balance. Excess rainfall that is not accounted for by evapotranspiration is available to become both runoff and recharge. The amount of water draining below the root zone which exceeds the catchment stream capacity to discharge as base flow or interflow contributes to the filling of the groundwater store and rising water tables. Zhang et al. (1999) developed two empirical relationships to describe the potential excess rainfall or non-transpired water for forested and cleared catchments varying in annual rainfall for southern Australia on the assumption that the most important influence on the amount of evapotranspiration, and hence excess water is the vegetation type. Figure 30 compares the potential runoff calculated using the Zhang curves, with the gauged runoff from tributaries in the Hunter Valley observed during 1975 to 1998.

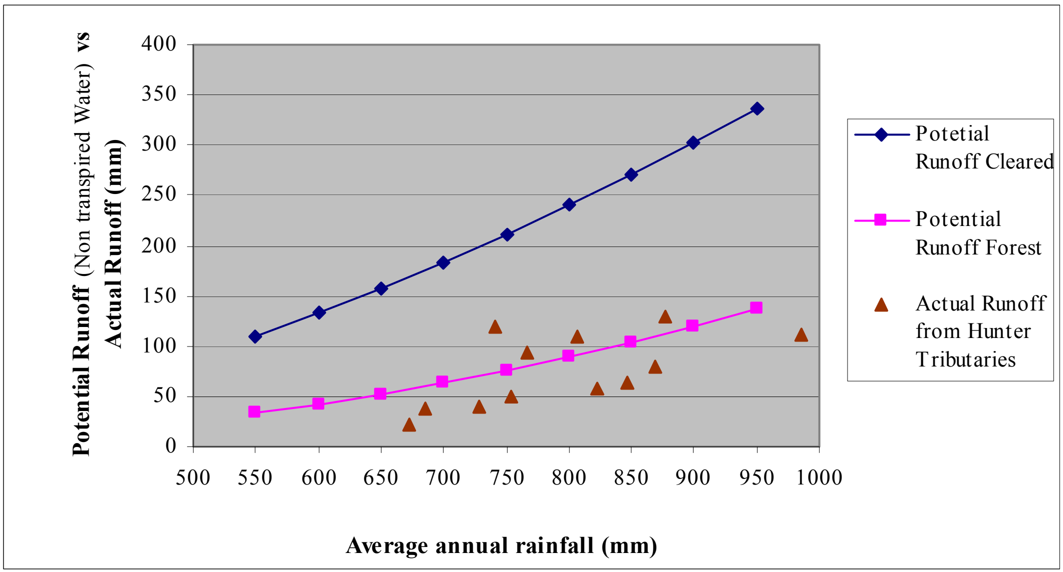


Figure 30. Comparison of actual depth of runoff vs annual rainfall from Hunter River tributaries, and theoretical potential runoff for cleared and forested catchments from Zhang et al. (1999)

Pan evaporation varies across the basin from 1600 mm a year at Scone to 1650 mm a year at Patterson. The theoretical, evapotranspiration utilises from 65% to 80% of the rainfall for cleared catchments increasing in efficiency with lower rainfall, and 85% to 95% for forest. However, this represents less than 50% of pan evaporation. Potential evapotranspiration in the Hunter Catchment is, therefore, likely to be limited more by rainfall than by evaporative demand.

As only three of these catchmernts are essentially forested, (>80% trees) several factors could be at work which may explain why all catchments appear to produce runoff amounts similar to the theoretical forested potential runoff :

1. Non-transpired water exceeds the discharge capacity of the stream, and is currently contributing to rising water tables. That is, the actual non-transpired water may be greater than that indicated by just the runoff. Soil types can significantly affect the proportion of non-transpired water entering the groundwater system rather than contributing to runoff.
2. Sufficient area is forested within these catchments to significantly impact the runoff.
3. Actual evapotranspiration is higher than the theoretical potential described by the Zhang curves in the Hunter. That is, the Zhang curves are not valid for the Hunter.
4. Surface water pumping may be significantly affecting annual flow volumes from these catchments.
5. Significant groundwater outflow is occurring in sandy streambeds, which is not recorded in the surface runoff data.
6. There is a scale issue. That is, flow is proportional to area, and therefore depth of runoff integrated over a larger area is diminished. This is the case in the Goulburn River, which is six times larger than any other tributary. It is likely that individual tributaries within the Goulburn system produce greater depth of runoff than the 22 mm indicated here.

Cornish (1993) measured increases in water yield of 150 to 250 mm from small, forested catchments near Karuah following partial clearing. The catchments were less than 1 km^2 in area with 1450 to 1750 mm average rainfall, and the extent of clearing varied between 29 and 79% of each catchment. The potential runoff difference calculated using the Zhang formula for full clearing is 330–400 mm for this annual rainfall range. 79% of this range is 260–316 mm. Cornish concluded that evapotranspiration from fully forested catchments in this area lay in the range of 1060–1300 mm, and was strongly influenced by aspect and elevation. The Zhang model suggests a range of 1075–1190 mm. Therefore the Zhang model provides reasonable bounds for assessing evapotranspiration efficiency in the Hunter catchments; allowing for the possibility that non-evaporated rainfall over and above the catchment runoff becomes recharge, and is potentially filling a groundwater store.

'The infrastructure currently in place along most unregulated rivers does not impact on medium and high stream flows. Generally, it is only at low flows that significant extraction occurs.' DLWC (2000). Low flows, even without pumping, are unlikely to account for more than 25% of total annual flow. An additional 20% runoff would not significantly shift the total catchment runoff from the forested potential line. Therefore, over exploitation of the surface water resource is not likely to be the sole reason for low runoff from these catchments.

The proportion of mapped landuse in the tributaries is shown in Table 25.

	Crop (%)	**Grassland (%)**	**Trees (%)**
Black Creek	0	47	34
Dart Brook	8	74	16
Doyles Creek	0	5	95
Foy Brook	0	94	3
Glennies Creek	0	48	42
Goulburn River	9	42	48
Martindale Creek	1	6	93
Pages River	4	89	6
Rouchel Brook	0	78	22
Upper Glenbawn	3	78	17
Wollombi Brook	1	18	80
Wybong Creek	10	74	16

Table 25. Summary of landuse as a proportion of tributary catchments

If the Zhang curves are accepted then it appears likely that a considerable proportion of the theoretical potential non-transpired water has been available to contribute to the filling of groundwater systems during the base period of this investigation. Although not definitive, this lends qualified support to the basic assumption of this audit that rising groundwater trends can be extrapolated predictively.

At face value Foy Brook (93 mm), Pages River (110 mm), and Black Creek (119 mm) are likely to offer the greatest scope for manipulation of the water balance through vegetation change.

10.2 GEOLOGY AND CYCLIC SALT AS A DETERMINANT OF SALT SOURCE IN OBSERVED STREAM FLOW

Although geology was specifically used as a basis for predicting future salt loads from groundwater in this study, the role of geology as a determinant of the salt load observed in-stream from 1975−1995 was not. That is, the source of that proportion to the salt load already observed in river flows has not been identified with any particular geology or combination of geologies. Several authors have estimated salt loads associated with geology in the Hunter Catchment (Creelman 1994, Bembric 1993 and Kellet et al. 1989). Values reported by Creelman (1994) are listed in Table 26. They do not necessarily correspond well with the values used in the predictive component of this study (see Table 25) or with in-stream salt loads calculated in this study for the 1975−1998 period per unit area of the Hunter River tributaries. That is, these authors assume that geology and cyclic salt input determine the salinity hazard for sub-catchments in the Hunter Catchment. This is not supported by the analysis in this study. That is, tributaries with very little Permian geology (high hazard geology), such as Rouchel Brook, can have high (30 $t.km^{-2}$ a year) salt export rates.

Geology	Annual salt release ($t.km^{-2}$ per year)
Triassic	5
Carboniferous, metavolcanics and glacial sediment	4–5
Wollombi Coal Measures (Late Permian)	4–5
Greta Coal Measures (Early Permian)	30
Whittingham Coal Measures (Late Permian)	40

Table 26. Predicted salt releases from various rock types in the Hunter Valley from Creelman (1994)

Values of potential salt load per unit of discharge area calculated from groundwater rates of rise, specific yields, and salinity vary between province and geology. Table 27, shows the values used in the predictive component of this study. Interestingly, they tend to be the reverse of the values reported by Creelman. Note, however, that these loads are calculated only for the portion of the catchment that is estimated to be the discharge area. Values for current salt loads are calculated per unit area of the whole catchment. Creelman (1994) obtained his estimates by adjusting values reported by Bembric (1993) for the influence of cyclic salt. Bembric had previously made his estimates from stream flow data.

Cyclic salt is a significant input to the Hunter salt balance varying from approximately 4 $t.km^{-2}$ a year in the west to 30 $t.km^{-2}$ a year on the coastal fringe. In the Hunter Catchment below Singleton cyclic salt varies between 10 to 15 $t.km^{-2}$ a year.

Geology	Quaternary alluvium			Tertiary volcanic	Triassic sedimentary			L. Permian sedimentary			E. Permian sedimentary		Carboniferous sedimentary		
Province	C	W	SE	All	C	W	SE	C	W	SE	C	SE	N	W	SE
Annual salt discharge ($t.km^{-2}$ per year)	22.9	4	0	1.8	31	15.4	5.2	22.6	10.8	11.8	5.7	4.3	23.5	7.8	23.5

Table 27. Potential salt load per unit area of discharge by geology and province

A brief analysis of the influence of topography as one of a number of additional factors that may influence the salinity hazard associated with geology was made with a view to finding criteria by which catchments may be ranked for management intervention. The source of the variation found in this study between tributaries was examined by comparing the annual in-stream unit area salt load for 1975–1998, adjusted for cyclic salt input, with the proportion of the catchment area occupied by each geology within the calculated FLAG wetness index. Although this analysis found a demonstrable relationship between topography, geology and increasing salt load adjusted for cyclic salt for both the Early Permian Sediments and the Carboniferous and Devonian Sediments, there was no apparent relationship with the remaining geologies. The result shown in Figure 31 is speculative given the very coarse scale of the geology mapping used, and the coarse estimates of cyclic salt inputs. Cyclic salt inputs were estimated from material published in Creelman (1994).

The relationship does, however, suggest that the Carboniferous and Devonian sediments are a lesser source of salt than the early Permian, only associated with large salt load where the corresponding wetness index is high. That is, hazard associated with topography significantly interacts with the hazard associated with geology. Therefore, a low topographic hazard combined with a high geological hazard, results in high salt loads; and a high topographic hazard combined with a low geological hazard, also results in high salt loads.

The same catchment salt loads adjusted for cyclic salt compared with the proportion of the catchment area occupied by a geology independent of topography appeared to behave randomly. However, early Permian sediments occupy 98% of Black Creek which has the highest observed unit salt load adjusted for cyclic salt (50 $t.km^{-2}$ a year).

When distinguishing between catchments on the basis of salinity hazard, additional factors such as topography should be used. Geology by itself may not be a sufficiently good predictor. The use of the FLAG wetness index has been helpful in this context.

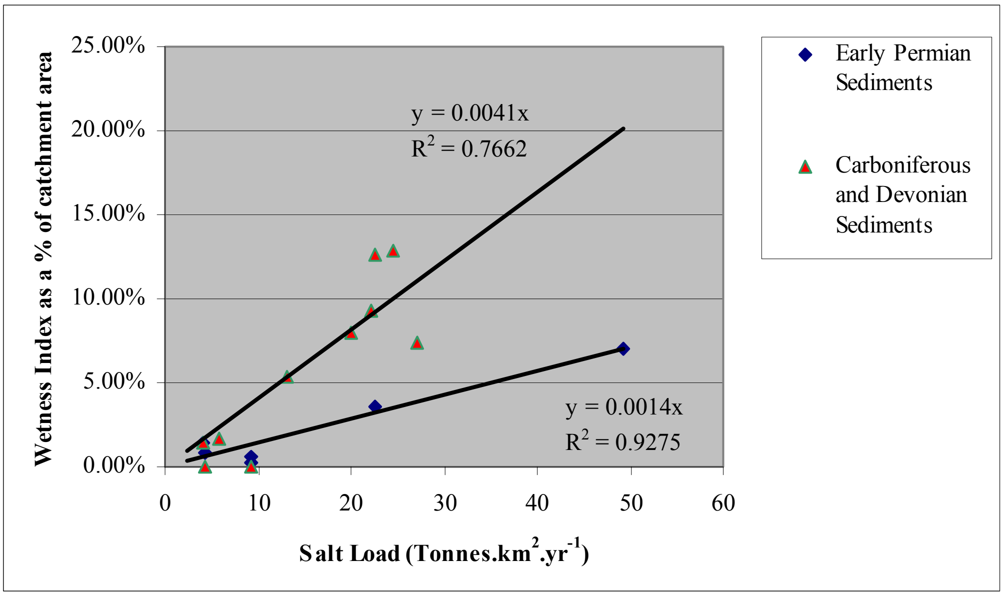


Figure 31. Speculative relationship between geology, topography and increasing salt load per unit area adjusted for cyclic salt input for Hunter River Tributaries and Residual catchments under current conditions

10.3 ZERO FLOWS

Reporting salinity distribution values for the tributaries is made difficult by the fact that most experience significant periods of zero flow. Median and 80th percentile salinities have been calculated using the current distribution case (note: constant loading case was only assessed for the mainstream). During periods of zero flow salinity values have been set to a maximum observed value. Therefore, the median and 80th percentile values, which are necessarily sensitive to this value, represent the hazard within tributaries; but not necessarily the distribution of salinities exported to the mainstream. During zero flow periods where water users continue to pump from pools, salinity values are likely to be much worse than the values reported here due to increasing concentration with evaporation. The tributaries vary in the degree to which they are ephemeral. The Goulburn River at Sandy Hollow only experiences zero flows for 3% of the time, whilst Rouchel Brook, the Pages River, Black Creek and Wybong Creek experience zero flows for 10%, 6%, 13% and 13% of the time respectively. Dart Brook, Martindale Creek and Wollombi Creeks have zero flow for 26%, 30% and 24% of the time respectively, whilst no flow was recorded in Foy Brook and Doyles Creek for 42% and 51% of the record period 1975 to 1998. Rising groundwater pressures are likely to result in increased flow duration mainly by increasing base flows with corresponding increases in high salinity flows.

CHAPTER ELEVEN

CONCLUSIONS AND RECOMMENDATIONS

The historic data for the Hunter Valley from 1975 to 1999 show evidence of a background rising trend in groundwater pressures across geologies, and the catchment as a whole. Although the number of bores analysed is small in proportion to the area of the whole catchment, rising trends that were identified previously were confirmed by further fieldwork in the course of this study.

The analysis of stream salinity trends for ten gauged locations across the catchment does not on the whole indicate a worsening stream salinity problem in the Hunter Catchment. Analysis of trends within the stream salinity data for the base assessment period is confounded by the paucity of data and the very significant changes imposed on the catchment hydrology by development. No firm conclusion regarding positive, negative or nil trends in the historic stream salinity data can be made with confidence. Recent rising trends in the upper Hunter River at Muswellbrook may support a link with rising water tables; whilst falling trends at Liddell and Greta may be the result of several factors.

For example, the following factors may play a part:

- falling groundwater trends in alluvial aquifers in the lower catchment
- changes to river regulation following the commissioning of the Glennies Creek Dam
- the effect of the introduction of the Hunter River Salinity Trading Scheme (HRSTS).

DLWC (2000) in the State of the Rivers Report show rising trends in the Hunter River at Singleton for the period 1970 to 1979 and falling trends from 1980 to 1998. Falling trends in the Goulburn River at Sandy Hollow are at odds with rising water tables in the catchment but may be influenced by groundwater pumping in the alluvial aquifers.

Assuming that rising groundwater trends will lead to increased stream salinity, this study has undertaken to quantify the likely impact of increased salt export from groundwater on stream salinity in the Hunter River and its tributaries to the nominal end of system at Greta. Salt load and salinity predictions have been calculated for the target dates 2010, 2020, 2050 and 2100.

The audit analysis of 'current' conditions reveals the pattern of observed contributions by the tributaries to the salinity of the catchment as a whole. A predictive scenario for future conditions is then examined. There are limitations on this scenario. The evidence for its likelihood is concrete, but the size of the data set is small compared to the area to which it has been extrapolated. Although landuse change is generally thought of as the cause of rising water tables, no clear link has been established with the groundwater rates of rise examined in this study. The rates of rise have been extrapolated uniformly across all sub-catchments by association with geology; despite the fact that catchments vary in land use, vegetation and climate: and therefore in recharge and discharge potential. For example, Widden Brook and Martindale Creek are almost completely contained within national parks, and therefore are unlikely to be affected by anthropogenic salinity.

■ Conclusions

1. 'Current' salinity levels in the Hunter River catchment are generally higher than for similar sized catchments in the MDB (Beale et al. 2000). Median salinity in the Hunter River at Greta for the period 1975 to 1998 was 670 EC compared to 500 EC for the end of the Namoi River system and 230 EC for the Murrumbidgee River end of system (1975 to 1995).

2. Overall average annual salt load generated per unit area of the catchment at Greta, for the period 1975 to 1998, was comparable to similar sized catchments in the Namoi River and Macquarie Rivers, but somewhat less than for the Lachlan River and Murrumbidgee Rivers during the period 1975 to 1995.
3. Bores analysed in the Hunter Valley exhibit similar changes in groundwater levels to those found in the MDB over similar time frames. Groundwater levels are both rising and falling. The minimum trend for any single bore analysed was negative, -0.255 m a year, in the Hunter Catchment; and was also negative, -1.755 m a year, in the MDB. The maximum trend measured in any single bore was positive, 1.491 m a year, in the Hunter Catchment; and was also positive, 4.92 m a year, in the MDB. Average rates of rise vary between geologies ranging from negative, –0.09 m a year, to positive, 0.197 m a year, in the Hunter Catchment; and from negative, –0.188 m a year, to positive, 1.137 m a year, in the MDB.
4. Groundwater salinities also fall within similar ranges to those observed in the MDB. The average groundwater salinity is 2139 EC in the Hunter Catchment , and 1959 EC for bores used in the MDB audit.
5. The increases in salt load and salinity predicted in this study are explicitly the result of adding groundwater derived salt loads predicted from the trends in the tributaries and residual catchments to the in-stream salt loads under 'current' conditions. Therefore, while it is recognised that river regulation will play a role in mitigating the downstream impacts, management strategies to ameliorate these trends must consider intervention at the source.
6. Extractive water use and river regulation significantly modify both the current pattern of salinity and salt load in the mainstream, as well as the impact of the predicted rises in inputs from the tributaries. Of all the salt mobilised within the catchment above Greta only approximately 60% passes out downstream.
7. Despite the predicted increase in wash off of salt in the tributaries, the most significant factor determining the simulated high salinity conditions in the Hunter River downstream of Muswellbrook into the future is the point source salt load associated with groundwater influx from major fault zones. These influxes have been modelled as a constant daily load. This in itself may add a bias to this effect similar to the difference noted in the two methods of salt wash off simulated for the tributaries. On the other hand, if groundwater pressures continue to rise in future, salt loads from fault zones may also rise. The magnitude of such an impact could be very significant.
8. During the period 1995 to 2000, discharge of salt from the Hunter River Salinity Trading Scheme was approximately 11,000 t a year. This point source pollution is timed so as to minimise the impact on stream salinity. This study predicts that salt loads generated within the catchment above Greta as a result of rising groundwater pressure and dryland salinity processes in the tributary catchments, will reach a similar magnitude by 2020. Although the impact of this additional load on salinity is relatively small; it may restrict the window of opportunity of the HRSTS as it currently stands, and limit expansion of the scheme in future.
9. As mining is further developed in the Hunter Catchment, pressure will increase on the trading scheme as the amount of salt to be discharged increases and the window of opportunity for such disposal shrinks. Although the trends in median and 80^{th} percentile salinities reported in this study are unlikely to shrink that window radically, the amount of salt coming on-stream is set to increase both as new mines are commissioned and old mines are decommissioned. This study

has not accounted for the impact of mine closure and the fate of salt within voids on future salt pollution.

10. Overall, the trends in salinity predicted in the study are not great. In the mainstream, salinity values are predicted to rise by no more than 10% over the next 100 years, for the most likely case. Change predicted in some tributaries will be greater, with a 10%, 13% and 33% change over 100 years predicted for Wybong Creek, the Goulburn River and Dart Brook respectively. Water users across the catchment are already experiencing the management risk implications of the salinity levels identified in the study. Surface water salinity already presents threats to the wine industry, power generation and town water supplies. The trends show a gradual worsening of these current threats.

■ Recommendations

Setting water quality targets at any point along the river is in essence designed to protect assets and values downstream of the target location. A series of within-valley targets and strategies is required to address the problem at source, and to protect within-valley assets. Strategies to address dryland salinity primarily fall into four categories:

1. Vegetation strategies aimed at modifying the water and salt balance in recharge and discharge areas.
2. Engineering solutions such as rehabilitation of incised flow lines, groundwater pumping, storage and disposal similar to the current operation of the Salinity Trading Scheme; and changes to river regulation to maximise the effectiveness of dilution flows.
3. Market mechanisms to expand the scope of environmental trading schemes such as the HRSTS, introducing a range of tradeable offset actions for development consent for a range of environmental outcomes, including salinity credits, biodiversity credits and carbon credits.
4. Monitoring and evaluation.

To undertake such a strategy in an integrated manner further work will be required in prioritising catchments, prioritising interventions, and establishing the currency and exchange rate for tradeable rights. Accounting for gains and losses is, beyond doubt, the most critical issue to the efficiency of this process. Without an adequate monitoring system, the success or failure of the salinity strategy will be open to endless conjecture and is more likely to end in failure than success.

11.2 Further work

Ultimately reducing the risks associated with dryland salinity in the tributaries to counteract the trends predicted in this study will involve the rehabilitation of recharge areas and discharge areas within the Catchment as a whole. Primarily this will be achieved by manipulating vegetation both in the sense of the type of vegetation matched to land units and its management. This will be expensive; and as the current political consensus acknowledges that the whole community should pay, the public dollar needs to be strategically targeted. This will require a methodology to rank catchments, recharge areas and discharge areas in an objective priority order.

Further work will be required in the areas of:

- **Salinity hazard mapping including layers assessing the spatial hazard associated with recharge risk.** Prioritising areas for intervention needs to be achieved on the weight of all the available evidence. Outputs of the current study such as the FLAG Wetness index, annual salt load and annual salinity statistics incorporated in a weights of evidence framework will add value to existing GIS layers used in this process.

- **Rapid stream survey of the stream network within the tributaries analysed in this study.** Not all recharge and discharge necessarily represents a salinity problem. Not all parts of a catchment contribute equally to the salt load coming from a tributary. Identifying which streams and geologies contribute saline discharge, and which contribute fresh water will add value to the hazard mapping process. It will also allow priority recharge and discharge areas to be identified down to the property level. A one-off survey of stream EC during a low flow, and a high flow event, coupled with detailed geology information, can provide information on the relative importance of geologies and geomorphological features such as paleo-channels and faults.
- **Evaluate scale of intervention required.** Hazard mapping and mapping of relative recharge risk associated with rainfall, soil type and landuse can be achieved as in the process advocated above without putting specific numbers on recharge and discharge. To evaluate the level of intervention necessary for a desirable level of salt load or salinity reduction will require realistic estimates of the impact of vegetation and management changes on the water and salt balances within the tributaries. Projects modelling recharge and salt mobilisation currently employed by DLWC Centre for Natural Resources in the MDBC should be extended to selected tributaries in the Hunter Catchment. The recharge modelling project and the CATSALT modelling framework can provide information on the water and salt balance impacts of changed vegetation management as well as evaluating the area treated against the in-stream salt load and salinity outcomes. Information on the scale of intervention required for a specific cost benefit is essential to establishing the currency and exchange rate for environmental offset trading.
- **Mine rehabilitation study**—The importance of the mines and power generation industry as point source salt polluters is well recognised and an efficient pollution licensing system has been put in place under the Salinity Trading Scheme to minimise the environmental impact. The coal seams exploited by the mining industry are found within the early and late Permian geologies within the catchment. These geologies were formed in marine environments and contain large quantities of connate salt held within the consolidated rock matrix. The coal seams themselves are more permeable than the rest of the rock matrix, and form the aquifers contributing saline groundwater to the mine pits. The groundwater salinity is a result of the surface area of the rock matrix it is in contact with, and its residence time. At present this groundwater seepage is intercepted and stored before discharge to the river. Questions arise as to the fate of this seepage following the back filling of the mine pits with the crushed over-burden as they are decommissioned. Seepage into these voids will bring groundwater into contact with an artificially very large surface area of crushed rock material with a very high salt store. Potential problems may occur where very high salinity groundwater from these voids escapes the site contaminating surface runoff, and fresher surrounding groundwater systems. A comprehensive study quantifying the seepage and salt dissolution processes, their likely effects on surface and groundwater flows, acceptable management protocols for decommissioning mines, and the continued role of the Salinity Trading Scheme in this process must be carried out as soon as possible.
- **Groundwater monitoring network.** As stressed elsewhere in this report, the groundwater data available for analysis in this study has been gleaned from a small number of bores; relative to the size of the catchment, and the scope of the association with the geology used to extrapolate the identified trends. Anecdotal evidence suggests that for large areas in the west of the Hunter catchment, particularly in the Goulburn River Catchments, groundwater has not been explored because most groundwater is known to be highly saline. A groundwater monitoring network comprising existing bores and additional bores should be established and monitored regularly to specifically address the issues of standing water level trends and salinity. Particular emphasis

should be given to filling knowledge gaps in the tributaries. Combining information from the rapid stream survey recommended above and the FLAG wetness index would be a useful way of targeting the location of the bores.

- **Stream gauging network particularly in the Goulburn River catchments.** The region should consider extending its stream-gauging network to include continuous flow and salinity measurements in all the tributaries. In the past, flow gauging in many tributaries has been problematic due to the physical nature of the stream beds and difficulties in applying flow height to volume ratings as bed configuration in sandy streams continually shifts. In the Goulburn River sub-catchment rainfall runoff modelling using the Sacramento model was attempted with the aim of producing simulated flows for the whole 1975 to 1998 period. This exercise had to be abandoned, as insufficient accurate flow data was available to calibrate the model. Considering the importance of salinity in the Goulburn River sub-catchments identified in this study, careful consideration should be given to overcoming some of these technical aspects.

CHAPTER TWELVE

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