TABLE 5

COMPONENTS OF LATERAL FLOW IN CONFINED AQUIFER

Area from which flow is derived	Annual flow (Ml)	Percentage of total
Northern Margin (Recharge Zone)	5 600	45
Aquifer Beneath Lake Alexandrina	3 000	25
Eastern and Western Saline Zones	3 400	30
TOTAL	12 000	100

3. Salinity

The salinity in the confined aquifer varies markedly, the lowest salinities coinciding with the positions and salinities of the modern rivers (Figure 33). Quality of recharge water from the rivers controls the minimum groundwater salinity, which is in the range 1 000-1 500 mg/l.

The zones of better quality water parallel to the rivers reflect the flow paths of the groundwater from the recharge zones, perhaps enhanced by coincident pre-Pliocene karstic erosion features.

The salinity plan is a simplification of the true salinity distribution, because the aquifer is known to be stratified (Figure 34) and the private wells which are used for salinity data tend to sample only the top 10-20 metres of the aquifer. There are undoubtedly many small anomalous zones of higher or lower salinity not represented, but the general distribution is considered reliable. In addition there are serious difficulties in obtaining samples not contaminated from the unconfined aquifer (see discussion on pages 25 to 30).

Of particular interest for the long term management of the water resource are the steep salinity gradients bordering the irrigation area, particularly to the west and north-east.

RELATIONSHIP BETWEEN THE AQUIFERS

1. Potentiometric levels

The establishment of observation wells in the unconfined aquifer in 1976 made it possible to compare potential differences between aquifers. This was achieved by contouring differences between water levels in the two aquifers for April-May 1976, and December, 1976 (Figure 35).

The contour plans show two distinct zones, one with small head differences (0-2 m) and the other with head differences of up to 15 m. The north-western margin is difficult to classify in this way as the limit of the confined aquifer is not well defined.

Throughout the main study area the head difference is positive downwards, (potentiometric level of upper aquifer higher than that of lower aquifer) or very close to zero, implying that virtually all leakage between aquifers is now in a downwards direction.

There is a spatial correspondence between the cones of depression in the two aquifer systems, although there is virtually no water withdrawn by pumping from the upper. This suggests that downward leakage from the upper aquifer is taking place, and probably helping to balance withdrawals from the confined aquifer.

The distinct zonation of the head difference between the aquifers is probably a combination of two factors:

(1) Effective confining beds separate the two aquifers in the zone of large head difference, and major vertical leakage takes place from the upper aquifer where head differences are small.

(2) There are greater irrigation withdrawals in the zone of small head difference, which has caused preferential depletion of the upper aquifer there.

The former is probably the dominant factor.

ESTIMATION OF RECHARGE FROM ANGAS AND BREMER RIVERS

1. Confined Aquifer Flow Net Analysis

Using Darcy's Law it is possible to calculate the flow of groundwater from the northern margin of the confined aquifer to the irrigation area. The rivers are the only significant source of recharge from the north, and the groundwater flow from the north is therefore a measure of that recharge. The lithology and thickness of the upper aquifer are such that its hydraulic conductivity is likely to be at least an order of magnitude lower than that of the confined aquifer. Lateral flow from the recharge zone in the unconfined aquifer is probably so small that it can be neglected as a loss from the rivers in this calculation. Flow in the confined aquifer is probably a good measure of total recharge from the rivers, at a level of accuracy of one to two significant figures.

On the basis of the flow net analysis (Figure 32) the recharge to the confined aquifer from the rivers is 5 600 Ml year^{-1}, most of which probably comes from the Bremer (hydraulic gradients in the confined aquifer are steeper near the Bremer, and its flow is obviously greater).

2. Stream Gauging - current meter work

During 1976 current meter measurements were made at several locations on the River Angas to assess the diminution of flow. The work showed a loss of about 20000 m^3 day^{-1}, regardless of total flow (Sinclair, 1976), or about 3000Ml $year^{-1}$, when the 100-200 days of flow per year across the recharge zone are considered.

3. Stream Gauging - permanent stations

In 1971-72 nine staff gauges were established by the Department of Mines on the Angas and Bremer Rivers (Figure 36) with the aim of measuring losses in flow. Several problems were encountered with the gauges, notably damage by floating logs during floods and erosion of the river channel at times of low flow (thus lowering the apparent stage measured at the gauge). In addition the frequency of measurement by local farmers (24 hours) was found to be inappropriate, because flood peaks passed through the area in a much shorter time. The data will be useful for the design of a more sophisticated monitoring system by the E. & W.S. Department, and to assist future modelling of the flow regimes. Recharge estimation from it is difficult, but work is in progress, and will be reported separately.

WATER BUDGET

1. Unconfined aquifer

Inflow comes from river channels and floods, both unmeasured, and from recirculation of excess irrigation water. The aquifer transmissivity is so low that lake recharge is probably insignificant compared with other uncertainties.

Losses to the confined aquifer are obviously the main outflow, as the cone of depression in the irrigation area is permanent. Leakage from the aquifer has been estimated to take place at a minimum rate of 4 500 Ml/year, considering hydraulic separation between the aquifers and measured leakage coefficients of the confining bed (Appendix 3). Depletion of the aquifer (the discrepancy between inflow and outflow) has been estimated at 500 Ml/year, by measuring the loss from storage averaged over 20 years of irrigation (Appendix 3 and Figure 37).

The water balance for the confined aquifer (page 25) suggests that leakage from the unconfined aquifer may be as great as 13 000 Ml/year, of which 9 000 Ml/year can be shown by differences to be balanced by recirculation of irrigation water.

A water balance for the unconfined aquifer can thus be written in the form:

INFLOW		= OUTFLOW	- CHANGE IN STORAGE
3 500	+ 9 000	= 13 000	- 500
Rivers Recharge	Irrigation Recirculation	Vertical Leakage	Depletion averaged over 20 years

Water level observations will show whether further depletion is taking place in the aquifer.

Recharge along the lower reaches of the rivers will have to be measured or estimated if this component of input is to be refined. This could prove a very difficult task, due to abstractions by irrigators and ponding of floodwaters. If irrigation application rates are ever measured, the excess recirculation (recharge) to the unconfined aquifer could easily be estimated knowing the evaporation rate of lucerne. The salinity of the recirculating water could also be calculated (see page 32).

2. Confined aquifer

INFLOW

There are two mechanisms for input of water to the aquifer in the irrigation area.

The first is lateral flow of water under the influence of natural and induced hydraulic gradients; the second is vertical leakage from the unconfined aquifer, made possible by reductions in head caused by irrigation withdrawals.

1. Lateral flow

Total lateral flow into the cone of depression has been calculated by flow net analysis to be 12 000 Ml year^{-1} (Figure 32). Flowlines show that it can be apportioned to flow from the northern recharge area, the aquifer beneath Lake Alexandrina and the aquifer to the west and north-east.

2. Vertical leakage

The results of attempts to measure this input have been ambiguous (Appendix 3). A method of difference between lateral flow input and estimated outflow might be the most satisfactory way of resolving the problem.

OUTFLOW

The sole outflow is that from pumped wells, as the hydraulic gradient never allows flow towards the lake in the south of the area.

The amount of water transpired by lucerne was found to be 1 042 mm per year by Holmes and Watson, 1967, for a site at Murray Bridge. They made an estimate of 1 200 mm ± 10% for continental potential evapotranspiration. Wiesner (1970) gives a similar estimate of 42 inches (1 070 mm) as the total water requirement of lucerne in Victoria.

Based on the land use map for March 1976, the average evapotranspiration from groundwater-irrigated areas for one year would be 16 000 megalitres (Appendix 5) for an average rainfall of 400 mm (Langhorne Creek and Milang P.O. data).

The authors estimate the application of water for irrigation to be at least 10-30% more than evapotranspiration, and approximately 25 000 megalitres per year has been used as a maximum estimate. This infers that 9 000 Ml/year is the size of the component of recirculated irrigation water - an input to the unconfined aquifer.

DISCUSSION

Until a better estimate of the amount extracted is available, it will be difficult to refine the water budget for the confined aquifer. It is quite clear however that withdrawals are considerably larger than natural recharge from the rivers.

The data available for outflow from the confined aquifer can be used to provide a second estimate of the amount of vertical leakage from the unconfined aquifer, as a steady-state situation exists.

The water balance equation can therefore be written:

INFLOW		= OUTFLOW	
12 000	+ 13 000	= 25 000	(Megalitres per year)
Lateral Flow	Vertical Leakage	Irrigation Withdrawals	

The modern groundwater system is shown diagrammatically on Figure 38 together with the postulated system prior to major irrigation withdrawals, as discussed in Appendix 6.

It is stressed that all the components of the water budget have been estimated from limited data, and are not particularly reliable. They suggest that vertical leakage is of the same order of magnitude as lateral inflow, that recharge to the unconfined aquifer deserves more study and that withdrawals should be measured directly as a first step if the water balance data are to be improved.

CONFINED AQUIFER SALINITY CHANGES

There is an inflow of groundwater into the aquifer in the irrigation area, partly by lateral flow within the confined aquifer and partly by vertical leakage from the unconfined aquifer. The potentiometric surfaces for both aquifers show that the cones of depression rarely, if ever, recover enough to allow flow towards the lake in the south of the area. The excess irrigation water probably infiltrates to the unconfined aquifer, there being no artificial drainage system to intercept this flow, and therefore returns eventually to the confined aquifer. The only salt removal from the area is achieved by the sale of lucerne which is carted away. This is a very small component, and can be ignored.

Therefore there must be a net inflow of salt to the confined aquifer in the irrigation area by vertical leakage from the unconfined aquifer, and by lateral flow in the confined aquifer. This can be estimated from present data.

Irrigation removes salt from the confined aquifer in the short term, but does not represent a long term loss, as the salt eventually will recirculate as vertical leakage from the unconfined aquifer.

Farmers have complained for some years of the rising salinity of irrigation water, especially around the margins of the area. Evidence cited includes the abandonment of some irrigated farmland, and salinity increases from 1 500 to 3 500 mg/l have been documented from some irrigation supplies.

A grid of 90 wells has been sampled annually since 1970 to provide information about salinity trends within the aquifer using the measured conductivity of the water sample. This is a sample population of about half the total number of irrigation wells, and was expected to be adequate to monitor any changes.

Gerges and Williams (1975) documented the results of monitoring from 1970 to 1975, and concluded that the cause of large increases (arbitrarily taken as greater than 10%) was leakage of saline water via corroded casing. There were no clear trends of rising salinity in particular areas. Statistical techniques have since been applied, and these are discussed below (page 29).

There are several causes of changes in salinity of water samples taken from a well penetrating the confined aquifer.

(i) Lateral migration of saline water

The hydraulic gradient is everywhere towards the centre of the cone of depression during the irrigation season. Wells near the edges of the area (where there are steep hydraulic and salinity gradients) may be adversely affected by lateral flow. Using Darcy's Law it is possible to calculate a velocity for the lateral flow of saline water.

$$\text{Velocity} = \frac{1}{\text{porosity}} \times \text{Hydraulic Gradient} \times \text{Hydraulic Conductivity}$$

The porosity of the limestone can be assumed to be 0.3, similar to the value used for Gambier Limestone by Templer (1972). Higher values of porosity for South Australian bryozoal limestone have been measured, however they apply to extremely porous material and cannot reasonably be applied to the whole of the confined aquifer in this area.

Hydraulic conductivity (transmissivity/aquifer thickness) can be estimated from the aquifer test data in Appendix 5. A maximum estimate of 25 $m^3 day^{-1} m^{-2}$ has been used.

The maximum hydraulic gradient which can reasonably be used for the calculation is $\frac{3}{1\ 500}$ (taken from an end-of-summer potentiometric contour plan).

$$\text{Velocity} = \frac{25 \times 3 \times 365}{0.3 \times 1\ 500} \text{ metres/year}$$

$$= 60 \text{ m/year}$$

This value uses the highest reasonable values of parameters, and is probably representative of maximum velocities in the area.

If gradients of the order of $\frac{3}{1\ 500}$ are assumed to have existed for 20 years (an exaggeration which ignores the non-pumping season) the maximum movement towards the irrigation area is likely to have been about 1 kilometre. Occasional exceptionally high or low velocities are likely in any geological environment, because of inhomogeneities in the aquifer material.

This calculation indicates that some salinity increases observed in wells near the edge of the irrigation area are caused at least partially by lateral flow.

(ii) Vertical leakage from the unconfined aquifer

It is known that most leakage between the aquifers in the area will take place from the upper, unconfined aquifer to the lower, confined aquifer. There are generally higher salinities in the upper aquifer than the lower, and there are two mechanisms for leakage.

(a) Leakage via poorly constructed wells (Figure 39). Very few wells in the area have cemented casing, and leakage through corrosion failure or down the annulus between the casing and the wall of the hole is likely to occur in most wells. Pumping induces a much greater head difference and therefore more leakage between the aquifers in the vicinity of the well than the regional head differences deduced from observation wells. The most significant increases in salinity will occur in areas of greatest salinity water in the unconfined aquifer.

(b) Leakage by regional vertical flow. The water budgets and observed response of the upper aquifer to withdrawals from the lower, indicate widespread leakage from the upper aquifer to the lower. Again the most significant effects will be in areas of highest salinity in the upper aquifer, and these occur in areas where geological conditions allow maximum leakage.

Both mechanisms will be active in the area; the former will dominate samples taken from most irrigation wells, because most have uncemented casing.

(iii) Salinity variations within the confined aquifer

Wells that have been drilled with careful water sampling have shown that salinity stratification occurs (Figure 31). This means that the salinity of water pumped from a well is controlled to some extent by the proportion of the aquifer penetrated, the duration of pumping prior to sample collection, and the pumping history prior to the pumping for sample collection. This relationship is only known for the Departmental aquifer test wells, which did not show variations in salinity during pumping because they fully penetrated the aquifer.

(iv) Statistical treatment of data

All data were examined for statistically significant salinity-time trends. Regression lines were calculated, together with standard errors for the regression lines (results and data in Appendix 7) for the data from each well. The work was carried out by Mr. G. Pilkington, of the Geophysical

Services Division. He concluded that the data were of limited value, in particular that

(a) the number of years of readings was not sufficient to establish salinity trends because of the high variability of the measured values, together with the relatively slow rate of change expected, and

(b) 72% of the wells had statistically meaningless trends.

Of the 80 wells measured more than twice, 59 had a positive salinity trend, and 21 a negative trend. This is an indication of overall salinity increases in the area, together with irregular zones of variable water quality, variable vertical leakage past uncemented casing, and varying pump-sampling times. No quantitative work on the data available is sensible.

In summary it is not easy to interpret the causes of salinity change in individual irrigation wells in the area. Monitoring is useful to test individual wells for failure, but the results have not quantified any definite trends of aquifer salinity.

Lateral flow within the confined aquifer

Potentiometric contours are available for March-April and September every year. A conservative approximation of salt inflow can be obtained by assigning six months of the year to each plan (the September configuration, with low salt inflow, is probably over-emphasised, giving an under-estimate of the rate of salinity increase).

Darcy's Law allows the calculation of the volume of water flowing into the irrigation area knowing transmissivity and hydraulic gradients. Using flow lines to divide the surrounding area into salinity zones the salt inflow for each zone can be calculated using the formula

Q_s = TilC x 10^{-6}, where

Q_s = inflow of salt (Tonnes day^{-1})

T = transmissivity ($m^3 day^{-1} m^{-1}$)

i = hydraulic gradient (mm^{-1})

l = width of salinity zone, measured perpendicular to flow (m)

C = salinity of groundwater (mg/l)

Figure 40 shows the irrigated area and the salinity zones chosen for the calculation (separated by groundwater flowlines) with values of T, i, l and C used for the calculations for the March and September plans.

The annual salt inflow on this basis is 30 000 tonnes $year^{-1}$ (to 1 significant figure). The groundwater beneath the lake is probably derived from the Angas and Bremer rivers, and probably still has salinities in the range 1 500-3 000 mg/l, which are likely to decrease with time because of the input of better quality lake water. Water from the east also may come from the lake under the influence of pumping but it is the saline groundwater between the lake and the irrigation area which will first move in.

3. Leakage from the unconfined aquifer

The vertical leakage value has been estimated at 13 000 Ml $year^{-1}$ from the water balance, and using a rough value of 7 500 mg/l to represent the "average" salinity of the unconfined aquifer in the leakage zone, about 100 000 tonnes/year is estimated to be leaking into the confined aquifer in the irrigation area.

This estimate assumes that the salinities measured in the unconfined aquifer are at present largely independent of the salt inflow from recirculating irrigation water. The salinity of recirculating irrigation water has not been measured, but can be estimated. The salinity will increase from the well head proportionally to the ratio of application to evaporation, or $\frac{25}{16}$ (1.6). On this basis the salinity of recirculating water would be of the order of 3 000-5 000 mg/1.

4. Well construction leakage

The salt influx from the upper aquifer via poorly constructed wells is difficult to estimate. Most leakage will occur when pumps are being operated, under the influence of drawdown in the well. It is considered to be a minor problem when considering the salt balance of the confined aquifer, because

(a) the low hydraulic conductivity of the upper aquifer must limit horizontal flow towards a well, and

(b) salt leaked down under the influence of pumping is likely to be removed immediately from the confined aquifer by the pumping process.

This is not the same as stating that leakage past poorly constructed wells is not serious, because salinity of the water produced at the well head may be increased substantially. This affects crops, and gives an exaggerated impression to the landowner of the rate at which regional groundwater salinities are increasing.

5. Withdrawals

An estimated 25 000 Ml of water is pumped annually from the confined aquifer, with an approximate salinity of 2 000 mg/l. This is a loss of 50 000 tonnes/year.

6. Discussion

In the long term the water in the unconfined aquifer will be displaced to varying extents by recirculating irrigation water which will itself ultimately reach the confined system again.

The salt balance from the confined aquifer can be written for the short term in the form:

INFLOW - OUTFLOW = CHANGE IN SALT STORAGE

100 000	+ 30 000	- 50 000	= + 80 000 (tonnes per year)
Vertical leakage	Lateral flow	Irrigation withdrawals	Salt accession to Confined aquifer

It has been stated that there is no significant change in the quantity of water held in storage, so the water must show an overall increase in salinity. This can be estimated to be 40 mg/l per year, if the aquifer is assumed to be homogeneous and perfectly mixed. It is probably of the correct order of magnitude, but should not be used for quantitative work on rates of salinity increase.

The salinity increase estimates made on the assumption of perfect mixing in the aquifer are known to be much smaller than the apparent increases that are measured by samples taken from some production wells in the area. Most wells take their water from the upper 10-20 metres of the aquifer,

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**Volume of water in the confined aquifer in irrigation area*

= 80 km^2 (area) x 75 m (thickness x 0.3 (porosity)

= 2 x 10^{12}m^3)

and will thus show a salinity increase biased by the salt influx from vertical leakage and that caused by faulty well construction. Wells near the margins of the zone of good quality water may show the effects of lateral migration of saline water. Wells penetrating limited zones of poor quality water, such as the one between the rivers, may improve their water quality in the short term as the poor quality water is displaced by better. The predicted rate of increase gives the area a limited life under present extraction conditions.

Salt budgets may be calculated for separate parts of the irrigation area in the future when computer modelling is undertaken.

Figure 41 shows diagrammatic salt movement in the aquifer systems.