GROUNDWATER FLOW IN THE CAMPASPE AND LODDON VALLEYS OF NORTHERN VICTORIA: AN ENHANCED ROLE FOR THE SHEPPARTON FORMATION

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Recent work on the fluvial aquifer systems of the Campaspe and Loddon Valleys in northern Victoria has shown that a two-aquifer conceptualisation and use of 'typical' hydraulic parameters for the Calivil Formation regional aquifer and its notional aquitard the Shepparton Formation, may mask the true nature of their interactions. In the highland tracts of the Loddon and Campaspe Valleys the regional aquifer system comprises the Calivil Formation and much of the Shepparton Formation. On the southern Loddon Plains, intensive groundwater development occurs from both the Calivil Formation and a Shepparton Formation 'sand sheet' aquifer, which follow separate paths across the plain, dictated by an evolving late Tertiary palaeogeography. Whatever the aquifer system invoked, the emphasis has been on horizontal down basin flow. At other times, upbasin flow of saline water under reversed hydraulic gradients into irrigation areas has been stressed, with the concerns for aquifer salinisation. Yet it is shown that in the Campaspe Valley, vertical flow from overlying or underlying aquifers poses a far more immediate salinity threat to the regional Calivil Formation aquifer than upbasin horizontal flow. Overall, the role of the Shepparton Formation as a significant aquifer system, and elsewhere as a conduit for salinisation via vertical flow, has been largely overlooked. More generally, the lithological variability of the Shepparton Formation across north central Victoria strongly influences the behaviour of the regional aquifer system, including groundwater throughflow and groundwater development. This is especially clear on the permeable Campaspe Fan, which is the principal recharge area in the Campaspe Valley, with recharge coming from direct precipitation, the Campaspe River, irrigation, and the Waranga-Western and Campaspe No 1 channels.

Key words: hydrostratigraphy, geomorphology, recharge, aquifer interactions, aquifer salinisation

THE RIVERINE PLAIN AQUIFERS AND THEIR MANAGEMENT REQUIREMENTS

The basic hydrostratigraphy of the aquifers systems on the Riverine Plain in northern Victoria was established some 30-40 years ago (Macumber 1973, 1978a, 1978b) with a three-fold division into the Renmark Group, the Calivil Formation and the Shepparton Formation aquifers. The latter, although an aquifer in its own right, is often deemed to be an aquitard to the regional Calivil Formation aquifer. The Calivil Formation, at times together with the Renmark Group, forms the principal aquifer system on the southern Riverine Plain in both Victoria and NSW.

Following the commencement of the dry years in 1997, surface water became less available and greater emphasis was placed on groundwater, with a subsequent fall in groundwater levels. Through the extensive monitoring system, groundwater level and salinity data variously covering the past 40 years was available, from the pre-development period in the late 1960s onwards. This showed that across the major irrigation areas, seasonal groundwater levels had fallen significantly below their former levels, invoking much debate about what was sustainable. Concerns grew about the possible depletion of the groundwater resource.

Additional hydrogeological studies were carried out in recent years to underpin the development/review of groundwater management plans for the regional aquifers on the Victorian parts of the Riverine Plains, including the Loddon, Campaspe and Murray Valleys (Katunga Groundwater Management Area). This led to a re-assessment of the earlier understandings on the nature of the aquifer/groundwater and inter-aquifer interactions, resulting in some fundamental modifications/additions to the conceptualisation of these relationships especially that of the Shepparton Formation aquifer and its implications for groundwater recharge, vertical flow, and aquifer salinisation.

THE CALIVIL/SHEPPARTON FORMATION AQUIFER SYSTEM WITHIN THE HIGHLAND TRACT OF THE LODDON VALLEY

The main valley system of northern central Victoria was initiated in early Tertiary times and infilled in the lower to middle Tertiary with carbonaceous Renmark Group sediments, which were also deposited extensively further downbasin across the plains. The presence of Permian glacial sediments concentrated along the Loddon Valley, and encountered commonly in the mines and in drilling, suggests that the valley is to some extent tectonically controlled, thereby preserving the glacials (Macumber 1978c). In middle Miocene times, the Riverine Plain was an extensive peneplain, referred to as the Mologa Surface (Macumber 1978a, 1991), which was formed across Renmark Group sediments and Palaeozoic sediments, metasediments and granites. In perhaps the early part of the upper Miocene, the highland valleys were rejuvenated and deepened, with a phase of downcutting removing much of the Renmark Group valley fill. The exhumed valleys were then infilled by essentially quartzose sands and gravels of the Calivil Formation (Macumber 1973), implying a previous period of deep weathering and flushing of the fines from the system. Whatever clay occurs in the Calivil Formation is often white and in thin discontinuous bands. The sands, gravels and thin white clays of the Calivil Formation are seen as including, and also being an extension of, the highland Deep Lead system of Hunter (1909), passing across the plains to become tributary to a trunk Murray Valley system in the north. The Loddon Valley system has an extensive highland tract with tributaries including the entire Avoca Valley system (Macumber 1991). The highland valley tract passes onto the plains in the vicinity of Bridgewater. By contrast, the highland tract of the Campaspe Valley lead system is relatively small, commencing downstream from Eppalock northeast of Bendigo and passing onto the plains near Elmore. The respective deep lead systems, whatever the aquifer combination, are the major path taken by groundwater passing northwards from the highlands to the plains (Fig. 1), where they fan out to become a sheet aquifer system.

Traditionally, the principal fluvial aquifers of northern Victoria are considered to be the lower to middle Tertiary Renmark Group, the late Tertiary Calivil Formation and the shoe-string sands within the otherwise clayey Shepparton Formation (Lawrence 1975). The Shepparton Formation mostly occurs to a depth of 60 to 65 m and blankets the deeper aquifers where present; it is commonly portrayed by its hydraulic parameters as a notional aquitard to the deeper regional aquifers. The 20 to 60 m thick coarse grained Calivil Formation is the principal regional aquifer both within the highlands and on the plains. Yet in both the highland tracts of the Loddon and Campaspe Valleys, the Calivil Formation forms part of a dual-formational aquifer system together with the lower sandy part of the Shepparton Formation. On the Campaspe Plains, the Calivil Formation forms a dual aquifer with the carbonaceous Renmark Group (Tickell & Humphreys 1987).

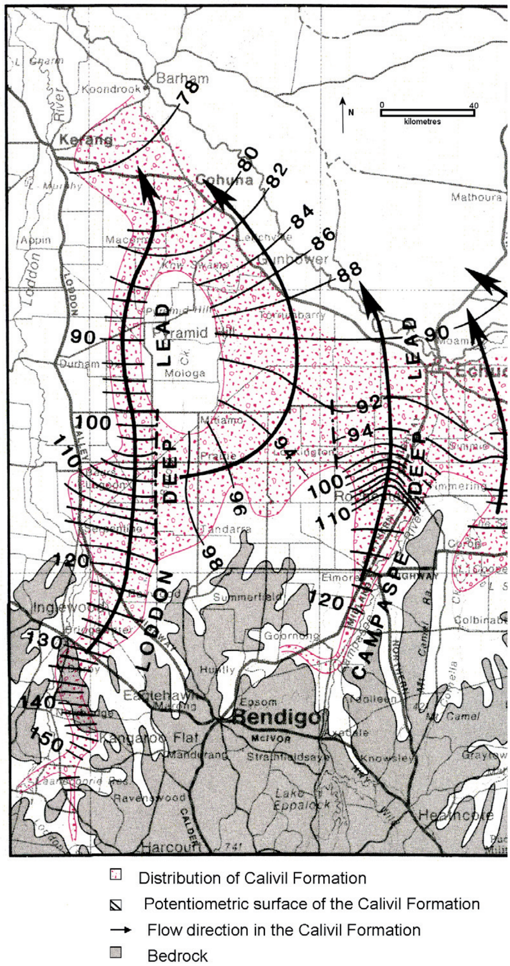


Fig. 1. The position and potentiometric surface of the Calivil Formation in the Loddon and Campaspe Valley Deep Lead Systems in 1990 (Macumber 1991).

Cross sections through the Loddon Valley at Laanecoorie and Woodstock (Hunter 1909) show the classic divisions identified within the highlands during the gold mining era, with the division into the coarser grained gravel and pebbly 'Wash' and the overlying sands 'Drift' coming to within 20 to 30 m of the groundsurface. They are in turn overlain by clays. For instance, near Eastville, Hunter (1909) shows a thick sand sequence present from the valley base at 90 m depth to within about 20 m of the surface (Fig.2). The section line crosses the Loddon Valley close to the 73672 bore (locality Fig. 3) which contains relatively fresh water with a salinity of ca 1300 EC µS/cm.

More recent drilling by Goulburn-Murray Water (G-MW) showed a similarly thick sand/gravel valley fill extending from Eastville northwards, about 30 km to Bridgewater at the highland front. The sand/gravel sequence is overlain by a more clayey part of the Shepparton Formation, which extends to 20-30 m below the surface. Thick sand sequences were encountered in the G8010270-5 series bores between Eastville and Bridgewater (locality Fig. 3). The full thickness of sand is clearly shown in the bore electrical conductivity logs, as can be seen in the case of bore G8010270/04, where it extends from 23 to 100 m (Fig. 4). Similarly, at the G8010271/03-4-5 piezometer nest site to the north (locality Fig. 3), sand occurs from 28 m to basement at 99 m in bore G8010271/03. Here, basalt is present from 8.5 to 18 m (Table 1). At Bridgewater the trunk lead system passes from the highland tract out onto the plains. A 100 m thick sand/gravel sequence occurs in the 51640 (Bridgewater 15) bore, commencing within 21 m of the surface and continuing to basement at 120 m, with only a few intervening thin clay seams (Table 1). This is perhaps the thickest known sand sequence in the Loddon Valley.

The lower part of the sand/gravel sequence within the highland tract is Calivil Formation and the upper part Shepparton Formation, however the continuity of the sand throughout much of the profile masks the boundary between the two formations. More generally, the sandy lower part of Shepparton Formation together with the Calivil Formation forms the regional aquifer within the highland valley from Eastville northwards. The classical division into a deeper regional Calivil Formation aquifer and a notional clayey Shepparton Formation aquitard, as commonly occurs across the Riverine Plains, does not occur in the highland tract of the Loddon Valley upbasin of Bridgewater. Furthermore, there are identical water levels at all depths spanning the Calivil and Shepparton Fomations in the 51640 piezometer nest at Bridgewater (Fig. 5) and all the G801027 series piezometers including the shallow basalt in the G8010271/04 bore (Fig. 6 and Fig. 7). This demonstrates very strong connectivity and no vertical flow across the entire valley-fill sequence from Eastville to Bridgewater which behaves as an essentially un-

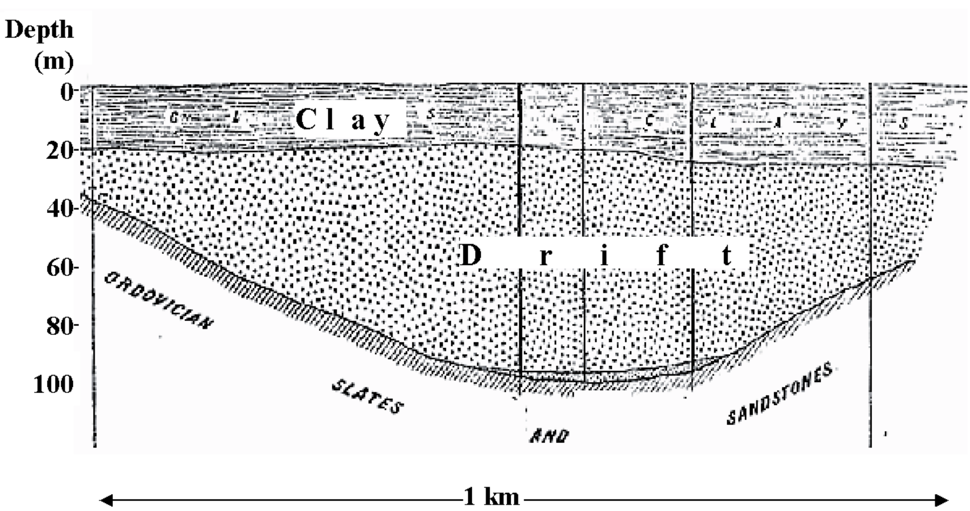


Fig. 2. Section line across the Loddon Valley at Eastville (Hunter 1909).

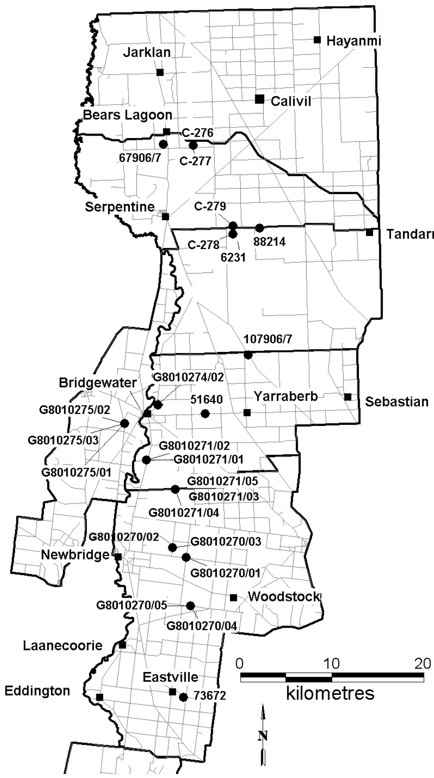


Fig. 3. Locality plan for monitoring bores, highland tract of the Loddon Valley.

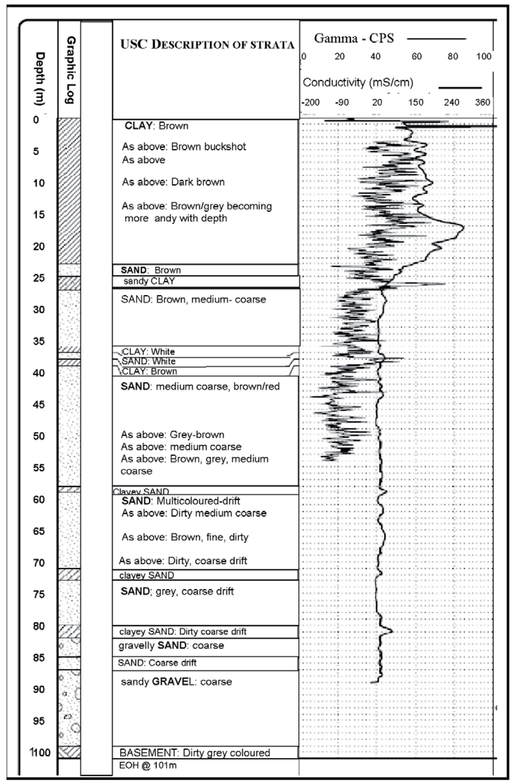


Fig. 4. Lithologic, gamma and conductivity logs of the G8010270/04 bore (from URS 2006).

confined aquifer. The response to development will therefore differ markedly from other areas where there is varying degrees of confinement of the Calivil Formation aquifer, in that specific yield will become more relevant than confined storativity, implying significantly lesser drawdowns when pumping as the aquifer is dewatered.

The boundary between the two formations becomes clear on the eastern Loddon Plain where the Shepparton Formation is present as a typical finer grained clayey sequence with scattered shoe-string sands, and the Calivil Formation is quartzose sand and gravels with some interbedded white clays. Across the plain, the Calivil Formation occupies a 60 m deep by 3-4 km wide trench cut into the Mologa Surface. While commonly overlying the Calivil Formation in the east, on the western Loddon Plain where the Calivil Formation is not present, the Shepparton Formation sits directly on the Mologa Surface.

THE AQUIFER SYSTEM ON THE LODDON PLAIN

Beyond Bridgewater, the Calivil Formation may be traced northwards across the Loddon Plain from the highland front towards Cohuna, near the Murray River (Macumber 1978a, 1991), where the Loddon system is graded to, and junctions with, a trunk Murray Valley system.

On passing downbasin, the thickness of the Calivil Formation infilling the Deep Lead trench decreases to about 20 m, due to the onset of the late Miocene marine transgression which led to the deposition of the Parilla Sand as a widespread sand sheet across northwestern Victoria (Fig. 8). On the lower Loddon Plain, the Parilla Sand at times grades laterally into red and blue grey clays of the Shepparton Formation referred to as the Yando Clay (Macumber 1991). The transgression caused an upbasin retreat of the zone of coarse grained sedimentation in response to rising

Table 1. Lithology of the 51640 (Bridgewater 15 bore) and G8010271/03 bores showing thick sand sequences.

From (m)	To (m)	Lithology 51640	Depth From	Depth To	Lithology G8010271/03
0.0	0.3	Surface soil	0	1	Topsoil
0.3	3.1	Clay	1	3	Clay red brown
3.1	15.2	Clay with fine gravel	3	8.5	Clay grey
15.2	21.3	Sandy clay	8.5	18	Basalt
21.3	22.9	Gravel	18	26	Clay reddish
22.9	36.6	Yellow sand	26	28	Clay grey
36.6	44.2	Yellow sandy clay	28	31	Sand brown
44.2	49.7	Yellow medium sand	31	36	Sand grey brown
49.7	51.8	Red sand	36	43	Sand fine grey brown med mud loss
51.8	57.3	Yellow sand	43	59	Sand fine grey brown poor mud
57.3	59.4	Fine yellow sand	59	62	Sand grey fine med mud loss
59.4	61.6	Coarse sand	62	67	Sand coarse grey med mud loss
61.6	65.8	Fine sand	67	70	Sand reddish clay mud loss
65.8	66.1	White clay	70	78	Sand brown & clay normal mud loss
66.1	78.0	Coarse sand	78	99	Sand white very coarse gravel
78.0	78.6	Grey and yellow clay	99	101	Basement
78.6	87.5	Coarse sand			
87.5	89.0	Cemented sand			
89.0	90.8	Coarse sand			
90.8	95.1	Cemented sand			
95.1	119.5	Coarse dark grey sand			
98.2	108.5	Coarse sand and gravel			
108.5	108.8	Yellow clay			
108.8	119.5	Coarse sand and gravel			
119.5	125.0	Blue clay (bedrock)			

base levels, and hence a northwards wedging of the Calivil Formation aquifer. The northwards thinning of the Calivil Formation causes regional groundwater discharge across the central Loddon Plain which is exacerbated at times of high groundwater pressures, as occurred between 1973 and 1997 (Macumber, 1991).

The sandy lower part of the Shepparton Formation emerging from the highlands diverges westwards from the course taken by the Calivil Formation between Bridgewater and Serpentine, and instead passes downbasin as a discrete sandy zone within the Shepparton Formation, towards Bears Lagoon and Jarklan. The separate paths of the Shepparton Formation and Calivil Formation depositional systems and hence sand sequences once on the plain, are clearly marked by the distribution of irrigation bores, groundwater allocations, and seasonal drawdown patterns beyond Bridgewater (Fig. 9 and Fig. 10 - Bore A). By contrast further to the east, sand occurs as the more typical lenses or shoe-string sands scattered throughout the otherwise clayey Shepparton Formation (Bores B and C, Fig. 10).

The vertical and lateral distribution of sand across the sand sheet and strong hydraulic connectivity along the sand sheet is shown by lithologies and hydrographs of bores at sites located south of Serpentine (bores 278 and 279), and a further 11 km north at Bears Lagoon (bores 67906 and 276) - locality Fig. 3. Both localities contain sites where rises in regional groundwater levels during the wet period from 1973-75 saw groundwater discharge causing otherwise dry streams to flow. The outflow continued for several decades and was especially evident during drought years such as 1976. The northern bores at Bears Lagoon are located 2.5 km apart and show thick sand sequences overlying the Mologa Surface (Fig. 12). Clay units also occur in the sequences, since the sand sheet is a zone of preferential, not exclusive, sand deposition. Piezometers inserted in the lower sand and upper sand units of the 67906/7 nest, and the lowest sand unit in bore 276 gave virtually identical hydrographs which were in turn almost identical, albeit at a lower elevation being further downbasin, to hydrographs from sand sheet bores 278 and 279 located 11 km to the south (Fig. 11), which indicates

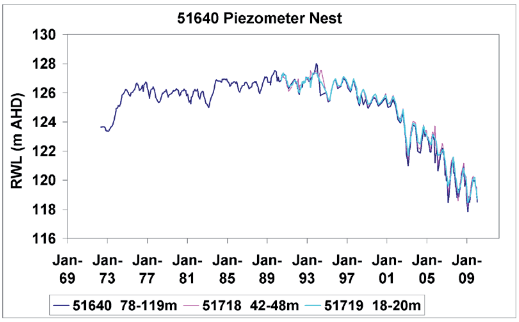


Fig. 5. Hydrographs of the 51640, 51718 and 51719 piezometer nest showing conformity of levels at all screened depths.

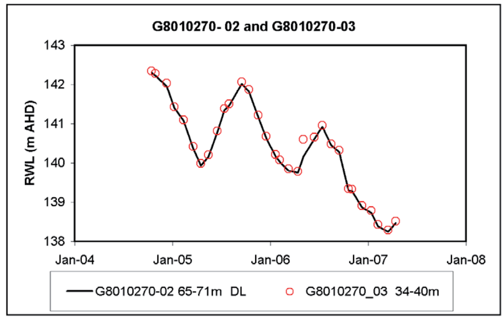


Fig. 6. Hydrographs of the G8010270/02 piezometer nest.

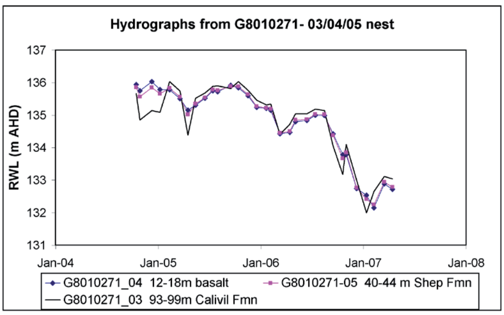


Fig. 7. Hydrographs of the G8010271/03-4.5 piezometer nest.

near identical responses both across and along the aquifer.

The westwards deviation of the sand sheet from the Calivil Formation trench is best explained by a change in the palaeogeography of the Loddon Valley in late Miocene times with the marine transgression, which deposited the Parilla Sand as a transgressive-regressive sand sheet across northwestern Victoria, entering the mid Loddon Valley from the west (Macumber 1978a, 1991). Fossiliferous Parilla Sand outcrops from Boort to beyond Kerang on the Gredgwin Ridge to the west of the Leaghur Fault, and is overlain and interfingers with the fluviatile Shepparton Formation beneath the mid-Loddon Plain. The definitive echinoid *Lovenia woodsi* occurs in the uppermost parts of the sequence west of Kerang, showing that the top of the Parilla Sand spans the Pliocene-Miocene boundary. The Parilla Sand at this point is about 84 m thick and the bulk of sequence, if not all, is Upper Miocene in age. Whereas the Calivil Formation in the Loddon Valley was graded to the trunk Murray Valley system in the north, the Shepparton Formation was graded to a shoreline established in the central Loddon Valley, further to the west. The position occupied by the sand zone in the lower part of the Shepparton Formation passes from about 20 m below the ground surface to the Mologa Surface, commonly at ca 60 - 65 m (Fig. 11). This is the same interval occupied by the marine Parilla Sand beneath the western part of the central Loddon Plain. On this basis it seems likely that the lower Shepparton Formation sand sheet on the plain and its upstream continuation within the highland tract of the Loddon Valley, is equivalent in age to the Parilla Sand, and therefore is Upper Miocene to lowermost Pliocene in age (Fig. 13).

In the Loddon Valley, there was a steady rise in groundwater levels up to 1997, followed by a steady fall commencing with the onset of the prolonged dry phase and a resulting increase in groundwater extractions (Fig. 5). During the 1973-75 wet phase, the recharge-discharge hinge line migrated 20 km upbasin (Macumber 1991). At the height of the rise, groundwater discharge from both the Calivil Formation and Shepparton Formation aquifers instigated base-flow streams on the plains, with their own distinct morphology. The stream traces produced by regional groundwater discharge are common across the upper Loddon Plains indicating that surface discharge accounted for significant quantities of down-basin groundwater flow during wetter periods in the past whenever regional hydraulic heads became artesian in the upper Loddon Plains.

Both the Calivil Formation and Shepparton Formation sand sheet hydrographs show a strong season-

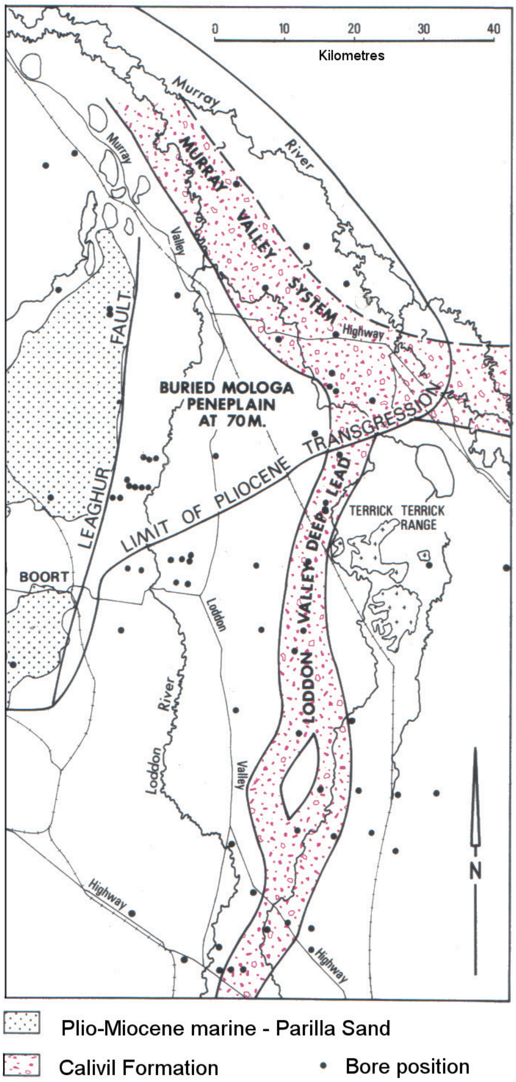


Fig. 8. The Loddon Valley Deep Lead from Bridgewater northwards to its junction with the Murray Valley system and the inland limits of the late Tertiary marine transgression in the central Loddon Plain (Macumber 1991).

al fluctuation in response to groundwater pumping. As groundwater levels fall, the shallow Shepparton Formation shoe-string sand aquifers and the water table fall do not fluctuate, but instead fall at the same rate as that of the top of the seasonal recovery curves of the regional Calivil Formation aquifer (Fig 14 and Fig. 15). The absence of pumping induced seasonal fluctuations in the shallower bores is due to buffering within the clayey Shepparton Formation. Similarly muted hydrograph responses in the Shepparton Formation to that of strong Calivil Formation fluctuations occur in the mid-Campaspe Valley (Fig. 31). In such instances the total groundwater system behaves as a single entity and drains as the regional groundwater levels fall, with losses from storage in both the aquifers; recharge is limited and its rate determined by the seasonal fluctuation differential. Therefore groundwater pumping may alleviate salinity problems in these settings by lowering water tables.

SURFACE - GROUNDWATER INTERACTIONS IN THE CAMPASPE VALLEY

Perhaps the most significant contribution to the understanding of groundwater flow on the Campaspe Plain was that from Tickell (1983) and Tickell & Humphreys (1987) who showed that in crossing the Campaspe Plain from near Elmore to near Echuca there was a pick up of ca 15 000 ML/yr of water in the regional Calivil/Renmark aquifer from ca 2860 ML/yr of throughflow near Elmore to 17 800 ML/yr south of Echuca. They suggested that between 36 mm and 41 mm/yr of groundwater recharge on the plain was required for this increase. Later modelling carried out by Chiew and McMahon (1992) suggested 30 to 55 mm/yr recharged the shallow Shepparton Formation aquifer across the Campaspe Plain.

In addition a number of isotopic and chemical studies were conducted, to examine recharge and flow across the Campaspe Plain (e.g. Calf et al. 1986; Arad & Evans 1987; Cartwright 2010). Calf et al. (1986) observed that shallow water less than 30 m was modern; the deepest modern water was at 52 m in the 60196 bore which overlies bedrock in an area to the west of the Calivil Formation subcrop. They note that while there was a general increase in age on passing downbasin, the pattern was more complicated since the bores drew water from near the top of the Calivil Formation which may have contained varying amounts of leakage from the Shepparton Formation. Furthermore they noted that there was no clear relationship between groundwater depth and age, or between the age of the water in the Calivil/Renmark aquifer and the Shepparton Formation. Arad and Evans (1987) considered recharge was from two sources. Firstly from the upstream part of the basin where the shallow Shepparton Formation sequences are thin and more permeable; and secondly across

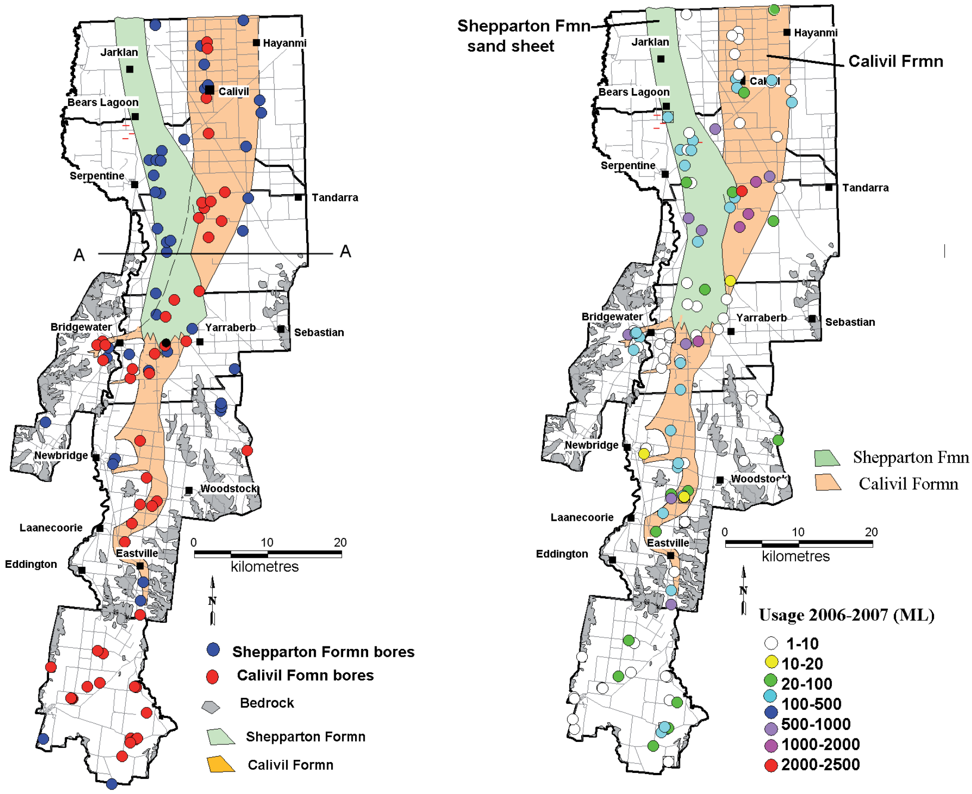


Fig. 9. Distribution of groundwater allocations by aquifer and usage in the Mid-Loddon Water Supply Protection Area.

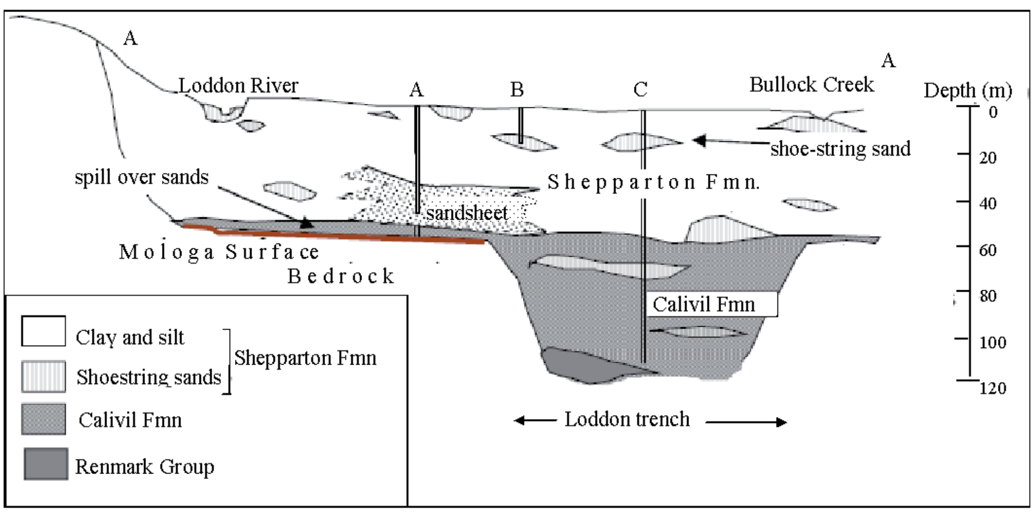


Fig. 10. Diagrammatic figure showing the distribution of sand/aquifer types on the southern Loddon Plain – Section line on Fig. 9.

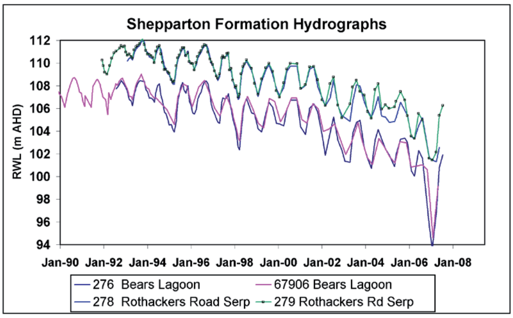


Fig. 11. Similarity in hydrograph response of Shepparton Formation sand sheet bores 276 and 67906 at Bears Lagoon and 278 and 279 located 11 km to the south, beyond Serpentine.

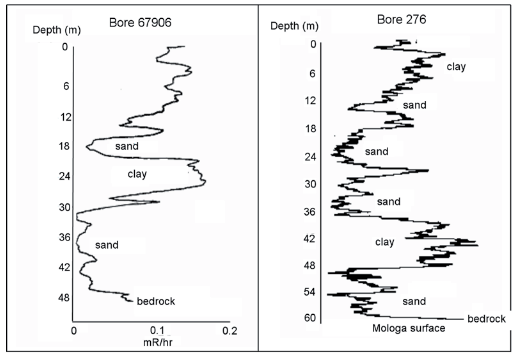


Fig. 12. Gamma logs showing sand distribution in bores 67906 and 276 located 2.6 km apart, transversely across the sand sheet at Bears Lagoon.

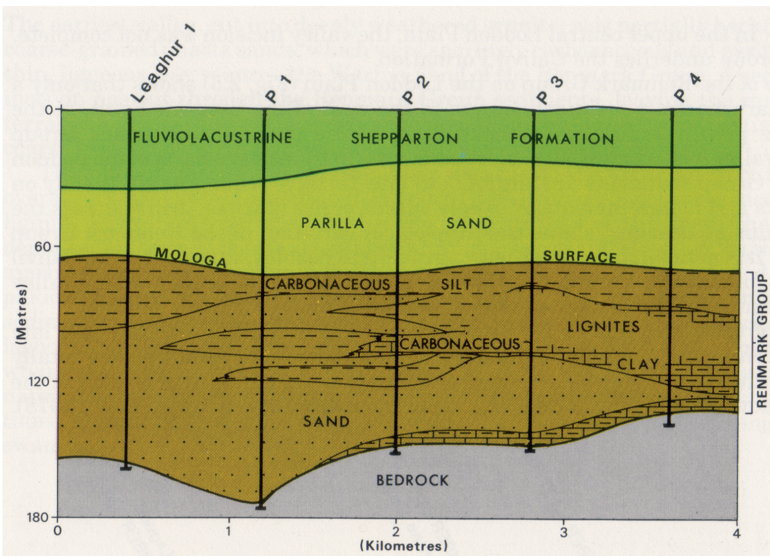


Fig. 13. Cross–section through the mid-Loddon Plain at Yando showing the marine Parilla Sand transgressing across the Mologa Surface and occupying the same stratigraphic position as the Shepparton Formation sand sheet (above).

the basin by vertical movement of water from the Shepparton Formation, whose heads are everywhere higher than those of the Calivil Formation. They showed that the deeper water in the Millewa 1 bore in the north was a mixture of Shepparton Formation and Calivil/Renmark water. On the other hand, Cartwright (2009) on the basis of 87Sr/86Sr isotope ratios in the Calivil-Renmark Group aquifer, concluded that recharge of the Calivil-Renmark aquifer through the Shepparton Formation occurs mostly in the area to the south of Elmore. He comments that groundwater from the Shepparton Formation is not leaking into the deeper Renmark Formation because of its substantially lower hydraulic conductivity. However, this view is clearly at odds with this study and other studies above, and that of Tickell and Humphreys (1987) who show that the bulk of the throughflow that passed into NSW from the Campaspe Valley came from recharge occurring between Elmore and the Murray River.

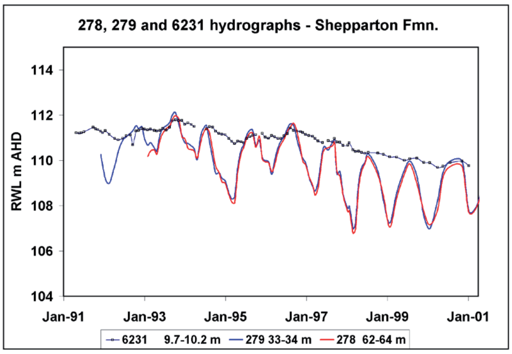


Fig. 14. Hydrographs of Shepparton Formation sand sheet bores 278, 279 and shallow bore 6231 piezometer nest showing falling water table (6231) in response to falling levels in the Shepparton Formation aquifer (Loddon Valley).

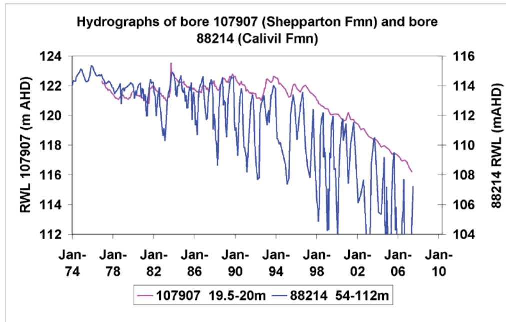


Fig. 15. Concomitant fall in groundwater levels in both deep (88214) and shallow aquifers (107907) between Bridgewater and Serpentine after 1996.

GROUNDWATER RECHARGE IN THE CAMPASPE VALLEY

The characteristics of the aquifer responses to recharge and discharge observed on the Loddon Plains is also the case on the Campaspe system**,** where the Campaspe River flows within a several hundred metre wide terrace system represented by the Coonambidgal Formation (Fig. 16). The channel sands of the river are at the same depth as the basal aquifer sand of the Coonambidgal Formation forming the terrace, and hence there is strong hydraulic interconnection between it and the river (Fig. 17).

The loss of water from the river to the surrounding areas and deeper aquifers is therefore a function of the connectivity between the Coonambidgal Formation and the surrounding Shepparton Formation. These relationships are clearly seen in a line of 7 bores (bores 5755 to 5761) near Elmore where there is good connection from the river via the Coonambidgal Formation into the Shepparton Formation, and hence recharging the regional aquifer. Two observation bores (5759 and 5760) lie within the terrace system of the Campaspe River, while others (5755, 5756, 5757 and 5758) are situated in the Shepparton Formation to the east of 5759 and 5760; bore 5761 is to the west and also in Shepparton Formation (Fig. 18).

The furthest bore (5755) two km from the river is saline. In the case of the two bores located on the Coonambidgal Formation terrace, high river flow induces recharge spikes in the bores (Fig. 19). The connectivity shown by the hydrograph responses in 5759 and 5760 extends laterally eastward into the area of bores 5758, 5757 and 5756 located in the Shepparton Formation which behave in a similar manner to that of the Coonambidgal aquifer, responding to peaks in river flow (Fig. 20).

The hydrographic evidence of river-groundwater connection is supported by the low salinity of the bores. Bores 5755 further to the east and 5761 to the west (Fig. 18) lie outside the zone of river influence as shown by their different hydrograph responses and their significantly lower levels. (Fig. 20) and the higher salinity shown by bore 5755. The area between bore 5760 and 5756 is a freshwater recharge mound sourced in the Campaspe River.

Beyond Elmore, there is a major change in the landscape as it passes from the highland tract to the plains tract, where the river is no longer contained within bedrock boundaries. Instead the river is confined to the west by a large alluvial fan, referred to as the Campaspe Fan (Macumber 2005). The fan is formed by ancient northwards trending 'prior' streams after the ancient Campaspe River emerged from the confined highland tract and fanned out across the plains thereby dumping its coarser grained sediment as channel, levee and near flood plain deposits (Fig. 21).

The levees of the prior stream sediments have built up above the general level of the plain and now form a slightly elevated area flanked by the Campaspe River to the east and the Bendigo Creek–Picaninny Creek to the west, together forming twin lateral streams. The apex of the fan is near Elmore and it extends across the central Campaspe Plain. The northern extent of the fan passes just beyond the

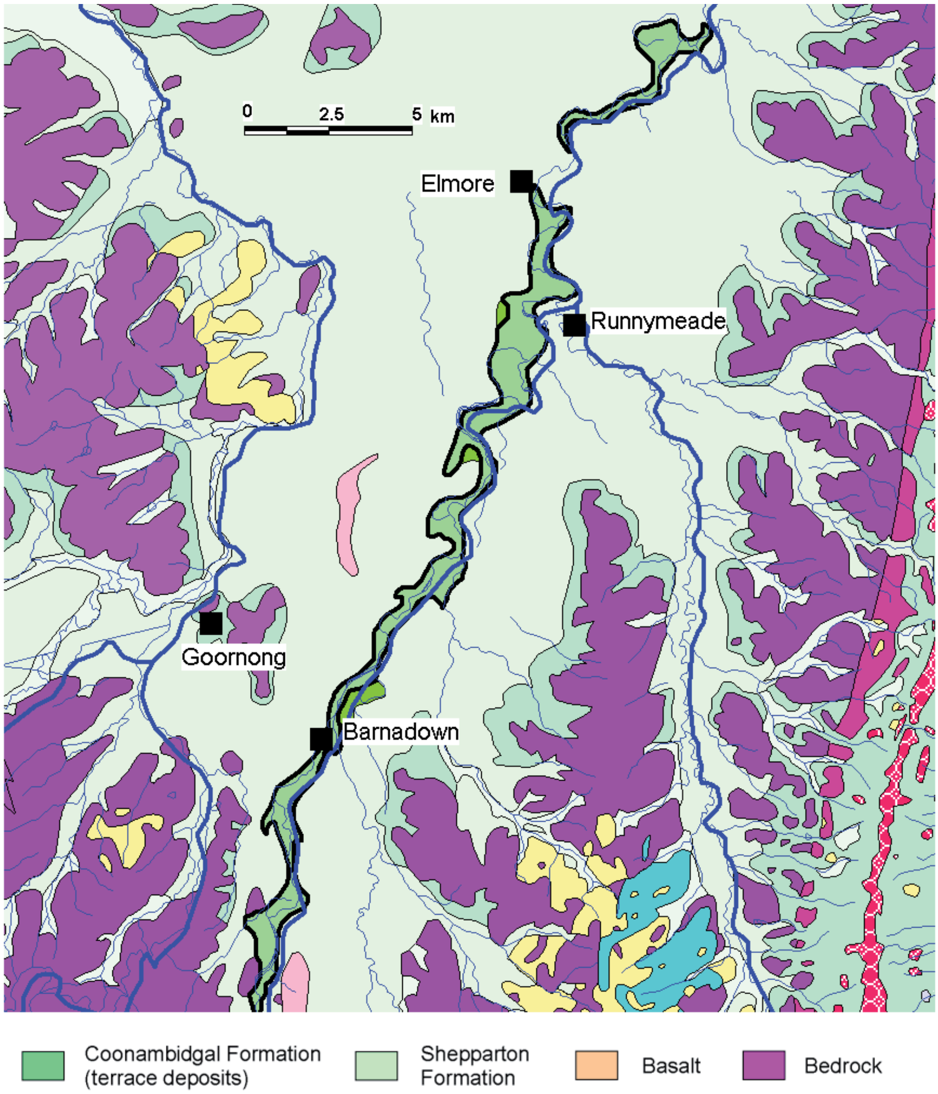


Fig. 16. Geology of the Campaspe Plains with the Coonambidgal Formation strip aquifer along which the Campaspe River flows.

Waranga Channel which is obliged to arc to the north to circumvent the raised fan (Fig. 21). On maps, the fan, being high in the landscape is readily identified by the lack of streams.

The Campaspe Fan is an area of sandy permeable soils formed on the coarser grained prior stream and levee sediments. It coincides with the Campaspe Irrigation District (CID) to the south of the Waranga-Western Channel. The role of the Campaspe Fan is central to any understanding of the behaviour of the aquifer system during groundwater development in the Campaspe and Rochester irrigation districts. A map of the hydrogeology of the Elmore-Rochester area (Ife 1988) with a salinity/yield matrix shows the distribution of fresh water in the Coonambidgal sediments along the river (Fig. 22) near Elmore, where the freshwater plume extends both lateral to the Campaspe River and northwards down the Campaspe Fan (see below). The east-west flowing Waranga Channel transects the fan in the north, cutting the path of the various north trending prior stream systems and thereby recharging the aquifer system as shown by

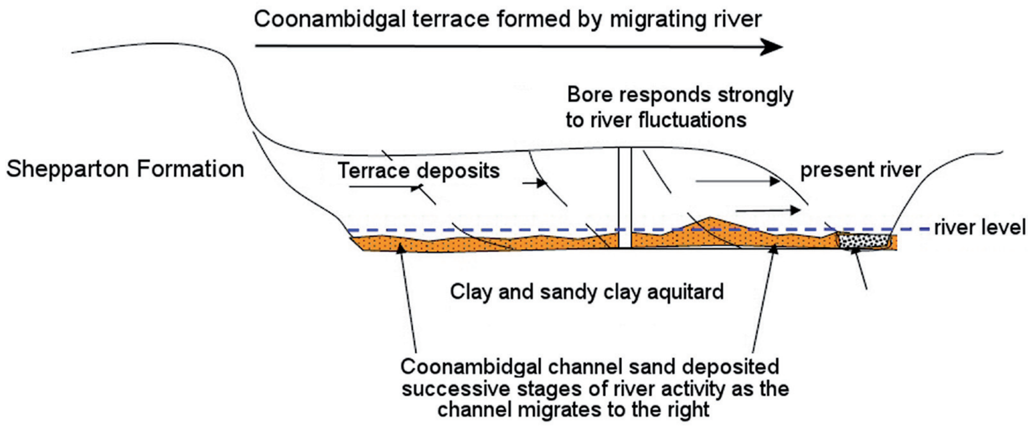


Fig. 17. Relationship between the river, the basal channel sands of the Coonambidgal Formation and the Shepparton Formation at Avonsmore Bridge (diagrammatic).

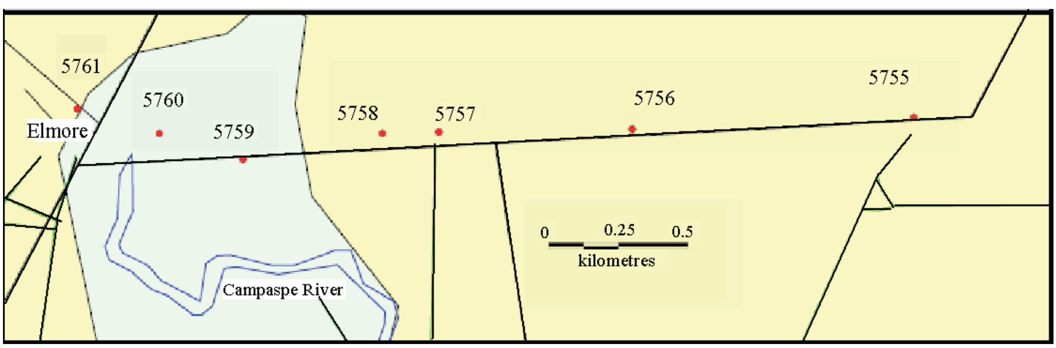


Fig. 18. Location of 5759 and 5760 on the Coonambidgal terrace (green) near Elmore.

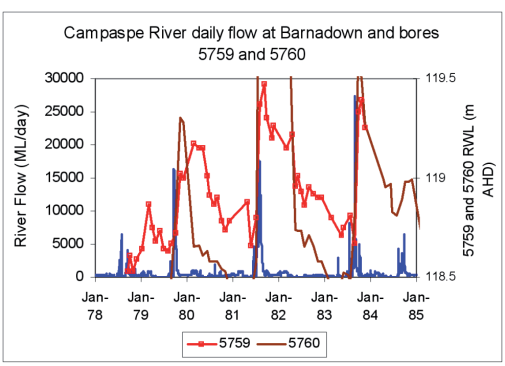


Fig. 19. Campaspe River flow (blue) and groundwater level response for the 5759 and 5760 bores located in the terrace area of the river.

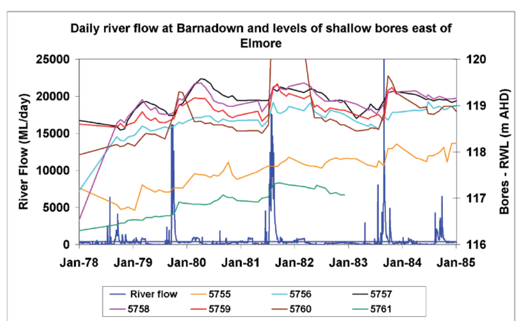


Fig. 20. Hydrographs of the 5755-5761 piezometer line with mound bores 5756 to 5760 having a 1 to 2 m higher head than the lateral bores 5755 and 5761.

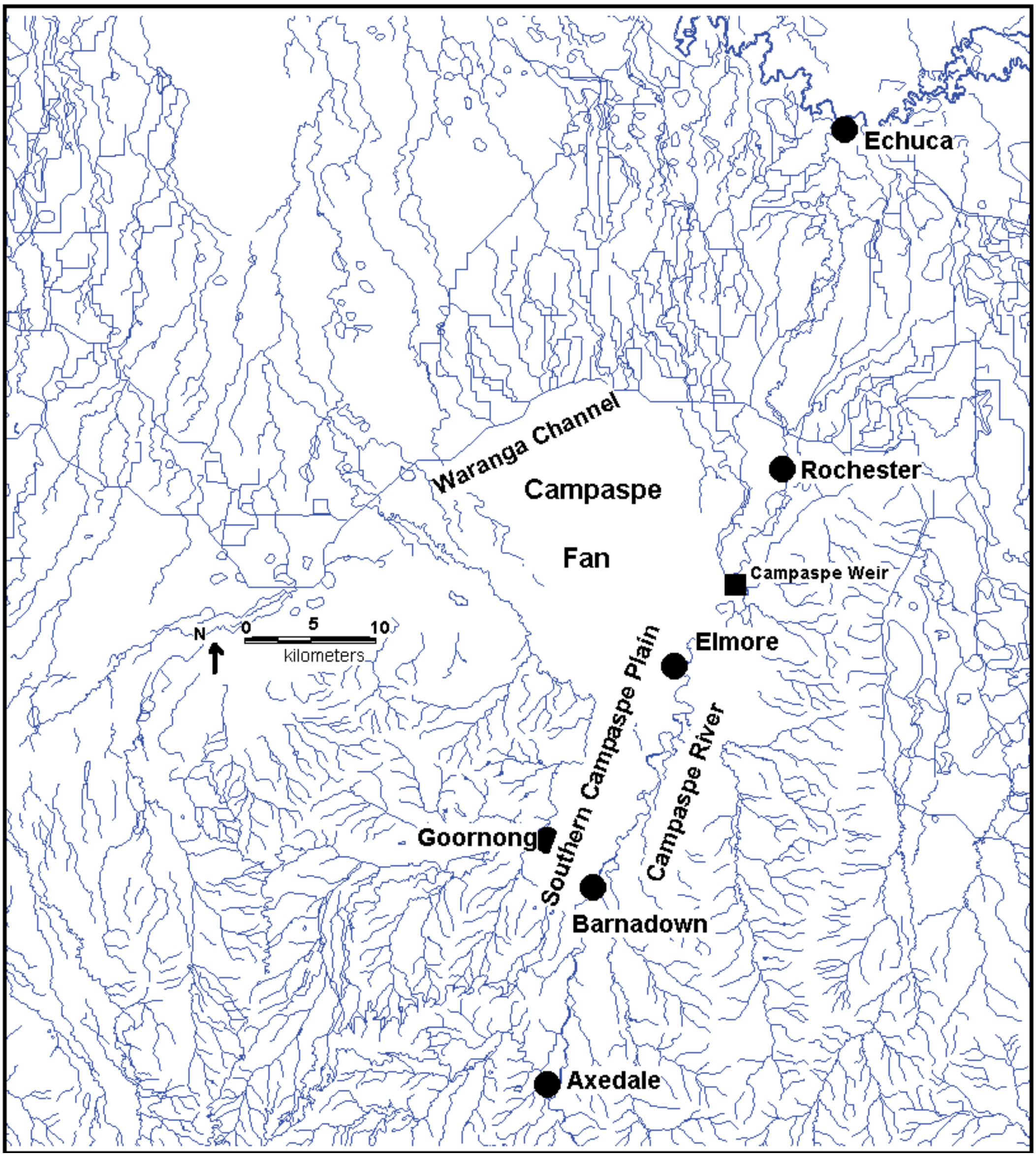


Fig. 21. Position of the Campaspe Fan between Elmore and Rochester as reflected in stream distribution.

the plumes of fresh water originating at the channel (Fig. 22). The Campaspe Fan forms a major zone of regional groundwater recharge for the Campaspe Valley shallow and deep aquifers northwards of Elmore. The coincidence of the fan with its highly permeable soils and the CID has led to the development of a high water table to the west of Elmore and Rochester aligned along the Campaspe No 1 Channel (Fig. 23). Groundwater mounding in response to recharge, running parallel to the fan, was described by Tickell (1983) for both the shallower (< 25 m) and deeper parts of the Shepparton Formation (25-50 m), and attributed to the presence of the CID. This feature appears to best relate to the Campaspe No 1 Channel, where the higher heads in the shallow sequence (116 m AHD) over those in the deeper sequence (112 m AHD) show downwards recharge (Fig. 23).

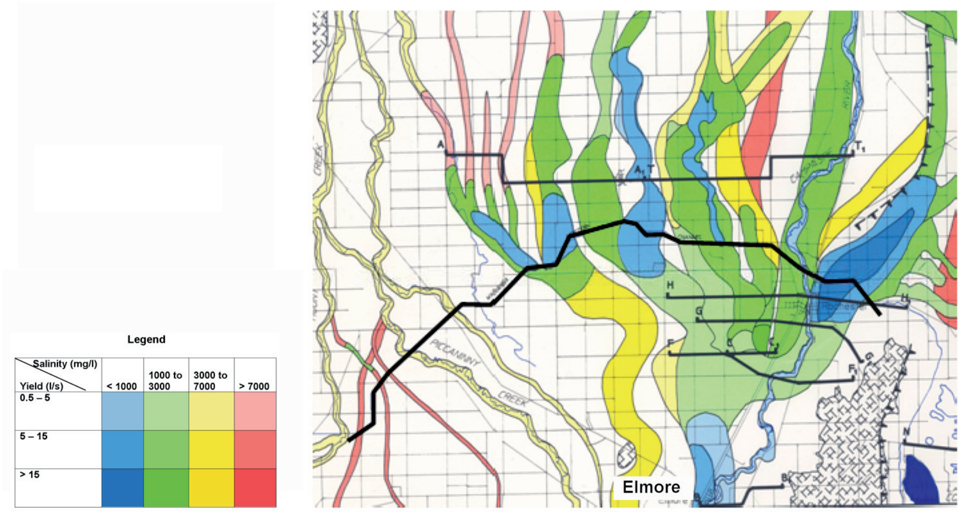


Fig. 22. Hydrogeological map of the area north of Elmore showing the salinity of shallow Shepparton Formation prior-stream aquifers. Fresh water plumes of recharged groundwater commence in the vicinity of the Campaspe River near Elmore, and in the vicinity of the Waranga Channel (from Ife 1988).

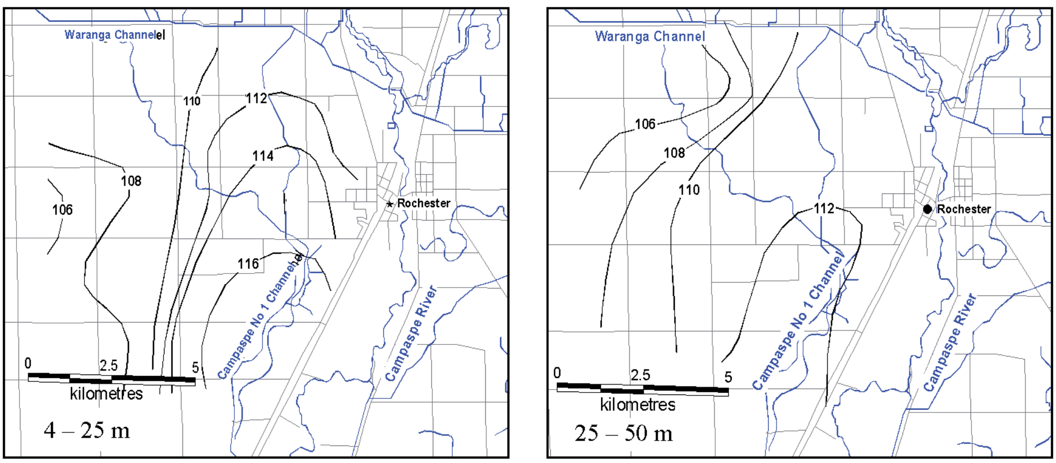


Fig. 23. Potentiometric surface of shallower aquifers between 4 and 25 m (Aug 1981) and 25 and 50 m (October 1981) – from Tickell 1982.

Apart from direct rainfall and irrigation recharge into the permeable soils, groundwater recharge also occurs from the many smaller channels of the CID, the main Waranga Channel, the Bamawm Main Drain, the Campaspe No 1 Channel (which passes down the centre of the fan) and the Campaspe River where it bounds the fan between Elmore and beyond the Campaspe Weir. The area covered by the Campaspe Fan is perhaps the most significant area for groundwater recharge within the Campaspe Deep Lead Water Supply Protection Area (Campaspe DL-WSPA). The impact of the Waranga Channel as a line source of deep recharge laterally transversing the fan causes mounding of the underlying potentiometric surface of the Calivil Formation (Fig. 24). There is a flattening of the potentiometric surface on the upstream side of the recharge mound and a steepening on the downstream side, as is the case wherever a

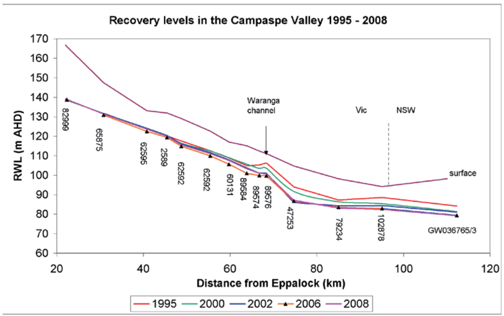


Fig. 24. Potentioetric surface (recovery levels) of the Calivil Formation down the Campaspe Valley showing groundwater mounding in the vicinity of the Waranga Channel.

line recharge source cuts diagonally across a sloping water table. This distortion of potentiometric surface of the Calivil Formation led to various interpretations in earlier years with the mistaken suggestion that it might be due to a basement constriction referred to at the time as the *Ballendella Barrier*.

While the Campaspe Fan is the major recharge area to the regional aquifer system, with significant loss from the river between Elmore and the Campaspe Weir, the situation upbasin of the Fan on the Southern Campaspe Plain (Fig. 21) is very different. In a number of Campaspe River bore transects, e.g. at Elmore South, at the Murchison-Goornong Road Bridge, the Avonmore Bridge and at English Bridge, there is strong interconnection between the river and the Coonambidgal Formation, but no evidence for river loss beyond the Coonambidgal Formation into the surrounding Shepparton Formation (Macumber 2005). This was shown to be the case in a series of bores (G8010638-Series) drilled by Goulburn-Murray Water alongside the Campaspe River on the Murchison-Goornong Road to investigate river/groundwater relationships. As was the case elsewhere, a strong river-Coonambidgal Formation connection was evident. Piezometer nests in the Shepparton Formation located immediately alongside the river (bores 4, 5 and 6 in Fig. 25), and in the adjacent Calivil Formation (bore 1, Fig. 25), showed that the Shepparton Formation below 12 m and the Calivil Formation form a single aquifer (Fig. 25) with identical hydrograph responses throughout this sequence (Fig. 26). This is the same pattern as occurs within the highland tract of the Loddon Valley (above). However, despite only a 4 m layer of uppermost clayey Shepparton Formation occurring between the base of the Coonambidgal Formation and the top of the Shepparton/Calivil aquifer, the river and the Coonambidgal aquifer were perched 3-4 m above that of the surrounding water table developed within the Shepparton/Calivil aquifer, suggesting no significant hydraulic connection (Fig. 26), indicative of a disconnected stream (Winter et al. 1998). The latter response is unlike recharge situations on the Campaspe Fan, with no mounding in the uppermost part of the Shepparton/Calivil Formation aquifer to indicate downseepage from the Coonambidgal For-

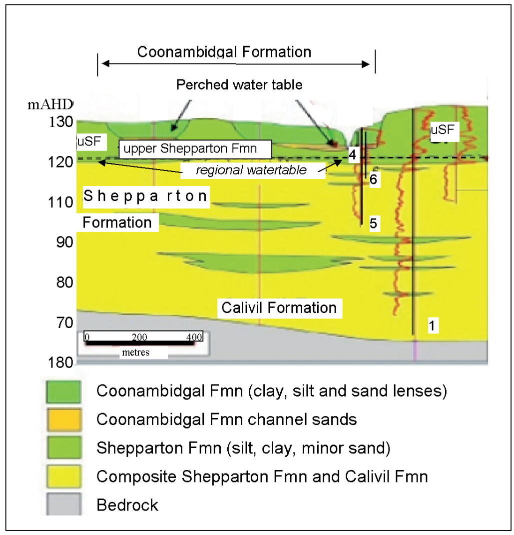


Fig. 25. Geological cross section at Murchison Rd bridge.

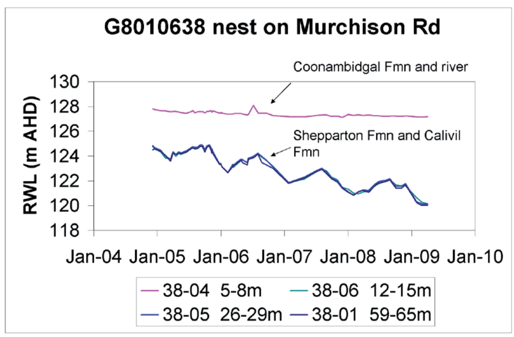


Fig. 26. Hydrographs of bores 04 (Coon F), 06 and 05 (SF) and 01 (Calivil F) – showing perching of the Coonambidgal Formation and the river, with no mounding in the Shepparton/Calivil Formation joint aquifer.

mation and hence loss from the river. This implies a low permeability for the interceding upper clayey part of the Shepparton Formation. The low permeability of the upper parts of the Shepparton Formation was recorded by Neivandt (1990), who after carrying out 240 infiltrometer tests in the upper Campaspe Plains, observed that the colluvial unit of the Barnadown - Elmore region of the Campaspe Valley present along the valley sides was the only surficial unit with the potential to significantly contribute to groundwater recharge to the deep aquifer (Fig. 27). He considered that collectively the recharge potential of other units was low. Neivandt also observed a strong interaction between the river and the Coonambidgal Formation but noted that such stream losses are not reflected in significant recharge to the Deep Lead aquifer as the Coonambidgal Formation is incised into the heavy clays of the Shepparton Formation, which are of low permeability.

The view of valley side recharge is supported by the pattern of stream flow, whereby large numbers of streamlets, emerging from the 80% of the upper Campaspe Valley catchment formed by bedrock, rapidly dissipate as they pass onto the southern Campaspe Plain (Fig 21). This process would be most effective during storms, and it was observed by Chiew and McMahon (1992) that recharge events on the upper Campaspe Plains relate to heavy storms, with a threshold in rainfall beyond which significant recharge occurs. Their model predicted that high rainfall events will produce correspondingly high diffuse recharge but relatively low river recharge. Chiew and McMahon (1992) determined by modeling that in their catchment zones 6 and 8 lying between Barnadown and the Campaspe Weir, the Campaspe River contributed 15 mm/yr of recharge to the shallow aquifers overall. However, while zone 6 includes the river recharge areas of the Campaspe Fan from Elmore to the Campaspe Weir, Zone 8 covers the areas where there is no physical evidence, including mounding, of significant river contribution.

Valley side recharge in the upper Campaspe Valley best explains the pattern of ubiquitous rises at rates of 0.2 to 0.25 m/yr across all aquifers in the Goornong-Elmore area since 1900 (Macumber 1978b) and relates to accelerated runoff caused by early clearing of the catchments. The potentiometric data for the upper Campaspe Valley shows that while there is a net resultant downvalley groundwater flow, there is also a strong lateral flow component towards the valley centre from the sides, which is the pattern observed wherever section lines across

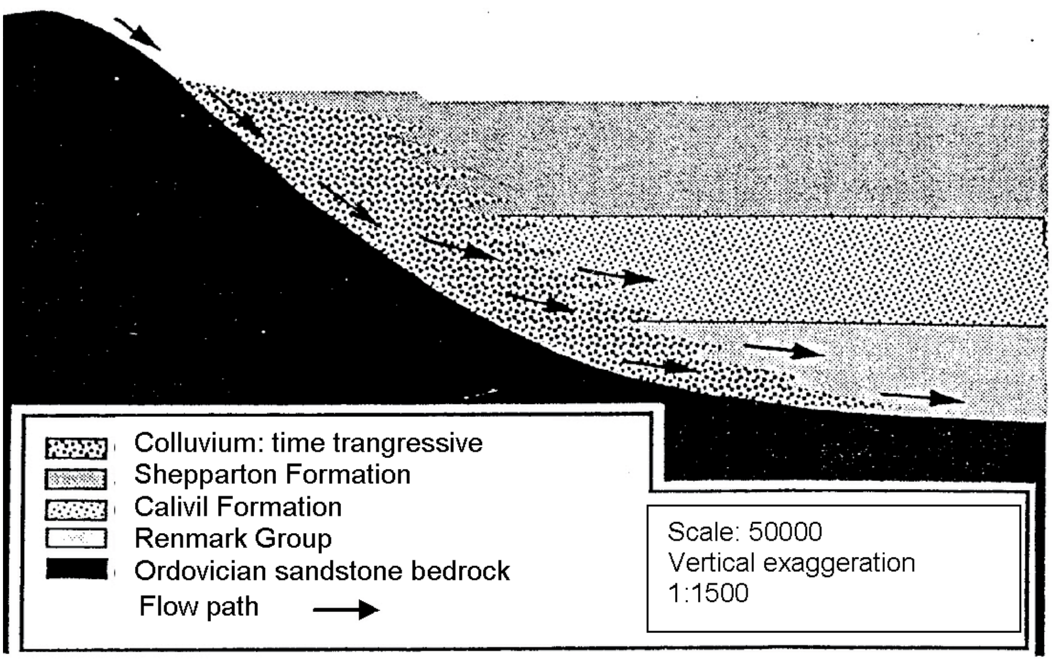


Fig. 27. Valley-side recharge (from Neivandt 1990).

the valley permit construction of flow nets, e.g. at Elmore south (Fig. 28) and near Goornong (Fig. 29). At Elmore south, during a long term pumping test with a large observation bore network of shallow and deep bores, preferential recharge pathways showing vertical downwards movement of water to the Calivil Formation, were observed only at sites 62600 and 62597, which are located towards the western side of the valley (Fig 29).

Groundwater flow towards the valley centre is counter to that arising from river loss, which would instead cause mounding beneath the river and valley centre, with a slope towards the valley sides. The situation in the upper Campaspe Valley is the reverse of that observed further downstream beneath the Campaspe Fan, where linear recharge features such as the Waranga Channel, the Campaspe No 1 Channel and the Campaspe River all produce groundwater mounding with downwards directed hydraulic gradients from the surface. The overall

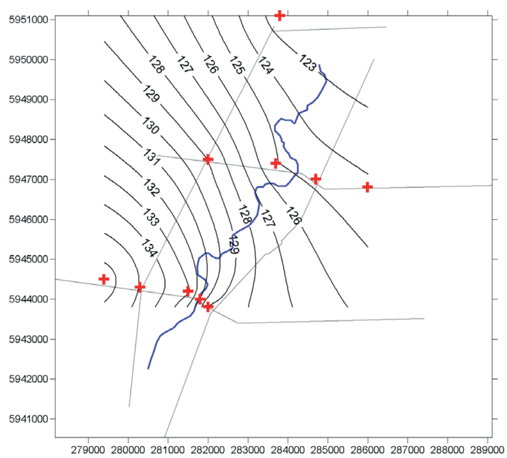


Fig. 28. Potentiometric surface based on piezometer lines east of Goornong.

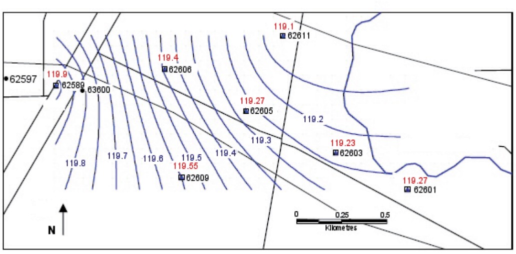


Fig. 29. Potentiometric surface, Calivil Formation, October1992 – South Elmore area.

effect of the hydrographic data and potentiometric data indicates that in the narrow upper Campaspe Valley, groundwater recharge occurs at the valley sides which, during periods of storm runoff, provides a significant, perhaps the largest part, of groundwater recharge on the plain. By contrast to the situation present on the Campaspe Fan, river recharge in the upper Campaspe Valley is minimal.

GROUNDWATER THROUGHFLOW

A downbasin throughflow of ca 2,800 ML/yr was estimated by Tickell and Humphreys (1987) across the Campaspe Valley close to where the highland tract passes onto the plains south of Elmore – their Section Line 'O-O'. They suggested that this increased to 17 800 ML/yr to the south of Echuca. Since that time there has been extensive development in the Campaspe DLWSPA to the north, and more recently in the Southern Campaspe Plains Groundwater Management Area to the south of the Tickell-Humphreys section line. In the case of the northern area, extractions now commonly amount to 20-30 000 ML/yr, causing a significant seasonal depression in the potentiometric surface which reached 18 m in May 2007, but once pumping ceased, quickly recovered by August (Fig. 30). The cone of depression does not extend upbasin beyond the Elmore area and there is no significant impact on throughflow at the 'O-O' section line located south of Elmore, despite the large downbasin extractions. On the other hand, the hydraulic gradient to the north reverses during the pumping season, with resultant loss of throughflow into NSW, and the development of a seasonal groundwater divide near the Murray River. On the basis of the Tickell and Humphreys' (1987) throughflow values of ca 18 000 ML/yr (Section Line 'C-C'), this suggests that a significant part of the ~ 30 000 ML annual consumption in the Campaspe DLWSPA comes from the net reduction of throughflow into NSW.

The absence of increased throughflow from the south indicates that all extractions within the Campaspe DLWSPA area to the north are compensated by increased local recharge, loss of storage, and by cessation of throughflow into NSW. The rapidity of recovery attests to the strong vertical component of groundwater flow in the north-central Campaspe Valley. A similar conclusion was reached by Tickell and Humphreys (1987), who noted a 15 000 ML/yr

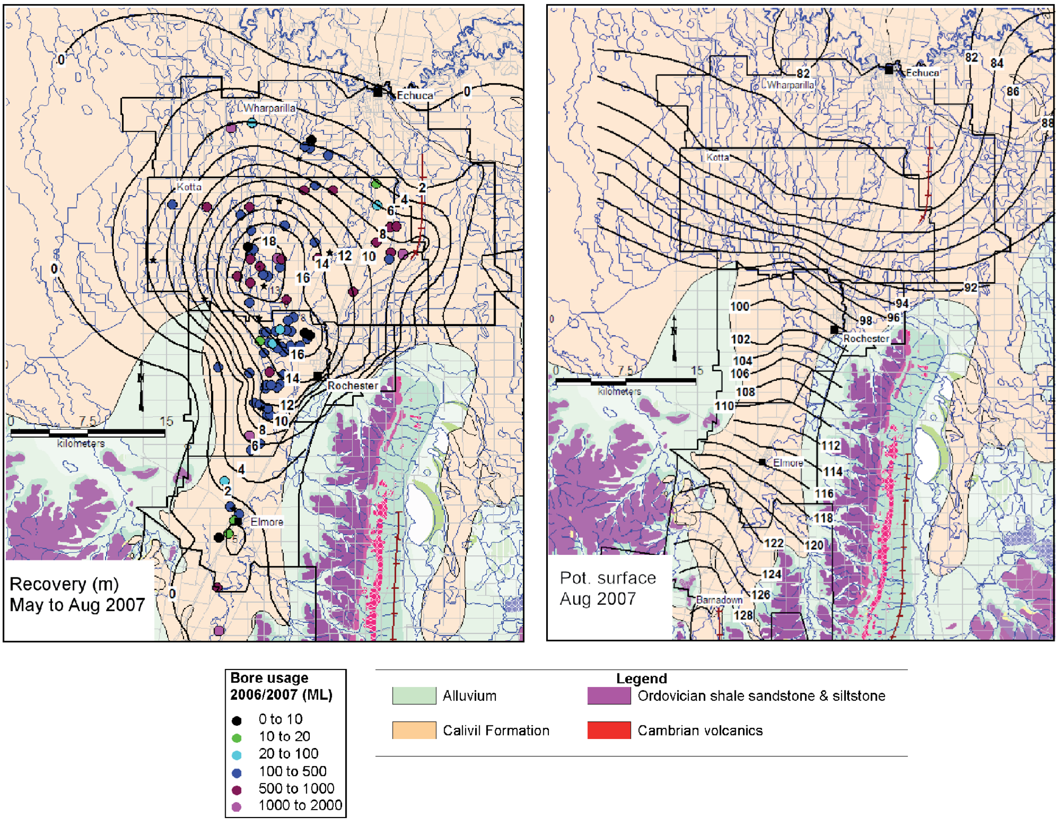


Fig. 30. Potentiometric surface of Calivil Formation August 2007 and extent of recovery from May 2007.

increase in flow between Elmore and Echuca, all locally recharged. They suggested that 36-41 mm of recharge occurred within the Campaspe DLWSPA after pumping was accounted for. At the time of the Tickell and Humphrey's (1987) calculation there were only relatively minor extractions upstream of the O-O section line, but since 2004, extractions in this area have increased to over 3000 ML/yr, thus equalling the throughflow but without impacting significantly on it (Table 2 and Table 3).

Therefore the behaviour of the regional aquifer in the southern and central Campaspe Plains beneath the Campaspe Fan is not analogous to that of a pipe, as might be the case if the aquifer were confined, but instead behaves like a sponge with localised vertical recharge and storage losses compensating for extraction losses. Only in the northern areas of the Campaspe Valley, where the aquifer is well confined by a tight and thicker Shepparton Formation, is there a significant impact on throughflow from extractions. In such areas the aquifer acts as a 'pipe'.

The varying vertical interactions between the Shepparton Formation aquifer (including the water table) and the Calivil Formation aquifer are reflected strongly in the different hydrograph responses on passing across the plains from Elmore to the Murray River. Here the influence of the Campaspe Fan on regional groundwater recharge is clearly seen. The CID covers much of the eastern part of the Fan between Elmore and the Waranga Channel. Outside the CID to the west, the area is in non-irrigated dryland. The Waranga Channel cuts across the lower end of the Campaspe Fan, and to the north beyond the channel is the Rochester Irrigation Area. The Calivil Formation hydrographs show a strong seasonality, reflecting the deep drawdowns over the pumping season and rapid recovery once pumping ceases, mostly over winter and early spring. The extent of the seasonal recovery

Table 2. Throughflow estimates from south of Elmore.

Section line	Tickell (1983)	SKM (1998)	Nolan (2005)	Trewhella (2005)
O-O	2862	2862	2862	3300

Table 3. Extraction rates between 2004 and 2008 in Southern Campaspe Plain GMA.

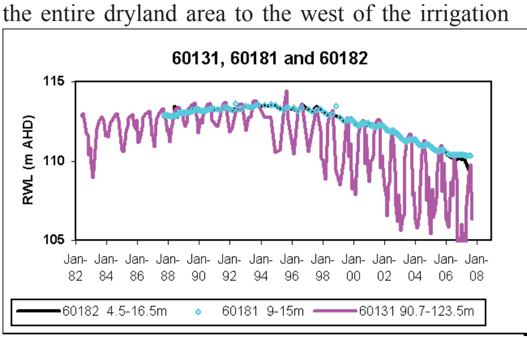
Year	2004/5	2005/6	2006/7	2007/8
Extraction (ML)	1279	1404	2990	3126

and the resulting potentiometric surface are shown in Fig. 30. Regional groundwater levels across the Campaspe Plain have been falling steadily since the commencement of the prolonged drought in 1997 which resulted in reduced recharge, lower surface water allocations for irrigation from the depleted Campaspe River, and increased pumping.

AQUIFER CONNECTIVITY AND VERTICAL FLOW ON THE CAMPASPE PLAIN

Beneath the dryland area to the west of the CID, shallow Shepparton Formation groundwater levels and the water table have fallen at the same rate as the Calivil Formation/Renmark Group aquifer. For instance, in the case of the 60131-60181 and 60182 piezometer nest (Fig. 31) where sand and gravel are scattered throughout the sequence from 10.5 m onwards, the levels of the shallow Shepparton Formation bores screened between 4.5 m and 16.5 m coincide with the top of the recovery curves of the deeper Calivil Formation aquifer, and decline at the same rate. The same is the case in the 60185/60132 piezometer nest. The absence of seasonal pumping responses in the shallow aquifer stems from the dampening affect on the Calivil Formation fluctuations by clayey units within the Shepparton Formation. This is a characteristic of groundwater behaviour across the entire dryland area to the west of the irrigation district. As a consequence, whatever recharge occurs, is in response to the seasonally fluctuating hydraulic gradients developed as a consequence of the difference between the annual drawdown and recovery levels. This is referred to here as a Type 1 hydrograph pattern and implies a semi-unconfined to semi-confined aquifer; it is a similar pattern to that shown above occurring in the dryland area of the Loddon Valley between Bridgewater and Serpentine (Fig. 14 and Fig. 15). In both cases, the entire aquifer system drains with water tables falling at the same rate, and in response to falls in groundwater levels of the Calivil Formation.

Beneath the irrigation area a similar pattern of deep and shallow falling groundwater levels is also present, however the shallow levels always remain at a higher level than the deeper levels - note that while the axes in each example cover different depths, their overall vertical range is the same (Fig. 32) allowing them to be superimposed. The higher heads in the shallower aquifers are attributed to irrigation accessions, resulting in a continuous recharge from the Shepparton Formation to the Calivil Formation. That the shallow and deep groundwater levels are nonetheless falling at the same rate is shown when the graphs are superimposed, with the right hand axis representing the shallow Shepparton Formation aquifers with its higher head, and the left hand axis representing the Calivil Formation. The pattern is referred to here as a Type 2 hydrograph pattern, and the aquifer is



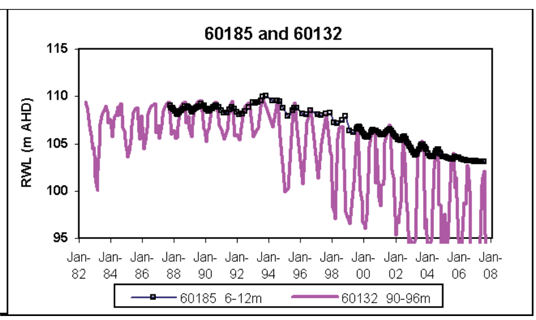


Fig. 31. Hydrographs of 60131 and 60182 piezometer nest and the 60185 and 60132, located west of Rochester outside the CID (Type 1 pattern).

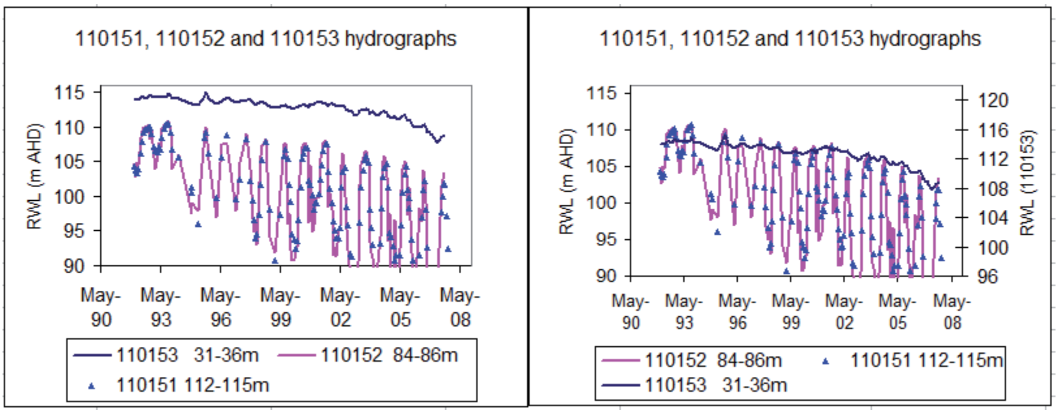


Fig. 32. Hydrographs of Calivil Formation and Shepparton Formation piezometer nests in the CID, showing coincident fall in levels, but with the levels of the shallow piezometers being 7 and 9 m above those of the deep piezometers (Type 2 pattern).

semi unconfined to semi-confined, as in the dryland area to the west.

Passing northwards beyond the Campaspe Fan, the Shepparton Formation is more clayey and the aquitard increases in effectiveness to produce a more confined system. This is reflected by the hydrograph patterns in that, unlike the case further south, there is no significant impact of the decline in levels of the deeper aquifers on the shallow aquifers, and their respective hydraulic heads are essentially unrelated. This is referred to as a Type 3 hydrograph pattern (Fig. 33). Recharge to the deeper aquifers is relatively minor in this area because of the tighter aquitard, and the aquifer is largely confined. Even so, Arad and Evans (1987) note that in the Millewa 1 bore in the northern parts of the region there is a continuous decrease in salinity from top to bottom, reflecting natural vertical mixing. They observe that a conceptual model for the mixing would start with a downward leakage of more saline groundwater into the Calivil Formation, followed by lateral flow downbasin of the mixed water.

The distribution of Types 1 to 3 hydrographs is given in Fig. 34, with Type 1 hydrograph pattern found over the dryland area of the Campaspe Fan, extending northwards to just beyond the Waranga Channel, Type 2 covers the area of the irrigated CID, again to just beyond the Waranga Channel, and Type 3 is in the northern area where the Shepparton Formation aquitard is tighter and thicker.

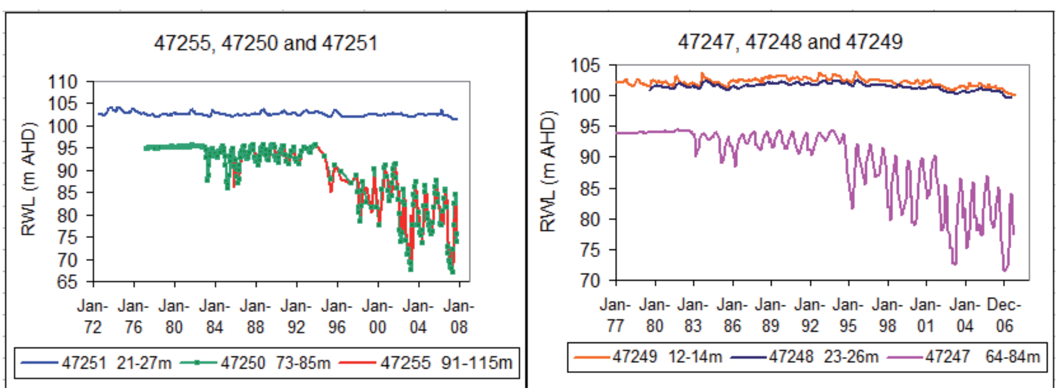


Fig. 33. Hydrographs of shallow and deep bores in the northern areas of the Campaspe DLWSPA showing no impact of falling groundwater levels in the deeper regional aquifers on the shallow Shepparton Formation and hence water table (Type 3 pattern).

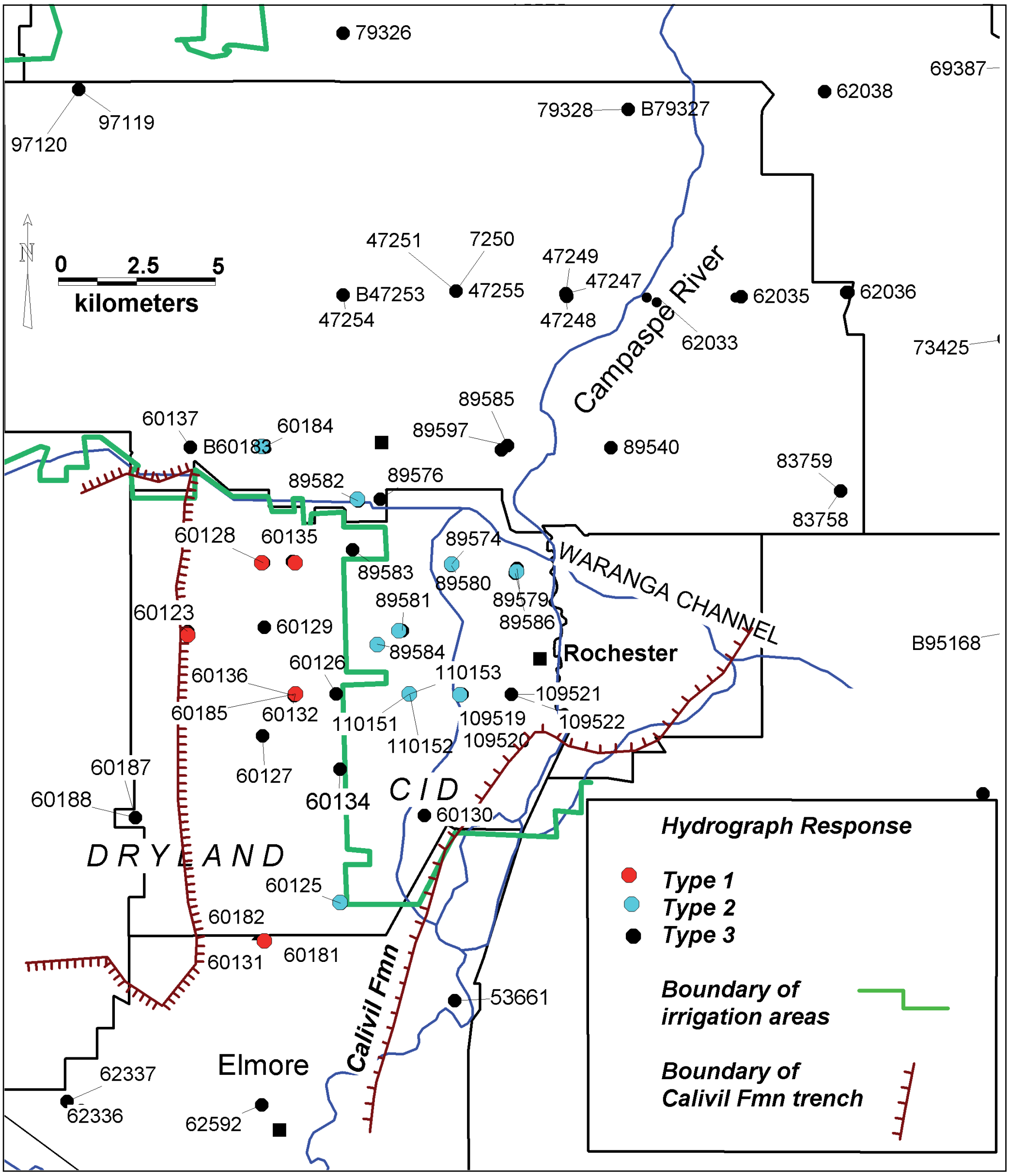


Fig. 34. Distribution of hydrograph types in the central-lower Campaspe Valley.

VERTICAL FLOW AND AQUIFER SALINISATION ON THE CAMPASPE PLAIN

The areal distribution of the hydrograph types is mirrored by different salinity distributions in both the Shepparton Formation and the Calivil Formation, although the Calivil Formation aquifer is mostly fresh. The Shepparton Formation aquifer on the dryland area of the Campaspe Fan contains fresh water, but beneath the irrigated area it is brackish to saline, with a sharp boundary between the two (Fig. 35). The higher salinity in the Shepparton Formation is considered to arise at least in part from recharge of irrigation leaching fraction. North of the Waranga

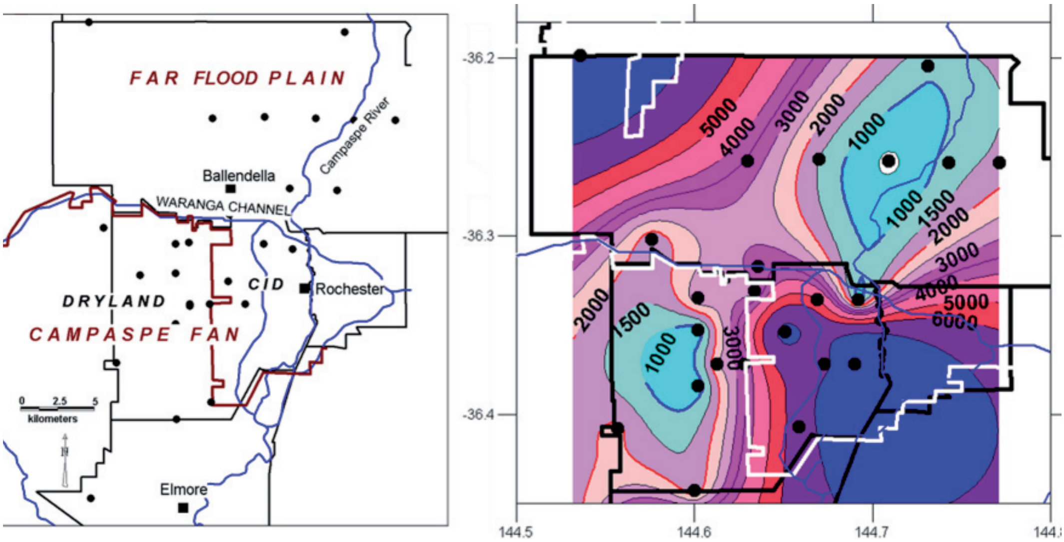


Fig. 35. Salinity distribution (EC) in the Shepparton Formation in the central-lower Campaspe Valley.

Channel the groundwater salinity is variable but generally becomes more saline on passing nothwards beyond the Campaspe Fan.. Fresher water in a plume extending to the northeast appears related to leakage from the Waranga Channel and/or the Campaspe River, and corresponds with a similar plume recorded by Ife (1988) – Fig. 22.

On passing laterally across the Fan from the dryland to the irrigation district the salinity of the Calivil Formation aquifer also increases, suggesting that more saline water from the Shepparton Formation in the recharge area of the CID (Type 2 response) is being superimposed on the underlying Calivil Formation (Fig. 36). This is confirmed by the salinity data from pumped bores across the region since the mid 1980s, which show steadily rising salinity levels in the Calivil Formation concentrated within the area of the irrigated CID and an area to the northwest of the Waranga Channel, where Type 2 conditions persist (Fig 37). The areas where this occurs mostly coincide with the deeper part of the seasonal drawdown depression in the Campaspe DLWSPA situated on the Campaspe Fan (Fig. 38).

While instigated in the late 1960s, the CID became fully operational in the mid-late 1970s. Arad and Evans (1987) suggested that the stable isotope data indicates that, under the pre-1988 hydrologic regime, little irrigation drainage water had penetrated to the deep system. However they note that with the decline in aquifer pressures induced by pumping, increased leakage from the Shepparton Formation down into the deeper aquifer could result in a degradation of its water quality. This is clearly the case at present (Fig. 37 and Fig. 38).

Some anomalous areas of increasing salinity lie in the northeast of the region, however in this area, where salinity is rising at 31 and 69 µS/yr (Fig. 38), the underlying Renmark Group aquifer is brackish, and while the Calivil Formation remains relatively fresh, pumping could induce upwards flow from the Renmark Group. The same threat occurs across the northern-most areas of the Campaspe Valley, and is due to saline water originating in the Corop Basin to the east of the Coliban Range at the eastern boundary of the Campaspe Valley, which passes northwards via the Renmark Group into the north-western Campaspe Valley. Tickell and Humphreys (1987) showed 800 ML/yr of water coming from this area. In the north-western and northern areas of the Campaspe Valley it seems likely that increases in salinity may arise from the upwards movement of brackish or saline water into the Calivil Formation aquifer from the Renmark Group as pumping progresses.

Therefore increased salinity in the Calivil Formation may be explained by downwards vertical leakage from overlying more brackish Shepparton Formation aquifer mostly beneath the Campaspe Fan, and from upwards movement from the more saline Renmark Group aquifer in the north. The often claimed likelihood of drawing saline water

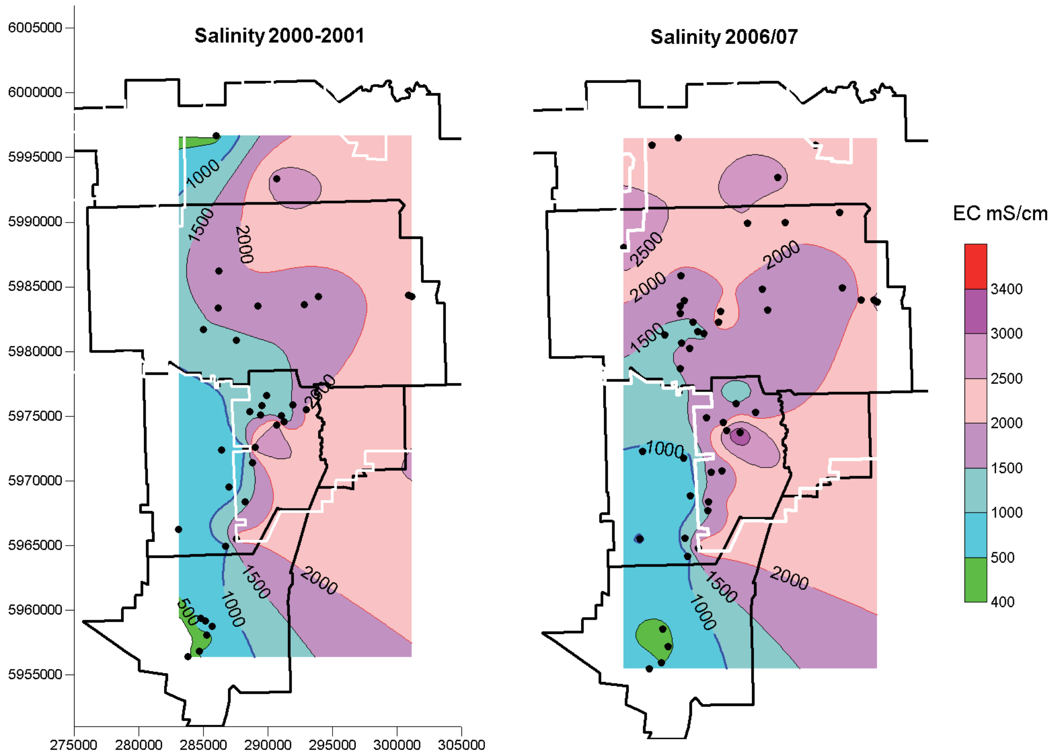


Fig. 36. Groundwater salinity of the Calivil/Renmark aquifer in 2000/2001 and 2006/2007 in the central-lower Campaspe Valley.

upbasin from NSW or from the areas to the west of the Campaspe Valley are remote, since the seasonal push-pull effect generated in the aquifer system during seasonal drawdown and recovery would cause a broad transition zone to develop between the northwards flowing fresh water and the downbasin brackish or saline groundwater, with virtually no impact of higher salinity from this source affecting the main irrigation areas. A lateral ingress of saline water into the irrigation district would only become a threat with a reversal of flow in response to a net upbasin hydraulic gradient.

SUMMARY AND CONCLUSION

The general conceptualisation of groundwater flow across the Riverine Plain in north central Victoria is that of a regional aquifer system consisting of the Calivil Formation and at times the Renmark Group, with a notional aquitard formed by the Shepparton Formation. Yet the Shepparton Formation is also deemed to be an aquifer in its own right through the presence of thin variously connected shoe-string sands lying within an otherwise clay and silt matrix. In general, emphasis has largely been placed on horizontal groundwater flow in the fluvial aquifers; however the role of the Shepparton Formation as both an aquifer and aquitard in different settings is far more complex, while the nature of the vertical flow between the Shepparton and Calivil Formation aquifers has been largely overlooked. From Eastville northwards, the highland tract of the Loddon Valley, commencing at depths of 20 m to 30 m, is infilled with a thick coarse grained sand/gravel unit formed by the combined Calivil Formation and the lower parts of the Shepparton Formation. This sand body forms a single regional aquifer in the highlands; it is 70 m thick at Eastville and 100 m thick at Bridgewater at the highland front. The overlying 20-30 m thick uppermost part of the Shepparton Formation is mostly clay with occasional thin basalt layers. Hydrographs

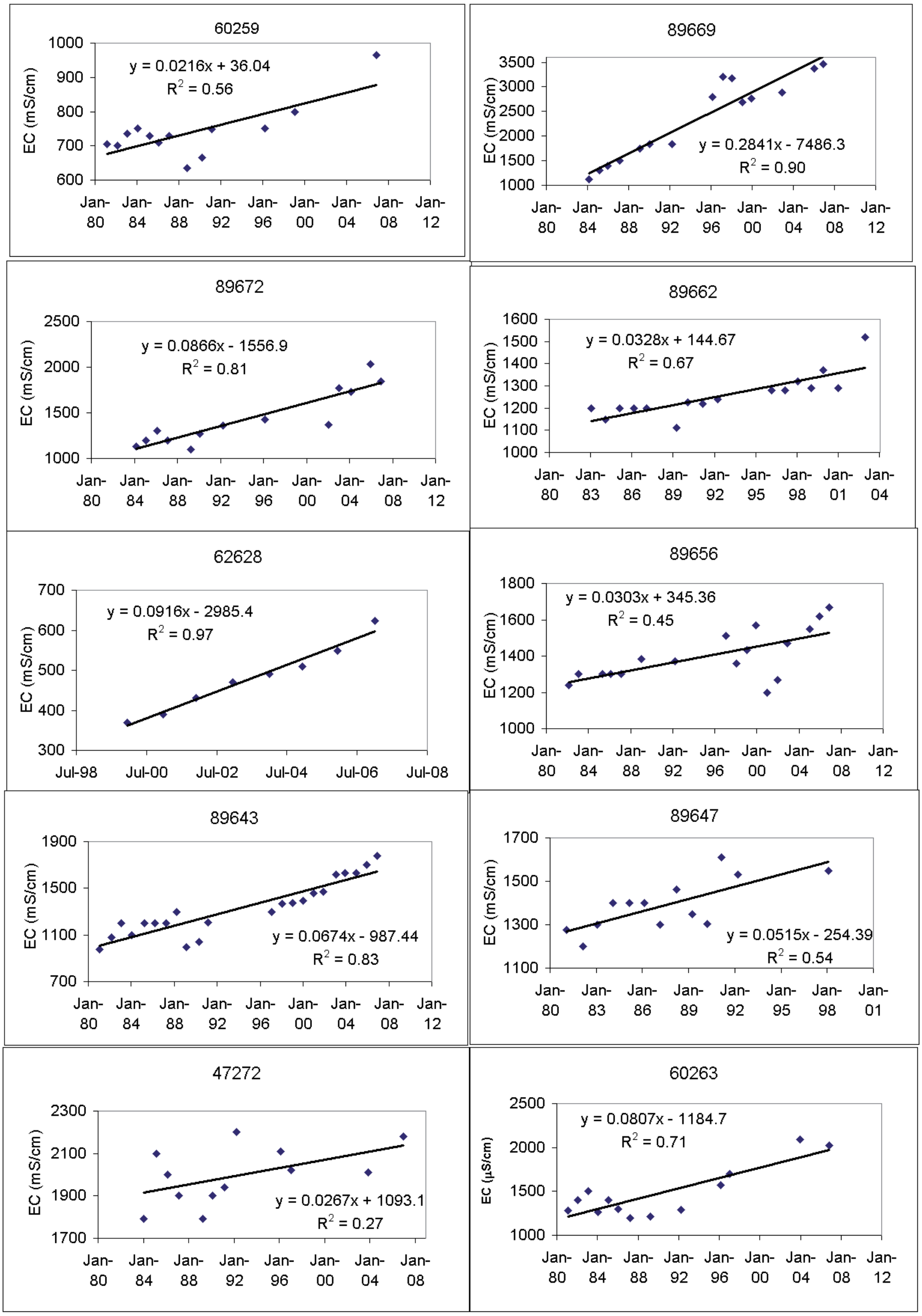


Fig. 37. Rising salinity (µS/cm/yr) in bores in the Campaspe DLWSPA from 1980 to 2007.

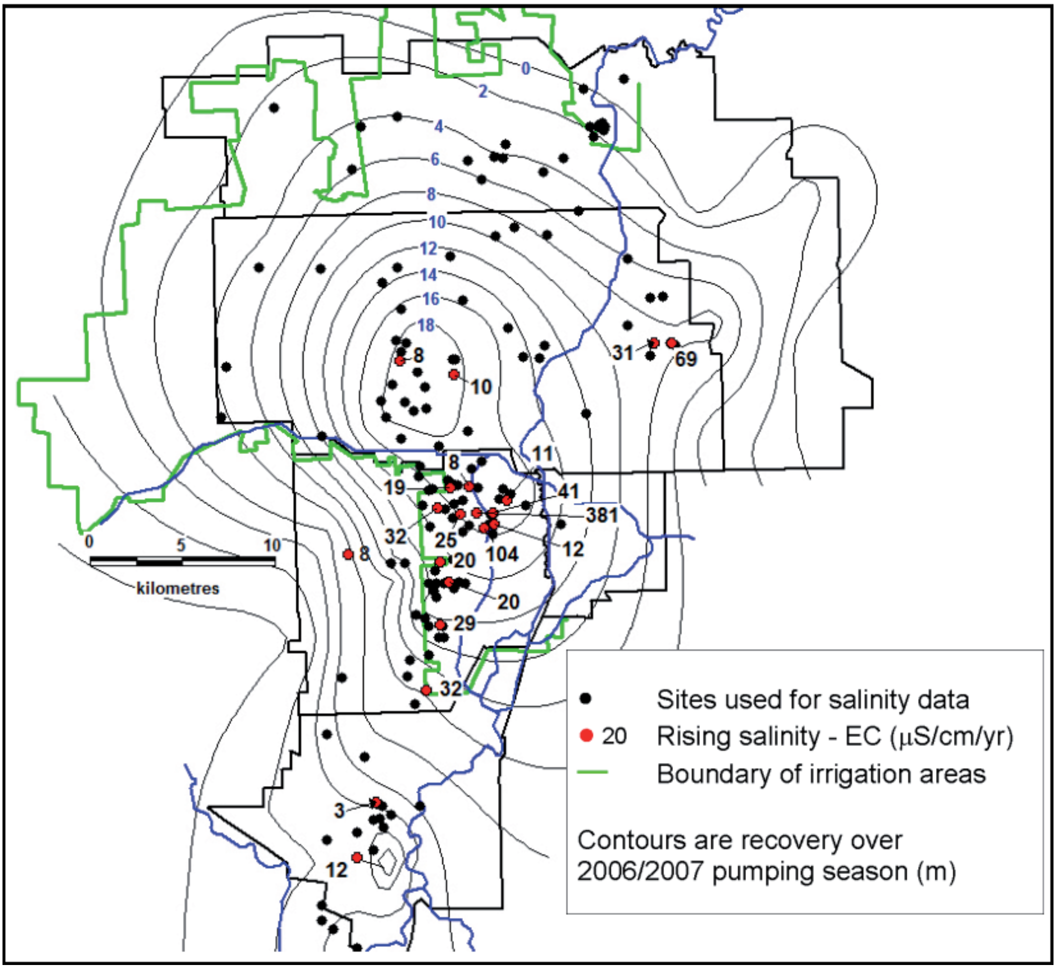


Fig. 38. Rates of rise in salinity (μS/cm/yr) in the Campaspe DLWSPA and the extent of recovery during 2006/7.

show identical water levels in vertical sections across the entire sequence suggesting an essentially unconfined aquifer system. A similar condition, whereby the lower part of the Shepparton Formation together with the Calivil Formation form a single regional aquifer, exists in the highland tract of the Campaspe Valley upstream from Goornong.

Beyond Bridgewater, the Calivil Formation occupies a 3 km wide 60 m deep trench, incised into the mid-Miocene Mologa Surface. The laterally confined Calivil Formation system passes north towards Cohuna where it becomes tributary to a Murray Valley system. However, after deposition of the Calivil Formation, the palaeogeography of the Loddon Valley changed markedly with the late Tertiary marine transgression and deposition of the marine Parilla Sand extending into the mid-Loddon Plain where it overlies the Mologa Surface. The lower sand sequence of the Shepparton Formation emerging from the highland tract diverges north-westward from the path of the Calivil Formation aquifer, as it was deposited by streams which were graded to a shoreline in the central Loddon Valley. The Shepparton Formation sand sheet overlies the Mologa Surface and occupies the same vertical stratigraphic interval above the Mologa Surface as the Parilla Sand, suggesting a time equivalence, and hence a mostly upper Miocene to lower Pliocene age, based on the presence of the index fossil *Lovenia woodsi* at the top of a thick Parilla Sand sequence to the west of Kerang (Macumber 1991). On the plains, groundwater allocations and pumping bores mark the divergent flow paths of both aquifers. Increased groundwater extraction and decreased recharge during the dry years from 1997, saw concomitant falls in levels across the aquifer system with water tables falling at the same rate as that of the deeper regional aquifers, suggesting characteristics of an unconfined or semi-unconfined aquifer. This was also the case in parts of the highland tract and dryland areas of the Campaspe Fan in the Campaspe Valley.

The highland tract of the Campaspe Valley is relatively small compared to that of the Loddon Valley – commencing north of the Eppalock Reservoir and passing downstream through Barnadown and Goornong to Elmore. In both the highland tract and on the plains, the Campaspe River flows within the ancestral river path marked by terraces comprising the Coonambidgal Formation. Beyond Elmore, the Campaspe Valley passes out onto the Campaspe Plain, there formed by an extensive elevated alluvial fan – the Campaspe Fan. The apex is near Elmore and the distal end lies beyond the Waranga Channel. The highly permeable Campaspe Fan is the principal recharge zone for the Calivil-Renmark aquifer, with recharge coming from irrigation, the channel system and the river. In the Campaspe Valley, groundwater levels rose steadily at rates of 0.2 to 0.25 m/yr until the mid-1990s and then began to fall. Large seasonal extractions up to 30 000 ML/yr from groundwater pumping, cause an extensive 18 m deep depression in the potentiometric surface which reverses the hydraulic gradient into NSW. However the potentiometric surface returns to its pre-pumping position over winter with increased vertical recharge from within the pumped area and some loss from storage. There is no commensurate increased throughflow from the south to compensate for these extractions. The explanation for the different throughflow responses lies in the permeability of the Shepparton Formation, which forms a tight aquitard in the north where the aquifer behaves as if it were a pipe. This is not the case in the south where the Shepparton Formation is relatively permeable and the aquifer behaves like a sponge.

On the Campaspe Fan, groundwater levels in the Shepparton Formation closely follow declining levels in the Calivil Formation with pumping from the latter causing a concomitant decline in water tables, as was the case in the central Loddon Valley. However further north, where the Shepparton Formation aquitard is thicker and tighter, this is not the case and water tables are essentially unaffected by pumping from the Calivil /Renmark aquifer. Beneath the CID on the Campaspe Fan, the groundwater in the Shepparton Formation is brackish. Salinity measurements from pumped bores taken over recent decades have shown that irrigation enhanced recharge through the Shepparton Formation causes gradual increases in salinity in the underlying regional Calivil Formation aquifer. This is not the case to the west of the CID on the dryland parts of the Campaspe Fan where the shallower groundwater is relatively fresh, suggesting that the irrigation leaching fraction may play a significant role in the salinity levels in the Shepparton Formation, beneath the CID.

North of Elmore, the permeable Campaspe Fan is the main area of recharge to the aquifer system, with recharge coming from the river, the irrigation area, and the Campaspe No 1 and Waranga-Western channels. Upstream of Elmore beyond the Campaspe Fan, the Campaspe Valley narrows markedly as bedrock makes up 75% of the catchment. The Campaspe River flows within a Coonambidgal Formation terrace, with the strongly interconnected river and Coonambidgal Formation aquifer near Goornong perched 3.5–4.0 m above the level of the surrounding and underlying water table. In this area there is no physical evidence of significant river recharge passing to the deeper aquifers, with recharge instead coming from the valley sides where storm run-off from the many small streamlets infiltrates where they attenuate on entering the plain.

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