HYDROCHEMISTRY

No detailed study has been made of the hydrochemistry of either aquifer system. Over the years of investigation numerous water analyses have accumulated, subject to all the uncertainties already discussed with respect to salinity.

Work reported in Williams (1978) is presented in full in Appendix 8, and Figures 42, 43 and 44. There are, in general, distinct differences in hydrochemistry between the aquifers systems, although there were a few anomalous samples.

The authors support the conclusions of Williams about high sulphates derived from the pyrite quarry at Brukunga, and higher bicarbonate concentrations in the confined aquifer being a reflection of aquifer material. It is also agreed that rigorous sampling would be necessary for any more detailed work.

It should be remembered that surface water chemistry will almost certainly have been modified by man's activities in the past 125 years or so, but that the well-damped groundwater system will respond very slowly. A lack of agreement between surface water and groundwater chemistry near postulated recharge zones may better be attributed to that than to more complicated hydrogeological mechanisms.

TRITIUM STUDIES

Simple tritium sampling was carried out on three observation wells near Lake Alexandrina to test for direct leakage into the confined aquifer. Enough water was pumped from each well to displace the column inside the casing several times, and thus obtain a true sample from the aquifer. The analyses were performed by Mr. Geoff Turner at the CSIRO Division of Soils.

Positive results near the Lake give the only direct evidence for the implied recharge induced by pumping from the confined aquifer. Further work will be reported separately.

WATER WELL DATA STUDY

The records of water wells in the area were systematically examined during August and September 1976.

Table 6 summarises the results.

Most of the data is at least 10 years old, and no systematic field work has been undertaken to record new wells or change in well use since 1967. Construction details are rarely well-documented, and geological logs are uncommon.

As a preliminary step towards upgrading the data, particularly with respect to the well use and construction details, the Water Resources Act has been used and the Schedule 5 form 1 sheets called for the area. These forms will supply basic information and will help in the planning of the field survey work to follow.

TABLE 6

SUMMARY OF WATER WELL DATA, OCTOBER, 1976

WELL USE	NUMBER
Irrigation	195
Non-irrigation	335
Abandoned/disused	230
Inadequate data	259
TOTAL	1 019

Since the proclamation of the Water Resources Act, in June, 1976, about 15 new wells have been drilled.

POLLUTION POTENTIAL

The obvious sources of groundwater pollution in the area are dairy effluent, domestic effluent, winery wastes and pollutants carried into the area by the Bremer and Angas Rivers.

No systematic study has been made, however it is believed that underground waste disposal is rarely practised. A school at Milang has a drainage well tapping the confined aquifer, but this is the only example known.

One of the main local sources of pollution, the Bleasdale winery at Langhorne Creek, discharges its wastes into a usually dry branch of the Bremer River, and later the solids are spread amongst the vines. This is not a major problem as the unconfined aquifer will receive the liquid wastes, and the area is one where downward leakage and withdrawals are both negligible.

Dairy wastes may affect the unconfined aquifer slightly in places, however its water quality is naturally low and rates of water movement slow, and the water resources of the confined aquifer are unlikely to be significantly affected.

The main problem in the area is the increasing pollution load of the Bremer River (Deland, 1976). The river is a major source of natural recharge to both aquifers, and its quality has been seriously degraded by several industries and an unworked pyrite quarry. The pollution is unlikely to have much effect on the groundwater in either aquifer in the short term (less than 10 years) but will affect water supply wells in future years if the problem is not checked.

Very little data is available for the River Angas. The pollution load is expected to be much lighter than that of the Bremer.

MANAGEMENT OF THE WATER RESOURCES

1. Current activity

There is no plan for long-term management of the area's water resources. Some control is being exercised upon drilling methods and surface water quality through the Water Resources Act.

2. Well Permit Applications

All permit applications for new wells are approved, and endorsed for a Class 2 licensed well driller to ensure that drillers working in the area are competent to pressure cement casing. New wells are therefore properly constructed although it is not possible to determine whether they should be permitted. From May, 1977 all permits have been endorsed with a condition requiring the backfilling of any existing well for which a replacement is required. Strata samples are required for some new wells, according to the data on Figure 45.

It has not been possible to refuse permits for new wells to irrigate greater areas of lucerne.

Another management problem is the condition of the 500-800 wells tapping the confined aquifer. Few have cemented casing, and the remainder will fail, or perhaps have already failed unnoticed. Their rehabilitation or proper abandonment is a pressing problem particularly as indications of salinity changes from these wells may be quite misleading. Until a proper well survey has been carried out, little planning or action can be undertaken.

3. Problems

To be effective, management must overcome the salt problem, by removing salt from the groundwater system, or by preventing its inflow, or by a combination of the two.

(i) Artificial drainage could intercept saline water below the root zone, but would be extremely costly to install and maintain, and would create a disposal problem. It would not solve the main salt inflow problem caused by saline groundwater.

(ii) The use of lake or Murray Bridge-Onkaparinga pipeline water for irrigation (in planned, more concentrated areas to minimise pipelines) would overcome the serious salinity problem. However this change in regime would reduce the vertical leakage from the unconfined aquifer, and would be likely to cause a rise in the water table. This has been avoided in the past by the very overexploitation which is causing the salinity problem.

(iii) Artificial recharge to the confined aquifer from the lake or the Murray Bridge-Onkaparinga pipeline could restore the groundwater flow through the area to discharge areas beneath the lake. This would prevent some or all salt inflow by lateral groundwater flow in the confined aquifer, reduce vertical leakage, and transport salt from the confined aquifer. To be effective in the long term the artificial recharge would need at least to balance the discrepancy between river recharge and irrigation withdrawals (i.e. about 20 000 Ml/year for the present intensity of irrigation). This could generate a rising water table problem beneath irrigated land.

(iv) Reducing the area irrigated until withdrawals were less than river recharge would redress the balance and groundwater flow through the area to the lake would again take place. To be effective this would involve a five-fold reduction in irrigation, and again water tables could rise beneath irrigated land.

RECOMMENDATIONS

The problem of managing the overexploited groundwater resources is complex and urgent, and it is strongly recommended that the Engineering and Water Supply Department assign it a high priority.

The main phase of investigation in the area is complete, however some aspects of the hydrogeology may require further work as the alternative management strategies are devised. Some of this work can be predicted, and is recommended here; the need for other investigations may become apparent in the future when computer modelling begins, and various management strategies are considered.

1. Lake Alexandrina Study

A quantitative study of the amount of recharge from the lake to the confined aquifer would be useful because the lake contains by far the best quality water in the area and is the only permanent surface water. This would involve drilling through the lake floor to prove the extent of the aquifer, geophysical work to locate infilled River Murray channels (impermeable boundaries) and further tritium studies of water in the confined aquifer near the lake.

2. River recharge study

Continuous measurement of flows in the rivers provide estimates of recharge. Studies of the recharge mechanisms based on surface mapping, observation well hydrographs, and possibly some drilling would be an integral part of the work, so that the effects on recharge of changes in the rivers' flow regimes could be predicted.

3. Measurement of withdrawals

One of the main uncertainties in all the water budget calculations is the amount of water being extracted from the confined aquifer. This is one of few quantities in the water balance equations which has the potential to be measured accurately and with relative ease, and this course of action is recommended.

4. Monitoring water levels

A programme of monitoring both aquifers is recommended.

Monthly monitoring of pairs of adjacent wells to both aquifers will be used, in addition to those already measured by local farmers. Figure 46 shows the locations of the wells selected.

Comprehensive measurement of all observation wells twice a year to draw potentiometric contours at the end of the irrigation season and just before the commencement of the irrigation season will be discontinued.

5. Salinity monitoring

(a) Continued annual sampling of the grid of irrigation wells is useful to monitor the water quality available to farmers, although it is not a good indicator of aquifer quality.

(b) A set of observation wells comprising new wells, which are constructed with cemented casing, should be established as the wells become available. Where possible the relationship between salinity and time of pumping should be established for each well, and rigorous sampling methods used.

6. Surface water quality

Degradation of surface water, particularly in the Bremer River, has been occurring for some years. As a primary source of recharge for both aquifers surface water quality at worst should be maintained, and preferably improved.

7. Local involvement

Numerous meetings and discussions with farmers have helped the progression and direction of work in the area because of their considerable local knowledge. Without their efforts and obvious concern it is unlikely that the investigation would have been undertaken.

Future work and planning would be strengthened by continuing to consult with them as much as possible.

CONCLUSIONS

The broad investigations by the Department of Mines into the groundwater resources of the area are now complete and it is considered that the next stage will involve co-ordinated studies by several departments to formulate a management policy, and give local landowners a clear indication of their futures as irrigators.

The present level of irrigation cannot be sustained without further deterioration in water quality which will force many farmers to give up irrigation, unless a major programme of artificial recharge to the confined aquifer is undertaken or an alternative water supply provided. Each of these might in turn create a rising water table problem beneath irrigated lands necessitating further capital investment in drainage and saline water disposal schemes.

The problems facing the irrigators are imminent, and the longer the time taken to make and implement management decisions, the fewer the options that will be available as water salinities continue to increase.

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The previous eight geologists each made their contribution to the investigation, and laid the foundations for the present understanding, and for future management.

Sam Hutton's efforts to measure flows in the rivers under difficult circumstances have been appreciated.

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APPENDIX 1

SUMMARY OF GEOLOGY AND GEOLOGICAL HISTORY

GEOLOGY

1. BASEMENT ROCKS

Weathered metamorphic rocks belonging to the Kanmantoo Group have been intersected immediately beneath the Tertiary sequence in a few deep wells. No Permian sediments have been observed in the area although a sequence at least 450 metres thick was identified 20 km to the south west (Ludbrook, in Parkin, 1969) in the Donna 1 petroleum exploration well.

2. Tertiary Sediments

A wide variety of Tertiary sediments have been identified, ranging from Eocene to upper Pliocene in age, recording depositional events near the present margin of the Murray Basin. Isolated outcrops of Tertiary limestone are known to occur in the adjacent hilly areas (Hansen, 1972, in Fig. 4 and Plate 7), and one has been quarried 25 km up the Bremer Valley, near the site of the proposed Monarto development. Thus the modern basin margin does not mark the edge of the marine Tertiary basin. Erosion and uplift along the known structural discontinuities in the area are presumably jointly responsible for the modern margin, at the northwest of the irrigation area. Geophysical and subsurface geological evidence has been used (Williams, 1978 and McPharlin, 1973) to infer the position of a fault which marks the north-western extremity of subsurface Tertiary sediments, where there is an abrupt rise in the basement rocks.

Medium to coarse grained clastic, fossiliferous limestones and sands of varying competence dominate the upper Tertiary sequence (Mannum and Ettrick Formations), with fossiliferous sands, silts and clays of the Buccleuch Group beneath, resting in turn on weathered Cambrian-Precambrian basement. The Tertiary limestone formations in the Murray Basin (see Ludbrook in Parkin, 1969) can be difficult to differentiate in the Angas-Bremer area on lithological grounds. The presence of the foraminifera *Lepidocyclina* is needed to distinguish Morgan Limestone from Mannum Formation for example. In the hydrogeological investigation these problems are irrelevant, and no attempt is made here to distinguish the formations, which together form one aquifer system. Figure 10 shows elevation contours of the top of the Tertiary limestone, important for hydrogeological reasons. Closed drainage basins near the Angas and Bremer Rivers indicates karstic weathering prior to the deposition of the Pliocene sands (Parilla Sand equivalents).

The west-east section and the north-south section along the modern rivers (Figures 5 and 6) reveals that the pre-Pliocene surface generally declines southwards and eastwards. The depression probably represents a broad river valley, with meandering rivers responsible for the deposition of the Pliocene Parilla Sand and Norwest Bend Formation equivalents. These formations overlie the erosional surface, and are possibly reworked in parts to form the early Pleistocene sediments. The Pliocene clastics thin or have been eroded completely near the modern river courses. Unfossiliferous sands interbedded with mottled, mainly grey clays are interpreted as the Parilla Sand equivalent (of upper Pliocene age), and occur throughout the northwest portion of the area. Near the Bremer River they interfinger with fossiliferous clastics correlated with upper Pliocene Norwest Bend Formation by Lindsay and Kim (1971), representing a minor marine incursion.

3. Quaternary Sediments

Following deposition of the Pliocene sediments, a variable sequence of non-marine fluviatile and lacustrine sediments was deposited over the entire area. Figures 8 and 9 are detailed geological sections. Data are mainly available from Department of Mines drilling, particularly from the 1975-76 programme.

The isopach map (Figure 11) shows a simple pattern, with thinning to the south east, approximately perpendicular to the margin of the Tertiary sediments. This suggests a source area to the northwest, a situation similar to the modern Angas and Bremer floodplain. The modern rivers are not perpendicular to the isopachs, inferring that minor north-south tilting may have occurred subsequent to deposition.

The Pleistocene sediments are interpreted as having been deposited in a lacustrine-fluviatile environment with the ancestral rivers meandering and depositing their loads as alternating beds of clastic sediments of extremely variable grain size.

The typical sequence consists of yellowish quartz sand of Chowilla Sand if present, overlain by pale olive grey sandy clay with few strings or nodules of brownish to red sand-silt, passing to brownish silt-sand with minor gravel. This is overlain by a sandy clay sequence, usually brown and rarely olive grey in colour, which contains calcrete nodules in the uppermost portion.

The sections exposed in the River Angas show clearly a recent phase of deposition of fine grey-brown silt in at least one phase (buried soil horizons are regarded as the best interpretation of conspicuous dark layers within the silt). This silt forms the natural levees associated with the rivers. Large wood fragments (up to 2 metres) are common in the silt, and appear to have been deposited with it. CSIRO work in the 1950's carbon-dated the wood at 3540 yrs B.P. ± 230 (Dury, 1964).

An older phase of deposition of unidentified massive, fine, red quartz sand in scour structures in the top of calcretized (?) Blanchetown Clay can also be observed in places.

Geological History (Williams, 1978)

The oldest known geological event recorded is the deposition of greywacke type sediments of the Kanmantoo Group in a large trough which developed as a result of sea floor subsidence along the eastern Mount Lofty Ranges in lower to middle Cambrian times (Thomson, *in* Parkin, 1969). Folding, uplift and intrusion by acid igneous rocks followed in late Cambrian to early Ordovician times (Delamerian Orogeny). The area remained a relatively stable land mass until Permian times when it was subject to widespread glaciation. During this time fluvioglacial and marine sediments were deposited throughout the area and remnants have been intersected in bores to the south in a probable extension of the Troubridge Basin (Wopfner, 1970).

There is no record from then until early Tertiary times when deposition commenced in the Murray Basin, although Daily *et al* (1974) present evidence for widespread lateritization in late Triassic-early Jurassic times and extrusive rocks on Kangaroo Island have been dated as Jurassic. The land surface during Cretaceous and early Tertiary was apparently one of low relief. Deep weathering has been observed in Cambrian rocks beneath Eocene sediments. This may be the same as that observed in Cambrian rocks beneath Oligocene sediments exposed near Hartley and Tertiary sediments in stratigraphic wells.

Tertiary sedimentation in the area was initiated by subsidence and marine transgression in the Eocene. Deposition of Buccleuch Beds, Ettrick and Mannum Formations continued with minor interruptions until the Miocene when it was terminated by uplift, probably along older structures, such as the Encounter Fault (Firman, 1973) and Bremer Fault (Thomson and Horwitz, 1962). The uplift exposed the upper part of the Mannum Formation which was later subject to karstic weathering. It is probable that the sediments were partially flushed of their connate water at this time. This stable land surface was one of flat relief with endoreic drainage, very similar to present day topography of the area northeast of Mannum and near Mount Gambier.

Renewed tectonism along older fractures in late Pliocene times resulted in gentle uplift to the north and west. This tectonism initiated fluvial deposition (and estuarine deposition basinwards) which has continued intermittently until the present time. A low gradient stream system developed under the influence of a moist climate. These streams eroded the Miocene aquifer surface to depths of at least 20-30 m along drainage lines very similar to the present system, depositing fine and moderately well sorted sediments (Parilla Sand and Norwest Bend Formation equivalents).

Flushing of the underlying sediments continued during this period.

Clastic deposition ceased near the end of the Pliocene. A warmer climate led to some lateritization and remnants of this profile can be seen toward the summits of the ranges to the north and west. Climatic conditions were suitable for formation of maghemite, reworked pebbles and grains of which are found in Pleistocene sediments overlying the Parilla Sand equivalents (which in places were themselves ferruginized).

In early Pleistocene times, further but more pronounced uplift resulted in erosion of much of the Pliocene sediment and dissection of the ranges to the north and west. Streams, initially under higher gradients, deposited coarse, poorly sorted sediments onto an aggradational flood plain which covered most of the area, interbedded with finer lacustrine sediments.

At the same time lacustrine sedimentation took place to the south under what is now Lake Alexandrina. Gypsum beds, with dune morphology and interbedded with clays, suggest exposure of the surface of the ancestral lake(s) toward the end of the early Pleistocene. By mid Pleistocene times, clastic sedimentation had again ceased. In the Milang Basin area, carbonate soil profiles (Ripon and Bakara Calcretes) then developed on a fairly stable land surface and under the influence of a drier climate (Firman, 1973). At the same time, sea levels fluctuated and carbonate sedimentation prevailed to the south. The sea level fluctuations must have affected drainage and water table gradients in the area. High levels would impede drainage, tend to flatten the water table and promote evaporative groundwater discharge. Aridity during this period probably influenced the quality of shallow groundwater and may explain the saline pockets found around the northern margin west of Langhorne Creek, away from the present day streams.

In late Pleistocene times fluvial sediments (Pooraka Formation or Blanchetown Clay equivalents) were deposited as a thin veneer over the older alluvium. The climate then became arid, fluvial deposition ceased and a system of northwesterly trending dunes developed. Evaporation pans formed in areas which were previously swamps or floodouts and consequently shallow groundwater became extremely saline.

Finally, a few thousand years ago, a phase of uplift with a contemporaneous moistening climate, revived fluvial erosion and deposition. Further but milder dissection of the ranges to the north took place and the older Pleistocene floodplain was incised by the Angas and Bremer Rivers to depths of up to 10 m. The moister climate led to dune stabilisation by vegetative cover and to partial flushing of swampy areas, although some evaporation pans and shallow saline groundwater still remains.

At present, infrequent floods still cover a wide area of the old floodplain but deposition is restricted to the river channels, flood irrigation and swamp areas around Langhorne Creek and Milang and to Lake Alexandrina. Dunes have to some extent become remobilised in areas where land clearance has stripped the vegetative cover.

APPENDIX 2

CALCULATION OF STORAGE CHARACTERISTICS OF THE UNCONFINED AQUIFER (J. Sinclair)

Sediments from the unconfined aquifer were sampled in 10 cm diameter push-tubes at various intervals over a total depth shown in the table below during the drilling of observation wells BRM 37 and FRL 62.

WELL	DEPTH INTERVAL (metres)
BRM 37	3.0- 3.30 6.0- 6.40 9.0- 9.40 12.0-12.40 15.0-15.40 18.0-18.30 21.0-21.30 24.0-24.40
	BOTTOM OF HOLE : 32 metres
FRL 62	6.0- 6.40 10.0-10.40 13.0-13.40 16.0-16.40 22.0-22.40 28.0-28.40
	BOTTOM OF HOLE : 38 metres

A soil moisture characteristic curve was obtained for each sample (Fig. 23). This is the functional relation between soil wetness and matrix potential. The pressure membrane apparatus yielded values for suctions ranging from 500 cm (50 kPa) - 10 000 cm (1 000 kPa). The pressure membrane apparatus enables a soil water pressure measurement to be made. The air pressure is raised within the chamber of the apparatus containing the soil samples, while leaving the soil water to drain through a semi-permeable membrane and to escape freely at atmospheric pressure. The soil water will be in equilibrium with a moisture content appropriate to the pressure difference between it and the air external to it. The water is at atmospheric pressure and the external air pressure is artificially raised above atmospheric pressure. This is equivalent to the external air at atmospheric pressure and the water under suction.

In the low suction range (60-600 cm) a suction plate assembly was used. In this, the soil samples rest upon a porous plate. The external air is at atmospheric pressure and the water is under the required amount of suction. The pressure difference across the plate is vacuum controlled.

To obtain a value of saturated water content in each sample, the soil moisture characteristic curves were extended down with a similar slope, then at a suction of 10 cm (the approximate boundary of the capillary fringe) the soil was assumed to contain its maximum water content, as for the water table level.

From the soil moisture characteristic curves and incorporating a dry bulk density conversion enabling water content expressed by weight (g/g) to be expressed by volume (cc/cc), a curve for saturated water content versus depth (metres) was constructed for both wells (Fig. 24). Considering the maximum recorded water level in both cases, then empirically allowing a drop in water level of exactly 3 metres, the depletion of water in the overlying sediments could be determined with the knowledge of the soil moisture characteristic curves. The difference in area between the two curves in the unsaturated sediments after a drop in water level of 3 metres is the specific yield of the aquifer (Fig. 25). The specific yield depends not only on the sediment type through which the water level changes, but also on the vertical height of unsaturated sediments.

Results obtained were:-

BORE	SPECIFIC YIELD
BRM 37	0.096
FRL 62	0.117

* For practical purposes a value of 0.1 can be used.

APPENDIX 3

ESTIMATION OF CHANGE IN STORAGE IN, AND LEAKAGE FROM THE UNCONFINED AQUIFER

ESTIMATION OF CHANGE IN STORAGE IN, AND LEAKAGE FROM UNCONFINED AQUIFER

1. Change in Storage

Using the value of storage coefficient (0.1) determined in Appendix 2, it is possible to estimate the loss of water from the unconfined aquifer if the change in potentiometric level with time is known. The water levels show a seasonal fluctuation which has not been measured over a long period, so the long term change in storage is best estimated conservatively using the highest seasonal water levels measured recently and comparing them with the estimated pre-pumping levels. August, 1976 was selected for the modern level.

Data from the aquifer tests (Appendix 4), the contours of head difference (Figure 35) and the geological observations from drilling the upper aquifer observation wells suggests that leakage occurs in the southern part of the area. The zone of leakage is taken to be mainly the area south of the 3 metre potentiometric contour line.

The pre-pumping potentiometric surface was simulated by assuming a linear gradient from the modern 3 metre contour to a zero contour at the shore of the lake, which was close to sea level before the construction of the Goolwa barrages. The area north of the 3 metre contour is not considered to have been depleted much since irrigation began. The change in head per unit area was determined using a coarse, variable grid, selecting values of head difference between simulated pre-pumping levels and August, 1976 levels, and assigning them to appropriate areas of the grid (Figure 37).

The overall change in storage was then calculated using the formula:-