Water Authority
of Western Australia

WATER RESOURCES DIRECTORATE

Surface Water Branch

Observed Changes in the Inflow Salinity to Wellington Reservoir, Western Australia

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Report No. WS 34

October 1988

OBSERVED CHANGES IN THE INFLOW SALINITY
TO WELLINGTON RESERVOIR, WESTERN AUSTRALIA

by I.C. Loh (Water Authority of W.A.)

- Draft Paper initially prepared in 1986
- Updated for ICM Workshop (1988)

To be published as one of six case studies of
CATCHMENT MANAGEMENT IN AUSTRALIA IN THE 1980'S
by P. Laut and B.J. Taplin

1. INTRODUCTION

The impact of agricultural development on the salinity of water resources in the south-west of Western Australia has been dramatic. Recent updating of the water resources inventory of Western Australia (WAWRC, 1984) indicates 35.3% of the divertible surface water resources of the South.West Drainage Division of Australia have salinities in excess of 1 000 mg/L TSS (brackish or saline). A further 17.0% is of marginal quality (500 to 1 000 mg/L) and only 47.7% remain fresh (less than 500 mg/L TSS). Prior to agricultural development virtually all the divertible surface water resources of the region were believed to be fresh.

The relationship between clearing native forest vegetation for agriculture and the subsequent increase in stream salinity has been clearly demonstrated in recent years (Collins and Fowlie. 1981; Loh and Stokes, 1981) although the first observation of the effects were reported early in the century (Wood, 1924). The permanent removal of deep rooted forest vegetation and its replacement with shallow rooted crops and pastures has led to an increase in the soil water passing the base of the root zone each winter. Consequently, groundwater levels rise (Sharma et al, 1982, Peck, 1983) and contribute additional groundwater disrharge to the surface stream system (Williamson and Bettenay, 1979). Increases also occur in the quantity of shallow subsurface seepage and surface runoff contributing to streamflow (Stokes and Loh 1982). The overall effect on stream salinity is a complex function of the quantity and particularly the salinity of the additional groundwater discharge, as well as the quantity and quality of the additional shallow seepage and surface runoff water.

Large quantities of salts have accumulated in the deep lateritic soil profiles of the Darling Range in regions with annual rainfalls of less than 900 mm per year (Dimmick et al. 1974; Stokes et al, 1980). Clearing for agricultural development in this region leads to very high salinities of discharging groundwater and results in typical average stream salinities in excess of 3 000 mg/L Total Soluble Salts. In higher rainfall regions where smaller amounts of salts have accumulated in the landscape, and where significant additional shallow seepage and surface runoff contribute to streamflow following clearing, much smaller and often undetectable changes in stream salinity occur following clearing (Loh et al, 1983).

While considerable knowledge of the causes and effects of agricultural clearing on stream salinity have been documented recently, historically it has been very difficult to unambiguously identify the effect of clearing in the catchment of Wellington Reservoir. the largest single developed water resource in the region (Figure 1).

Three reasons contribute to this difficulty. Firstly, there is a very high natural variation in the annual inflow salinity which are much larger than the yearly rate of salinity increase. Secondly, long records of good quality streamflow and quality data have not been available until recently. lhirdly, the one long term data set that is available is based on monthly sampling of water drawn from the reservoir (PWD 1984). Variations in the storage capacity, offtake level of supply, density stratification and seasonal carry over effects all complicate the use of the supply quality as an indicator of the water quality deterioration caused by the catchment clearing. In particular, it has not been possible to identify the variations in salinity caused by variations in inflow volume from the reservoir supply salinity record, thereby making it much more difficult to identify trends in the water quality record.

Numerous unpublished studies have been carried out on the monthly data supplied from the reservoir but only two attempts have been made to estimate the change in inflow quality. Loh and Hewer (1977) used historic streamflow and salinity data from subcatchments of Wellington Catchment to estimate inflow salinities typical of the late 1950 and early 1970s. Empirically based flow salinity relationships were developed for four sub areas of the catchment using data from the periods 1955 to 1960 and 1968 to 1974. In conjunction with statistically generated flow sequences for each sub-area, long sequences of monthly flows and salinities were simulated. The approach. however, only provided reliable estimates of the average inflow salinity at 2 periods of time although unverified estimates were made of the then current catchment conditions (late 1970s) by making subjective changes to the early 1970s flow-salinity relationships.

The primary objective of the study by Loh and Hewer (1977) was to develop improved reservoir operational rules to minimise the salinity of supply from the reservoir. In contrast Loh and Stokes (1981) developed a simple empirically based annual model of inflow salinity to assess the impact of past clearing and possible future land use activity on past and future inflow salinities to the reservoir. Annual flow volumes, and salt discharge from surface and near surface soils and from deeper groundwaters were estimated from historic annual rainfall data, and the time and spatial distribution of clearing across the catchment. Predictions of the historic set of inflow salinities spanned the period 1901 to 1980 although simulation of the effect of clearing extended to the years 2010 and beyond. To enable comparison with the available historic reservoir data, the modelled flow and salt-load figures were used as an input to a simple two season reservoir model and a reservoir salinity at the end of the irrigation season calculated. Comparison, were then made with the observed reservoir salinity each April since 1945.

Both studies have not been able to compare these results with a consistent data set of annual inflow salinities. The absence of a reliable set of inflow salinities has hampered the past identification of the relationship between clearing and streamflow salinity increases and continues to hamper the validation of catchment scale models which aim to predict the effects of land use change on stream salinity.

The objective of this report, therefore, is to document the best available historic set of annual inflow salinities and flow volumes to Wellington Reservoir, carry out analysis of any time trends in the inflow salinities and relate these to past clearing activities. In addition estimates are made of the current inflow salinities and the current rate of increase of salinity.

2. BACKGROUND

2.1 Wellington Reservoir

Located on the Collie River in the south-west of Western Australia, Wellington Reservoir supplies water to the Collie River Irrigation District on the coastal plain near Bunbury and provides potable water to inland towns as part of the Great Southern Town Water Supply Scheme (see Figure 1). Originally built in 1933 for irrigation supply only, it was raised in 1944 and again between 1955 to 1960 to cater for expansion of the irrigation district, to provide the drinking water for the inland towns water supply scheme and to provide future supplies for industrial development.

The current dam stores 186 x 106m3 of water at full supply level and has the largest draw of any single reservoir in the South-West of Western Australia. In 1983/84 the total draw was 76 x 106m3 of which 93% is supplied for irrigation and 7% for the inland towns.

2.2 Available Data

Direct monitoring of inflow volumes and salinities commenced in May 1969 with the establishment of a streamflow gauging station on the main Collie River just upstream of the reservoir at Mungalup Tower (gauging station 612002). Gauging stations representing the local inflow around the reservoir were constructed in 1972 (gauging stations 612004 and 612005) and salinity monitoring upgraded to daily sampling on the main Collie River in 1974. Consequently, from the water year 1974/75 (April 1 to March 31) accurate daily inflow volumes and salinities are available. From 1977 an additional gauging station (612019) was installed to improve the local inflow measurement.

Prior to 1974/75, however, inflow salinities and inflow volumes have to be assessed from reservoir sampling and reservoir operation records. Such calculations are subject to considerable errors. Nevertheless, they provide the only means of removing the complicating effects of reservoir evaporation and storage which mask the true historic pattern of inflow salinity.

Previous monthly estimates of Wellington Reservoir inflows have been calculated from a monthly water balance using records of spillage, draw, changes in storage, scour valve operation and rainfall on and evaporation from the reservoir. Many uncertainties remain in the spillway rating curves for both the old dam (1945 to 1955) and the partly constructed new dam (1956 to 1960). Consequently, significant errors may well exist in the main winter flows up to 1961. The assumptions of reservoir evaporation rates substantially affect the inflow volumes in the summer, low flow months. Errors from this source occur throughout the record but are more significant following the completion of the larger dam in 1961.

Historic monthly sampling for chloride ion and total salts by evaporation have been carried out from the reservoir surface and from the main water supply offtake since 1945. Because of problems with the repeatability of, and the use of different temperatures to determine the Total Salts by Evaporation the chloride ion titrations were considered a more reliable measure to determine valid salinity trends.

The surface waters of the region are remarkably similar in major ion chemistry with the chloride ion being, on average, about 88% of the negatively charged ions in solution. By weight chloride ion represents about 53% of all the major ions in solution (Loh et al, 1983). Regional relationships between chloride ion concentration and the Total Soluble Salts as defined by the summation of major ions has been developed and used to convert the early chloride record to salinity in Total Soluble Salts. The expression used was

$$TSS = 1.701\ Cl + 40$$

where TSS is Total Soluble Salts (sum of major ions in mg/L) and Cl is chloride ion concentration (mg/L)

3. COMPUTATION OF ANNUAL INFLOW SALINITIES Approach

From the previous studies of monthly inflow volumes one set of water year (April 1 to March 31) inflow volumes was adopted and an annual reservoir salt balance calculated to determine the salinity associated with each annual inflow volume.

Inflow salinities from 1945/46 to 1973/74 were determined by the annual salt balance equation.

$$INSAL = \frac{\Delta SL + DVOL \times DSAL + OVOL * OSAL}{INVOL} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where ΔSL is the change in reservoir salt storage between the 1st of April on successive years.

DVOL is the draw volume through the year DSAL is the average salinity of draw, OVOL is the overflow volume OSAL is the overflow salinity INVOL is the adopted inflow volume. and INSAL is the inflow salinity

Because this simple annual salt balance does not consider evaporation and rainfall on the reservoir there is no direct comparison with the monthly water balance used to calculate adopted inflow volumes. To ensure no bias is introduced in the inflow salinities calculated using the above equation, a consistent set of water volumes was required. Historic annual information on draw volumes (DVOL) and changes in storage (ΔVOL) and the adopted inflow volumes were used to calculate the annual overflow volume (OVOL) from

$$OVOL = INVOL - \quad \Delta VOL \quad DVOL \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

This approach effectively incorporates errors in the reservoir water balance into the annual overflow volume.

Estimates of the salinity of overflow and draw were made from records of monthly sampling in the reservoir. The annual overflow salinity was calculated from the arithmetic average of surface reservoir samples taken over the period of spillage each year. The annual draw salinity was determined by weighting samples, taken at the appropriate offtake level, in accordance with the average distribution of monthly water drawn from the reservoir. The change in salt storage each year was determined by the difference between the product of the storage volume and the average reservoir salinity each successive April 1. All calculations of salinity were calculated in chloride ion concentration and converted to an equivalent Total Soluble Salts following completion of the salt balance calculation.

Inflow volumes and salinities from 1974/75 onwards are based on the direct stream gauging and water sampling as noted in section 2.2.

Samples collected from these gauging stations have been analysed for chloride ion and conductivity in varying degrees since 1974, numerous samples being analysed for both. Results have been converted to equivalent TSS values sample by sample and stream salt loads calculated directly in terms of Total Soluble Salts. As there has been a deliberate move to change the basic measure of salinity from chloride to conductivity during the 1970's, care has been taken to ensure no bias has been introduced into the long term salinity trend from this change.

The resultant list of estimated annual inflow salinities and adopted inflow volumes are shown in Table 1.

4. TRENDS IN INFLOW SALINITIES

The large variations of annual inflow salinities are reflected in figures 2 and 3. Figure 2 plots the salinity and inflow volumes against time where figure 3 plots the salinity against the inflow volume, expressed as a ratio of the median flow. Multiple regressions involving the independent variables of both flow and time are necessary to quantify the time trend.

Numerous functional forms of the multiple regression can be assumed and the resultant salinity trend calculated. However, there appears no prior reason to adopt one time trend form over another. For this reason a simple exporential relationship between flow and salinity was assumed initially and the deviations from this average relationship computed.

An expression of the form

$$INSAL = A \left(\frac{INVOL}{INVOL_m}\right)^n \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where $INVOL_m$ is the median inflow volume,

was used in conjunction with least squares estimation of A and n. The resultant deviations from this relationship are plotted against time in Figure 4.

The average rate of increase in salinity from 1945/46 to 1983/84 was 17 mg/L. However, it is clear from figure 2 that the time trend is not uniform. Another significant feature is that the variability of salinity from year to year has increased through time. That is, the rate of the increase in dry year salinities have been much more than the increases in average years. In the context of equation (3) both A and n vary with time.

In order to determine an estimate of the average inflow salinity through time without imposing some functional time trend, estimates of the variation of n with time were made initially and equation (3) transformed to estimate A in the following manner

$$A_t = \frac{(X_t)}{(X_m)} \; Sal_t \qquad (4)$$

where the subscript t refers to the value in year t.

The variation of n with time was determined by subdividing the record into 4 eleven yearly groups and determining values of A and r for each group (see Table 2). As n is less sensitive to the time trend in average salinity than A, n was assumed to vary

linearly between the mid point of each 11 year period. From the results of Table 2

$$At = INSAL_t \; \frac{(INVOL)}{(INVOL_m)}(0.012\ NYR + .154) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5)$$

where NYR is the water year number from 1945/46.

As all variables on the right hand side of equation are known estimates of the salinity of a median year can be directly calculated for each year of record. The five year moving average of the calculated yearly estimates of the salinity of a median inflow year are plotted against time in Figure 5. An upper bound, average and lower bound curve were fitted by eye and also shown in Figure 5. The Fisher distribution free sign test, (Hollander and Wolf, 1973) was performed to check that the differences between the adopted average curved and calculated yearly values were randomly distributed about zero.

Figure 5 indicates that the salinity of an average inflow year has increased from 280 mg/L in 1945/46 to 720 mg/L in 1982/83. Extrapolation to 1985/86 indicates a current average inflow salinity of 880 mg/L. This represents a 600 mg/L rise, or an increase in excess of 300% over the 41 years.

5. DISCUSSION

5.1 Correlation Between Clearing and Salinity Increase

Although much of the early data is of poor quality and sometimes biassed by the limited monthly sampling (for example 1963) the dramatic deterioration in inflow salinity is clearly apparent.

Figure 6 plots the area cleared in the total catchment and should be compared with the trend in estimated inflow salinity (Figure 5). A clear delay between clearing and salinity increase is apparent. While clearing has been controlled by legilsation in 1976 the inflow salinity continues to rise in response to past clearing.

Previous estimates suggest that when the groundwater discharge reaches a new equilibrium under the current levels of clearing inflow salinities will approach 1 100 mg/L TSS (Loh and Hewer, 1977).

5.2 Regional Scale Modelling

While subsequent application of the model developed by Loh and Stokes (1981) has indicated that the prediction of 1 100mg/L TSS is of the correct order the time scale for the salinity increase are not compatible with the data set presented here. The effect of early clearing is overpredicted by the model and salinity increases tend to occur too rapidly following clearing.

Detailed finite difference groundwater simulations of a number of subcatchments in the eastern portion of the catchment have subsequently been carried out (Hookey and Loh, 1985). Results indicate that the groundwater responses to a unit area of clearing is dependent on the location in the landscape and the temporal pattern of clearing. That is the groundwater response is not simply a linear function of the cleared area. In one case the groundwaters rose beneath valley cleared areas but did not discharge to the stream at all. Groundwaters drained to the adjacent forest areas and only discharged to the surface following further upslope clearing. That is the initial valley clearing caused no salt discharge. The modelling also showed that the time to equilibrium (discharge equal to recharge) was approximately double the empirical figures used by Loh and Stokes (1981).

For regional scale modelling to successfully reproduce the observed increase in salinity of inflow to Wellington Reservoir the prediction procedure will have to account for both the spatial and temporal pattern of clearing.

5.3 The Rate of Increase in Salinity

An important feature of the inflow data is that the first 20 years showed an increase of 120 mg/L compared with a 480 mg/L increase in the following twenty years. Prior to 1955/56 the rate of increase (see Figure 7) was low at less than 5 mg/L per year. However, the rate of increase increased through the subsequent decade reaching 15 mg/L per year by 1965/66. The rate of increase continued to grow over the following 15 years to its current value of 30 mg/L per year.

This characteristic of the acceleration of the salinity deterioration was a major cause for delay in implementing action to halt agricultural development in the catchment. The period 1950 to 1965 was one of major agricultural development. During this period agricultural scientists and water resource engineers first become seriously concerned about the expansion of land release and clearing in the Wellington Reservoir catchment. However, evaluation of the raw reservoir salinity data to 1964/65 by the States Purity of Water Committee showed no significant time trend at the time and the correlation between clearing and salinity was not proven.

Two reasons contributed to this conclusion. Firstly, the rate of increase was still small relative to the yearly variation, and secondly the flood years of 1963 and 1964 had reduced reservoir salinities dramatically at the end of the period studied. Analysis of the inflow salinity data used here also showed no significant time trend to 1964/65. As the estimates of streamflow volumes and inflow salinities were not available in the mid sixties it was not possible to remove the effect of streamflow

variability. Significant correlations between salinity and flow were obtained with the current data set to 1964/65 and a number of multipule regression formulations were evaluated to jointly account for the flow variability and the time trend. The results were sensitive to the form of the multiple regression equation used and ranged from no significant time trend to a trend of 6 mg/L per year which was significant at the 1% level.

If reliable data sets had been available and careful and detailed analysis carried out it would have been possible, although difficult, to identify a significant deterioration by the mid 1960's. However, the rate of deterioration increased rapidly through the late 1960s. With the longer record and larger deterioration which subsequently occurred, identification of the deterioration became much easier.

This history provides a good example of the limitatoins of relying solely on regular monitoring programmes when studying problems which have long time delays between their cause and effect. By the time significant deterioration can be identified the activity causing the problem may have reached critical levels in terms of the future of the resource.

6. SUMMARY AND CONCLUSIONS

A consistent set of annual inflow volumes and salinities to Wellington Reservoir from the water year 1945/46 to 1983/84 was estimated from available reservoir sampling, operational records and from recent streamflow and water quality monitoring. The salinity of a median inflow year has increased from 280 mg/L TSS in 1945 to approximately 850 mg/L TSS in 1984/85. While large scale clearing on the catchment was controlled by legislation in 1976 the salinity of inflow continues to rise as saline groundwater discharge increases as a result of past clearing. Between 1945/46 and 1954/55 the rate of increase was less than 5 mg/L per year but has increased to the current level of approximately 30 mg/L per year. That is, the rate of increase in salinity has increased through time.

The annual variability of salinity caused by variations in inflow volumes has also increased with time. That is the rate of increase in dry years is higher than the rate of increase in median inflow years.

Comparison of past predictions of inflow salinities with the data set presented here suggested significant over-estimation in salinities in the 1950s and suggested that the time delay effects of past clearing are non-linear. Early valley clearing possibly caused little groundwater discharge or was much more delayed than the effect of subsequent mid and upslope clearing. Groundwater modelling studies of specific areas in the eastern portion of the catchment support such observations.

This re-evaluation of the original reservoir water quality and reservoir operation records has emphasised some significant aspects of such long term monitoring programmes. Firstly, simple reservoir monitoring programmes are usually not sufficiently descriminating to readily identify water quality deterioration without long periods of record (tens of years). Often gross deterioration must take place before such programmes can show statistical significance. Secondly, means of removing seasonal variability in water quality caused by streamflow volume fluctuations greatly improves the power to identify any water quality deterioration. Thirdly, statistical analysis of flow and salinity data is useful for identifying past salinity trends and both current levels and rates of increase of salinity. However statistical analysis of past data does not enable extropolation for more than a few years into the future. Future salinity trends are governed by the past clearing history and the hydraulic properties of the groundwater systems involved rather than previous levels of salinity.

7. ACKNOWLEDGEMENTS

The data presented in this paper has been collected and processed by the staff of the Water Resources Assessment and Management Section of the Public works Department, Western Australia. Their assistance is greatly appreciated. Mr R Murton and Mr M Hollett were particularly helpful in the computations of the annual inflow salinities.

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TABLE 1
INFLOW VOLUMES AND SALINITIES TO WELLINGTON RESERVOIR

WATER YEAR*	FLOW VOLUME		SALINITY
	106 m3	Ratio with Median Flow Year	mg/L TSS
1945/46	343.2	2.303	244
46/47	307.0	2.060	156
47/48	259.2	1.740	254
48/49	105.2	0.706	344
49/50	32.8	.220	307
50/51	70.4	.470	322
51/52	63.2	.424	326
52/53	106.1	.712	310
53/54	88.2	.592	355
54/55	90.2	.605	348
55/56	389.9	2.617	333
56/57	165.5	1.111	302
57/58	204.5	1.372	232
58/59	235.6	1.581	246
59/60	68.1	0.457	428
60/61	130.1	0.870	343
61/62	181.1	1.215	321
62/63	107.9	0.724	389
63/64	451.7	3.032	137
64/65	652.7	4.381	185
65/66	173.1	1.162	413
66/67	134.9	0.905	476
67/68	290.4	1.949	329
68/69	152.2	1.021	487
69/70	69.9	0.469	652
70/71	196.6	1.319	436
71/72	149.0	1.000	559
72/73	69.0	0.463	685
73/74	226.4	1.519	455
74/75	479.2	3.216	296
75/76	126.6	0.850	687
76/77	46.0	0.309	1162
77/78	79.0	0.530	1082
78/79	122.4	0.821	833
79/80	31.4	0.211	1323
80/81	93.8	0.630	1018
81/82	237.0	1.591	617
82/83	81.8	0.549	923
83/84	375.8	2.522	480

* Water Year is from April 1st to March 31st.

TABLE 2
SALINITY AND FLOW RELATIONSHIPS THROUGH TIME

Period	Number of Years	Mid Point of Data Sat	Flow Salinity Relationship Coefficients B	M	Significant Time Trend
1945/46-1983/84	39	1965	407	-.44	Yes
1945/46-1955/56	11	1950	28.5	-.16 (NS)	Yes
1955/56-1965/66	11	1960	329	-.42	No
1965/66-1975-76	11	1970	494	-.45	Yes
1973/74-1983/84	11	1078	678	-.52	No

Note. The time trend in was assumed to be linear and was calculated from the four points at 1950, 1960, 1970 and 1978 and resulted in the relationship.

TABLE 3
ESTIMATED SALINITIES OF A YEAR OF MEDIAN INFLOW

Water Year	Bi	Five Year Moving Average of Bi	Adopted Range of Median Inflow Salinities			Average Rate of change
			Lower Bound	Average	Upper Bound	
1945/46	278		275	275	275	1
1946/47	279	279 (1)	275	276	277	1
1947/48	280	277	275	277	279	1
1948/49	322	276	275	278	281	1
1949/50	226	274	275	279	283	1
1950/51	274	275	275	280	285	2
1951/52	269	273	276	282	208	2
1952/53	286	289	278	284	290	3
1953/54	311	321	280	287	294	3
1954/55	305	329	282	290	298	4
1955/56	433	323	285	294	303	6
1956/57	311	318	290	300	310	7
1957/58	255	323	295	307	319	9
1958/59	284	302	303	316	329	9
1959/60	333	308	311	325	339	10
1960/61	327	327	320	335	350	12
1961/62	343	338 (2)	332	347	362	13
1962/63	347	336 (2)	344	360	376	15
1963/64	207*	363 (2)	357	375	393	15
1964/65	325	380 (2)	370	390	410	15
1965/66	438	402 (2)	383	405	427	15
1966/67	409	420	396	420	444	20
1967/68	435	448	414	440	466	20
1968/69	491	459	432	460	488	20
1969/70	467	489	451	480	509	20
1970/71	494	497	470	500	530	20
1971/72	559	510	489	520	551	20
1972/73	474	523	508	540	572	22
1973/74	558	551	529	562	595	23
1974/75	531	564	551	585	619	25
1975/76	632	623	575	610	645	25
1976/77	627	661	599	635	671	25
1977/78	769	669	623	660	697	25
1978/79	748	699	647	685	723	25
1979/80	568	735	671	710	749	27
1980/81	782	718	695	735	775	28
1981/82	809	736	720	762	804	30
1982/83	681	773 (1)	746	790	834	30
1983/84	842		773	820	867	30
1984/85			800	850	900	

Notes: All valves are in mg/l Total Soluble Salts

(1) Based on a three year moving average
(2) Based on a four year moving average

* Data in 1963 was limited and biassed to a period of high flows.

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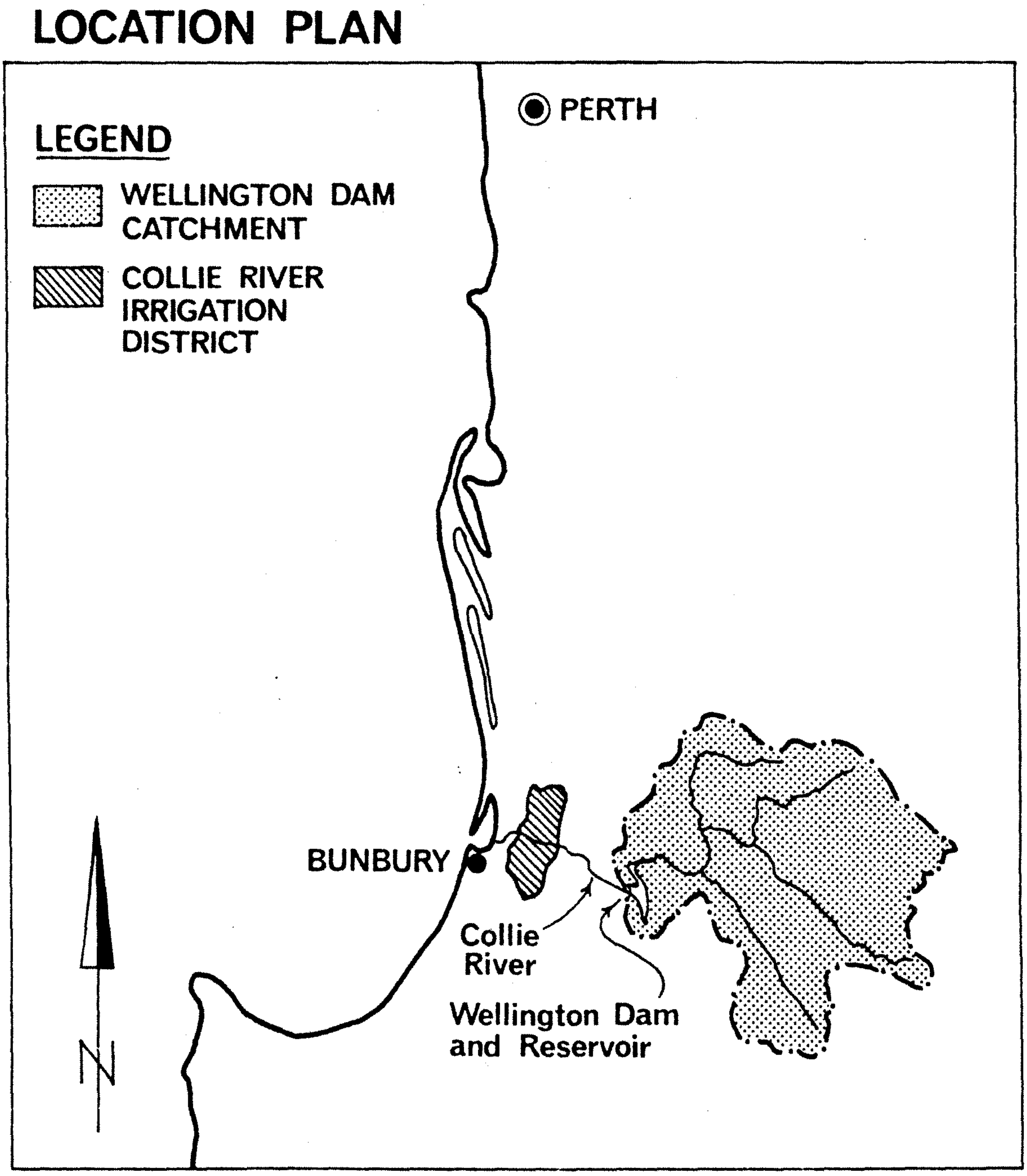

Figure 1 Location Diagram for Wellington Reservoir Catchment

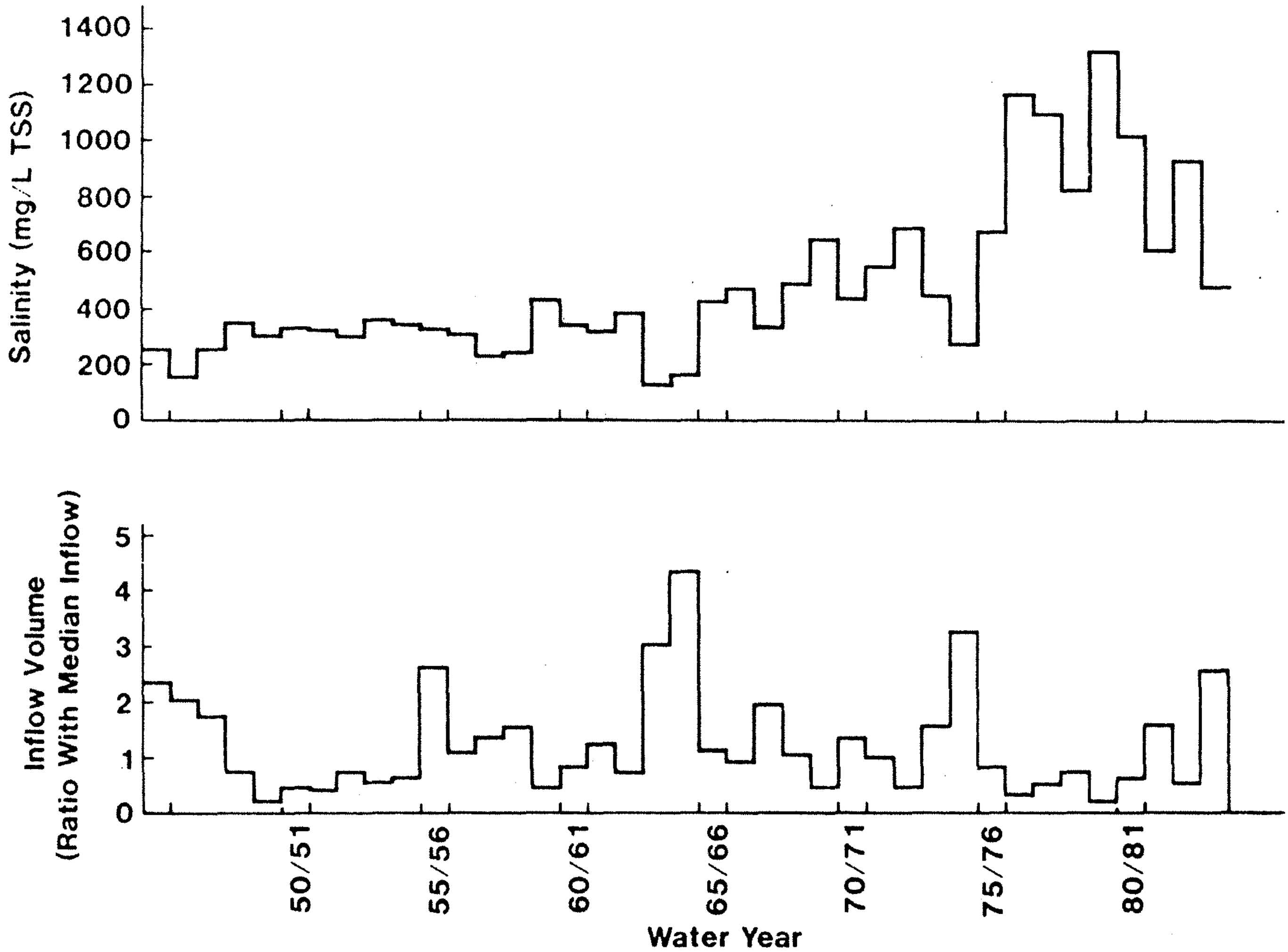

Figure 2 Annual Inflow Salinities and Flow Volumes to Wellington Reservoir between 1945/46 and 1982/83

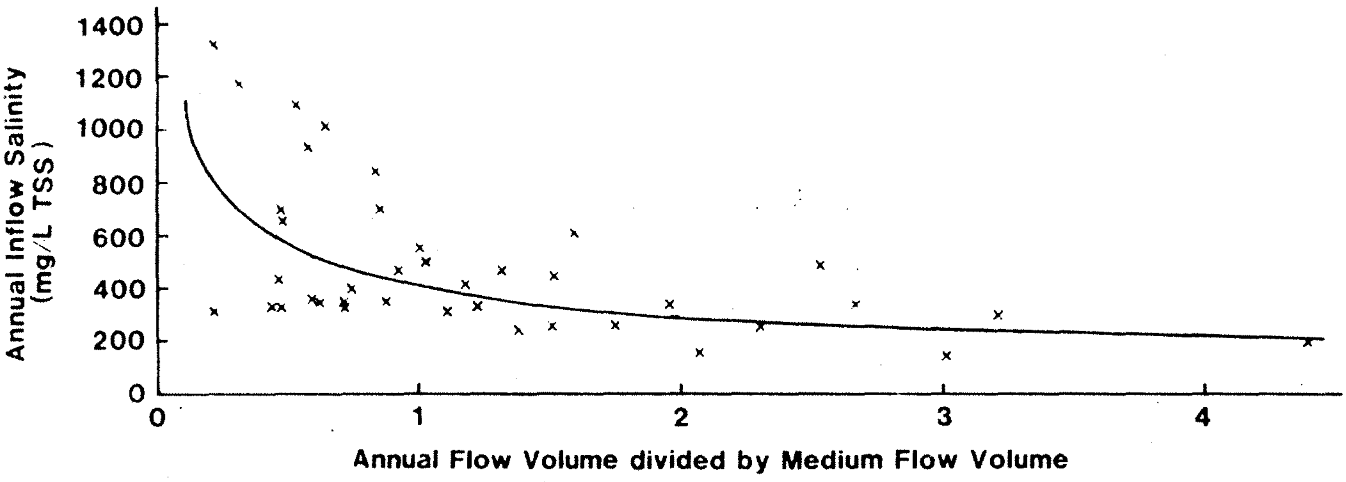

Figure 3 Relationship between Annual Inflow Salinity and Annual Flow Volume

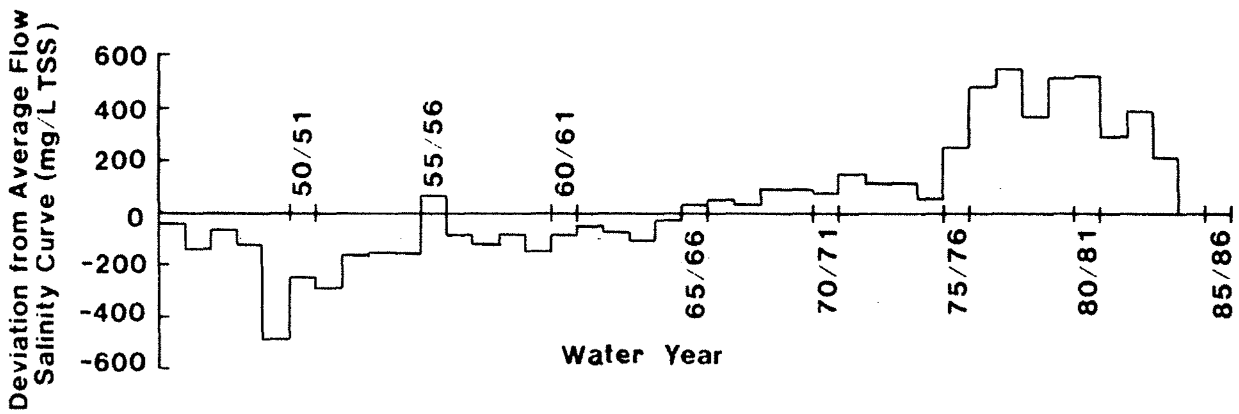

Figure 4 Time trend in deviations from average flow-salinity relationship

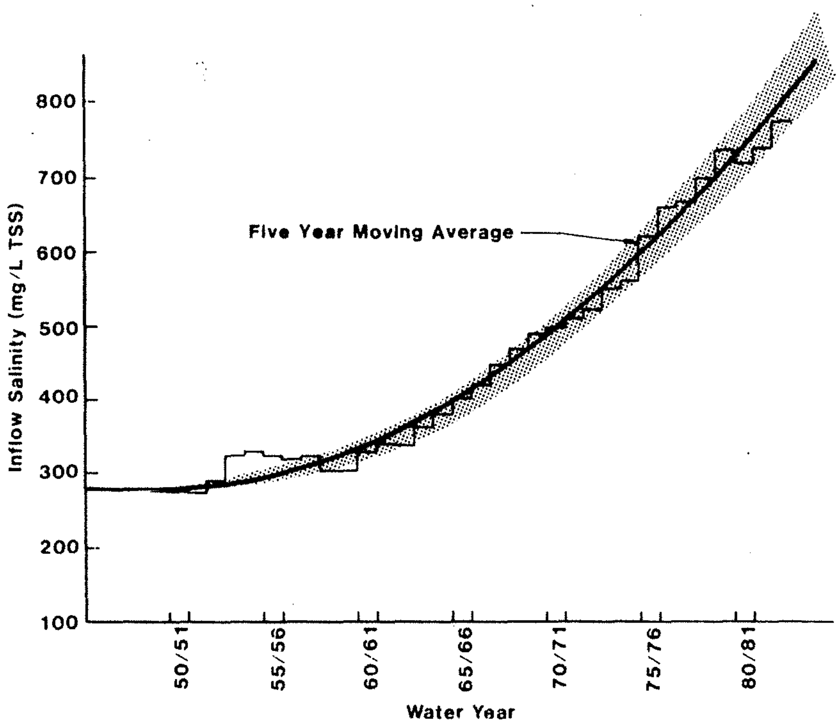

Figure 5 Time trend in the salinity of a median inflow year

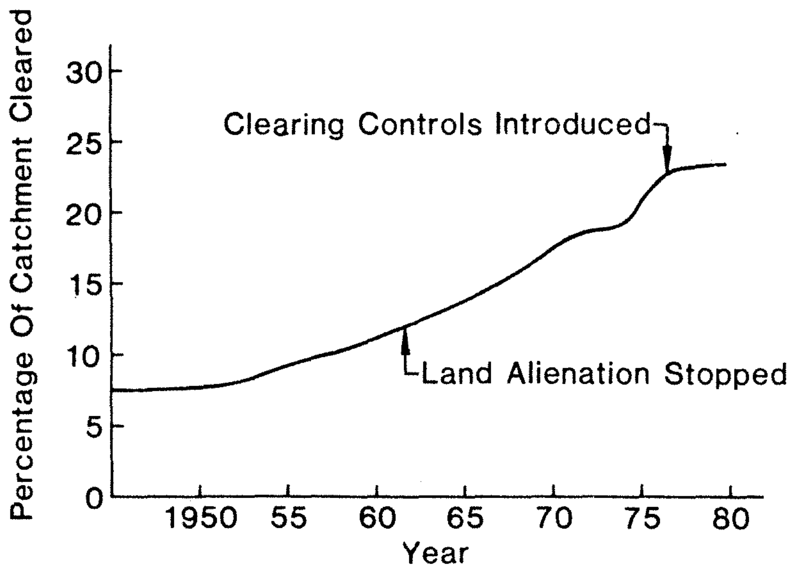

Figure 6 Historic clearing trend on Wellington Reservoir Catchment

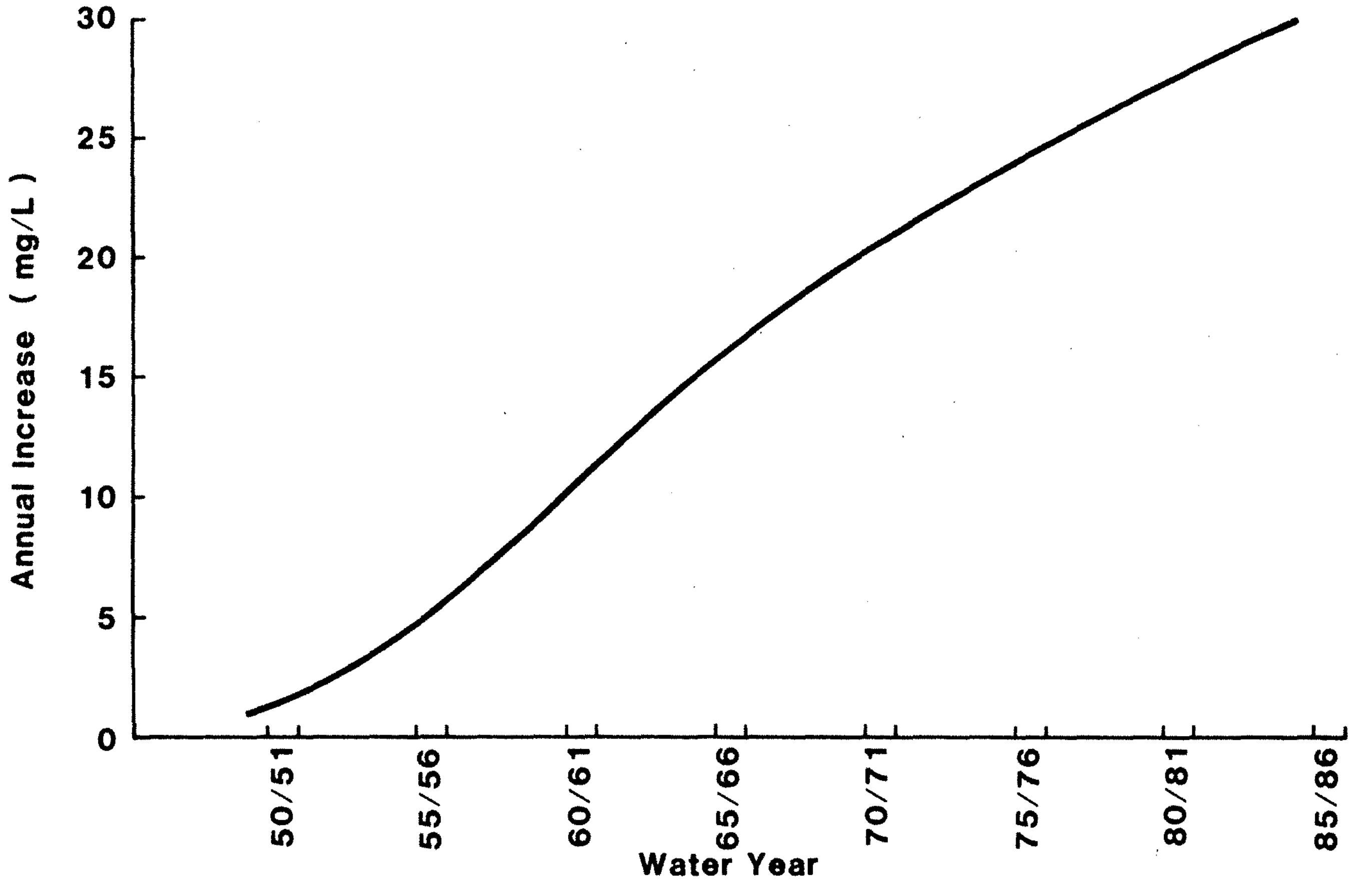

Figure 7 Rate of Increase in Median Year Inflow Salinity to Wellington Reservoir