

## 13. CONCLUSIONS

The structural and stratigraphic framework of the regional aquifer system in northwestern Victoria was established in the Tertiary period and has undergone little change since that time.

### Regional Groundwater Flow

At present, as in the past, regional groundwater flow passes northward, from recharge areas in the highlands toward regional discharge zones situated in the lower Loddon Plain and in the Mallee. The principal regional aquifers are the Lower Tertiary Warina Sand of the Renmark Group, the Late Tertiary fluviatile valley-fill gravels and sands of the Calivil Formation (now buried beneath 60 m to 80 m of Quaternary sediments) and its downbasin marine equivalent, the unconfined Parilla Sand.

Where groundwater discharges at the surface it affects the geomorphology, the soils, and the vegetation. For instance, in a riverine landscape, springfed effluent streams may commence flowing during times of higher pressures within the deeply buried, semi-confined Calivil Formation aquifer. These streams have a distinct geomorphic and sedimentologic character, which distinguishes them from other streams on the plain, and they are invariably brackish or saline. It is suggested that the presence of a zone of regional groundwater discharge across the path of a river system may strongly influence stream morphology. Further downbasin, in the Mallee region, groundwater discharge commonly occurs in small salinas and gypsum flats scattered throughout the linear dunefields, and in the larger groundwater discharge complexes - the boinkas. The Raak boinka is over 800 km<sup>2</sup> in area.

The groundwaters of northern Victoria are essentially a sodium chloride type, and, on passing downbasin, the chemistry rapidly evolves towards that of seawater. The ionic ratios of the groundwaters and surface waters suggest that there is an 'oceanic' overprint everywhere present from an early stage of their chemical evolution. Of the processes available, the most satisfactory explanation encompassing the high chlorinity and oceanic character is that of atmospheric salt accession, that is, cyclic salts. Whatever the salt source, it is clear that the evolutionary end point for Murray Basin groundwaters is one where the major ions Cl<sup>-</sup>, Na<sup>+</sup>, Mg<sup>2+</sup>, Br<sup>-</sup> and to a lesser extent SO<sub>4</sub><sup>2-</sup> attain relative ratios similar to that occurring in seawater.

### The Riverine Plains

On the plains, regional groundwater discharge occurs in the Loddon Valley, at the junction of the continental suite with the marine sequences. An important factor in the development of a zone of regional groundwater discharge in the lower Loddon Plain is the change in hydraulic conductivity across the regional groundwater flow path, brought about by the replacement of highly permeable channel gravels and sands of the non-marine sequences by the significantly less permeable marine sands. A second factor contributing to regional groundwater discharge arises from the nature of the aggradation in the Loddon Valley. Infilling of the deep lead trench was in response to base level rises during the Late Tertiary marine transgression. This resulted in an upbasin thickening of the continental suite. The resulting downbasin wedging of the coarse clastic regional Calivil Formation aquifer leads to the development of a regional groundwater discharge zone in the lower and central Loddon Plain. As a consequence of these two geological controls, almost the entire central and lower Loddon Plain has artesian or near-artesian groundwater pressures which convert the plain into a broad zone of regional groundwater discharge.

Despite the aquifers on the plains being confined by 60 m of Quaternary sediments, there is nevertheless a ready interaction between the regional groundwaters and the surface systems, resulting in a delicately balanced hydrological equilibrium.

The delicate hydrological balance within the groundwater system was demonstrated by the rapid 20 km upbasin expansion in the discharge zone of the Loddon Valley in response to several abnormally wet years during 1973-75. In the adjacent Campaspe Valley there has been a uniform

rise of about 0.25 m/year in potentiometric head of the regional Calivil Formation aquifer since the turn of the century, and steady rises of from 0.1 to 0.2 m/year in potentiometric head in the regional aquifers of the Goulburn and Murray Valley systems. Within the Mallee region, rises in the water table associated with the unconfined Parilla Sand aquifer have caused the salinization of the lower depressions, with the reactivation of salinas and gypsum flats in areas which were formally grassed and had tree cover.

The rising water tables now being experienced across northern Victoria, and the subsequent salinization of large areas of both irrigated land and dryland, are seen as a result of increased accessions to the groundwater systems brought about by the removal of trees and the introduction of various agricultural practices, such as irrigation, following European settlement. If the present trends continue it can be predicted that virtually the entire Riverine Plain—irrigated areas and dryland areas—will become a zone of regional groundwater discharge within 100 years. Similar land use changes have taken place across other parts of Victoria. The effect is the widespread appearance of land and stream salinization, both on the plains and in the highlands, in the latter instance the saline cycle of erosion is seen as a major factor in the modification of the Australian landscape.

The present day high incidence of salinity is not unique, but represents the most recent of a number of similar cycles of salinization which occurred naturally in the past and left their imprint on the land, the soils, the geomorphology and the groundwater chemistry. The physiographic evidence of earlier, naturally occurring cycles of higher water tables and salinization provides an important clue to the likely nature, direction and form of future groundwater discharge, with its own attendant salinity problems.

Throughout the study area there is marked contrast in the response of the regional aquifers to changes in surface water budget. During wetter periods, groundwater storages rapidly fill, and potentiometric heads and water tables may quickly rise. On the other hand, increased aridity, while causing almost instantaneous surface drying, has little immediate impact on the groundwater systems—the corresponding decline in water tables at these times is either slow or even nonexistent. Therefore, while high water tables and saline landscapes may readily arise under favourable hydrologic conditions, once this condition is attained it requires a very long and intense period of surface drying to reverse the process. For instance, the presence of prolonged and widespread lunette forming conditions following the regional drying out of the landscape in the late Pleistocene shows that the response of the groundwater systems to climatic change may lag thousands of years behind that of the surface systems.

While the response of the landscape to Quaternary climatic change is partly governed by the intensity of the climatic fluctuation, it is also strongly influenced by the pre-existing hydrologic character of the environment. In this respect, during times of increased aridity, the groundwater systems are a significant buffer to long-term environmental shifts within the drainage basin. The presence of certain groundwater influenced landforms, such as clay dunes, is not so much an indication of palaeoclimate as it is of palaeohydrology. These landforms often reflect hydrologic instability as the basin hydrology either re-adjusts to, or absorbs, the climatic fluctuation.

## The Mallee

The locations of the groundwater discharge features in the Mallee are largely determined by structural and topographic influences. Of special significance is the presence of north trending faults, such as the Danyo and Tyrrell Faults, across the westerly flow paths of the major aquifers.

The discharge of groundwater to the surface creates its own distinct suite of landforms, best seen in the aeolian Mallee landscape, where discharge commonly occurs in the large discharge complexes (the boinkas), or in the many small salt lakes scattered throughout the Mallee. While most of the water in the salt lakes comes from precipitation, the bulk of the salt is derived from the groundwater systems, thereby imposing a large degree of chemical uniformity on the salt lakes of

northern Victoria. In the semiarid continental settings of northwestern Victoria, groundwater brines form from concentrated lake water which seeps into the underlying aquifer. The loss of salt from lakes into the aquifers commonly occurs under high lake regimes, when favourable hydrostatic head differences permit reflux of lake brines. Further salt loss occurs as the lake finally dries out, at which time the concentrated bittern enriched lake waters fall below the salt crust or the lake floor to become the uppermost part of the groundwater system. Once the lake is dry, the salt crust, if present is periodically permeated by a fluctuating water table, and those ions not already at levels of saturation in the shallow groundwater are redissolved from the salt crust and enter the groundwater regime. This hydrodynamic process explains the absence of significant amounts of magnesium and potassium minerals in the thin halite deposits of Victorian salt lakes. It also explains the relative scarcity of halite producing lakes despite the fact that their salinities commonly reach the halite saturation stage during drying.

In the Tyrrell Basin, hydrostatically induced reflux processes have produced a groundwater brine body with salinities ranging from 90,000 mg/l up to 290,000 mg/l. It covers an area of about 200 km<sup>2</sup>, and occurs to a depth of about 70 m. The brines have formed within the last 32,000 years. The presence of dense groundwater infilling the aquifer beneath a lake has a major effect on the nature of lake–groundwater interactions, leading to the virtual capture of the regional groundwater flow system in the vicinity of the lake by means of up-flow along a Ghyben–Herzberg interface. On account of its greater density, the brine body may underflow an otherwise closing groundwater divide, and thereby open the lake basin to outflow via the groundwater systems. Similar high density groundwater brines are found beneath many of the larger salt lakes and boinkas of northwestern Victoria.

While groundwater discharge occurs at a number of points in the landscape, these discharge areas are not the final depositional point for salt carried by the regional groundwater flow system, but, instead, provide temporary storage sites—both at the surface as halite deposits and in the aquifers as brine bodies. The relatively short-lived conditions which favour salt accumulation within individual lake basins are eventually replaced by conditions conducive to outseepage into the aquifer, after which the salt continues downbasin towards the final continental repository—the Murray River. As a consequence, there are no significant thick salt deposits in northern Victoria, other than as groundwater brines.

In the Mallee, the regional groundwaters show marked uniformity and closely resemble seawater in both salinity and in ionic composition. The strong influence of regional groundwater flow on the salt lakes of northern Victoria is seen in their hydrochemistry, which invariably resembles a concentrated regional groundwater. The resulting uniform chemical character of the salt lakes enables the adoption of a chemical framework—based on the chloride and bromide ion concentrations in the lake waters. The chemical analysis of lake waters within this framework provides a guide to the nature of the annual cycle of halite precipitation and re-solution (if it occurs), and the paths taken during evaporitic concentration of lake waters; it also provides an insight into the interactions between salt lakes and the groundwater system.

In the lower regions of the drainage basin, groundwaters are commonly acid, and this has a significant influence on hydrochemical and biochemical processes in the discharge zones. Acidity in the unconfined Parilla Sand aquifer is caused by redox processes acting on iron and sulphur species, partly in response to climatically induced vertical water table movements during the Quaternary and Recent periods. The most significant change in water budgets observed in the late Quaternary sequences in the study area was the drying up of Lake Tyrrell at about 32,000 years BP, when lake water levels and regional water tables fell about 14 m.

In the Tyrrell Basin vertical redox zonation is paralleled by pH zonation, whereby acid groundwaters having a positive  $E_h$  are found closer to the water table, while neutral pH water having a lower  $E_h$  occurs at depth. At Lake Tyrrell acid springwater, with pH values ranging from about 4.0 to 2.6, outflows along the western margin of the lake and on the Tyrrell Creek salt flats to the south. The Tyrrell Creek for much of the time is a base-flow stream with a pH of about 4.

The acid springwater is derived from the regional groundwater. In contrast, neutral pH springwater occurs along the northeastern shoreline, derived from the more saline Timboram–Wahpool reflux brine generated in Lake Timboram. The differences in pH of the two inflowing waters are reflected in the hydrochemical processes active in the spring zone.

The high chlorinity and low pH of the regional groundwaters enable the ready transport of metal ions from upbasin source areas into the discharge zones. Where groundwater discharges around the perimeter of salt lakes, acid conditions in the spring zone are replaced by neutral conditions at the lake edge, thus providing an important zone for the precipitation of previously soluble ions. Iron oxide deposits of groundwater origin are a common feature of the shorelines of the larger discharge lakes, and this process may be responsible for many similar iron deposits and other metal ore deposits found elsewhere in continental settings. Indeed, the regional discharge zones in general and the spring zones of salt lakes in particular must be regarded as significant sites in continental settings for the concentration of metal ions carried by regional groundwaters. The groundwater discharge salt lake setting provides a simple model to explain certain of the syngenetic/epigenetic ore bodies where there is an association of red beds, evaporites and metal sulphides. Here, the source of metal ions may be either localized or disseminated throughout the aquifer system.

Finally, it is noted that the character of the groundwater systems in northern Victoria and their ongoing effects on the landscape are strongly influenced by a number of interacting factors which are themselves varyingly active through time. Of these factors, time itself is also significant in the flat Australian landscape where low hydraulic gradients produce long groundwater residence times. The climatic factor is of special importance since it determines total water availability. It subsequently controls the nature of the groundwater - surface water interactions which in turn strongly influences hydrochemistry and geomorphology. The nature of the interactions between the groundwater systems and surface waters, both determines in part, and is partially determined by, the positions and forms of the hydrological thresholds existing within a drainage basin. The positions of the thresholds fluctuate both temporally and areally in response to climatically induced variations in surface water availability.

Therefore, for a full understanding of the character of the groundwater systems, their evolution and their influence on surface processes, the groundwater and surface water systems must be regarded as aspects of a single integrated non steady-state flow system.