ESTIMATION OF LEAKAGE RATES THROUGH THE SHEPPARTON FORMATION AQUIFER, DENILIQUIN, NEW SOUTH WALES

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Australian Geological Survey Organisation
Environmental Geoscience and Groundwater Program

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Preface

The study described within this Record was undertaken as part of AGSO's Murray-Darling Basin Hydrogeological Project. The Project is concerned with the establishment of a sound conceptual model for the relationship between the groundwater systems of the Murray-Darling Basin and sustainable natural resource management.

Within this project framework, data analysis and knowledge-based activities are currently underway in cooperation with State water agencies. One such activity is the production of the Murray Basin Hydrogeological Map Series. The objective of the Map Series is to bring together the accumulated hydrogeological and related data into a common form across the Murray Basin. This data set (both in map form and in database form) will then be available for further interpretation and/or for management decisions.

As a result of the increased understanding of the hydrogeological system gained via the Map Series work, a number of subsidiary issues can now be undertaken. One such issue, the role of groundwater interchange between the Shepparton Formation and the deeper Pliocene aquifers in areas of intensive irrigation, is the topic of this Record. The work described here resulted from discussions held with officers from the Murray Region, NSW Department of Water Resources, at Deniliquin - and was made possible by the availablility of the Map Series data. Further supplementary data was made available from both the Deniliquin and Parramatta offices of the Department of Water Resources.

The Record is broken into two parts reflecting the division between the development of the analysis algorithms and the results of that analysis. Ross Brodie primarily undertook Part 1 of the work, while Andrew Tucker undertook Part 2.

Abstract

Rising watertables, leading to waterlogging and salinisation, is an emerging problem in the irrigation districts surrounding Deniliquin, southern New South Wales. Land and water management strategies within the region require an understanding of the interaction between the shallow Shepparton Formation aquifer and the underlying Pliocene Sands aquifer.

To this end, a regional characterisation of the direction and magnitude of groundwater leakage through the Shepparton Formation was derived from the borehole record and current 1:250 000 scale hydrogeological mapping. Using the raster-based functionality of a GIS, grids representing saturated thickness, head difference and vertical hydraulic conductivity (K_v) were compiled and combined. Methodology and software were established to allow for density and viscosity corrections due to variable groundwater salinity and temperature. These are reported in Part 2 of this record.

By summing the grid cells, the leakage to (or from) the Pliocene Sands aquifer was estimated for each irrigation district. These figures are usefeul in water balance studies. Leakage within the irrigation districts tends to be downwards, induced by loading of the shallow watertable aquifer from irrigation, rivers and drains. This is particularly true for the eastern districts of Berriquin (-0.3 ML/ha/yr) and Denimein (-0.2 ML/ha/yr). Higher localised leakage rates correspond with alluvial channel or fan complexes within the Shepparton Formation. In the Deniboota area, a small component of upward leakage (+0.01 ML/ha/yr) is apparent.

A prediction of temporal change in groundwater leakage used an annual projected rise of 20 cm/yr for Pliocene Sands potentials. This highlighted the sensitivity of the groundwater regime to rising potentials in the deeper aquifers due to regional clearing of native vegetation.

One option for water table control is deep drainage induced by sustained pumping from the underlying Pliocene Sands aquifer. The derived leakage rates were combined with watertable depths and aquifer salinity/yield within the GIS, to locate potential sites for deep drainage.

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Part 1: Determination of Leakage Rates

1.1) Introduction

Rising watertables leading to waterlogging, land salinisation and deteriorating surface water quality, is a major problem in the irrigation districts surrounding Deniliquin, southern NSW, as in other areas in the Murray Basin. Limited storage capacity in underlying Cainozoic aquifers limits any buffering against increases in recharge. Therefore, the watertable in the irrigation districts has risen rapidly in response to enhanced infiltration due to excess irrigation accessions and inadequate drainage. The depth to the watertable when irrigation commenced around Berriquin in 1939 was about 30 metres (Gutteridge Haskins & Davey, 1985). Monitoring has shown an average watertable rise of 0.25 metres/annum (Brereton & Phillis, 1990). This had meant that by 1980, 15,000 hectares of the Berriquin Irrigation District had watertables within two metres of the land surface. This had expanded to 91,300 hectares, or 25% of the total area, by 1990 (Carr, 1992). In addition, regional piezometric levels in the deeper aquifers are rising. This is a response to enhanced recharge from clearing of native vegetation.

Land and water management strategies for watertable control are being planned or implemented for the irrigation areas around Deniliquin: Berriquin, Denimein, Deniboota and Wakool/Tullakool. An understanding of the interaction between the shallow Shepparton Formation aquifer and the underlying Pliocene Sands aquifer is fundamental to the development of salinity control measures. In particular, the following issues need to be addressed:

i). The likely contribution of "deep lead pressure" (upward leakage from the Pliocene Sands aquifer) to watertable rise, and how this is expected to change over time,

ii). The role of deep drainage through the Shepparton Formation sequence in shallow watertable control, both under natural conditions or artificially by sustained pumping from the underlying and more transmissive Pliocene Sands, and

iii). The sustainability of long term pumping of groundwater in conjunctive use programs.

The objective of this study was to determine the rate and direction of regional groundwater leakage between the shallow Shepparton Formation aquifer and the underlying Pliocene Sands aquifer.

The study area is centred on the DENILIQUIN 1:250 000 mapsheet with adjacent 1:100 000 mapsheets from SWAN HILL and JERILDERIE, representing an area of about 25,000 km^2. Regional data compilation was limited to the New South Wales portion of this area, from the Wakool Irrigation District in the west to the Berriquin Irrigation District in the east (figure 1). In any one year, over 250,000 hectares of irrigated land in these districts produce rice, cereals, oilseed and vegetables as well as fat lamb, wool and dairy production.

1.2) Regional Geology

The Deniliquin study area is located in the Riverine Plain province of the Murray Basin, characterised by mainly fluvio-lacustrine sediments. Cainozoic deposition is over a basement of Siluro-Devonian granite, Ordovician metasediments and infrabasins of Permian diamictites, laminated claystone and coal measures as well as Triassic sandstones. Major outcrops of the Palaeozoic granites and metasediments are found at Ryan's Hill, south of Berrigan (Figure 2). The regional stratigraphy has been described in various reports and publications (Brown, 1989; Brown & Stephenson, 1992; Gates, 1986; Kellett, 1989; Pels, 1966; Woolley & Williams, 1978).

The basal *Renmark Group* (Ter) consists of unconsolidated mid-Eocene to Miocene carbonaceous silt and clay, lignite and intercalations of poorly sorted fine to medium quartz sand. Sediments are characterised by abundant carbonaceous and pyritic plant debris. Deposition is within an extensive floodplain and lacustrine environment with sand deposits confined to meandering river channels.

The Late Miocene to Early Pliocene *Calivil Formation* (Tpc) forms a sand sheet over the Renmark Group sediments, consisting of pale grey, poorly sorted coarse to granular sands, conglomerate and kaolin bands. Grainsize tends to decrease both vertically upwards and laterally downbasin, from quartz gravels to kaolinitic clay. The coarse grain size, a kaolin matrix and the lateral continuity of the sand bodies, implies deposition of deeply weathered upland material in a braided channel environment. The Late Miocene transgression with a rise in base levels, initiated the backfilling of the Calivil drainage regime up into the highland valleys. These coarse alluvial deposits, the 'deep leads', represent an important aquifer resource around the basin margin.

Towards the west, the Calivil Formation is overlain by and laterally grades into the *Loxton-Parilla Sands* (Tps), an extensive composite sandsheet deposited in marine shelf to strandplain environments. The eastern limits of the Parilla Sands represent the maximum extent of the Pliocene marine transgression into the basin. Fine to coarse, yellow-brown, well-sorted quartz sand is the dominant lithology, with minor clay, silt and pebble conglomerate.

The Pliocene to Recent *Shepparton Formation* (TQs) overlies and interfingers with the Pliocene sand deposits and constitutes much of the surface geology of the study area. The fluvio-lacustrine sediments are mainly mottled, variegated clay and silt, with subordinate shoestring lenses of coarse to fine polymictic sand and gravel. These sands and gravels represent channel deposits within the dominant finer grained overbank and lacustrine environments of the aggrading floodplain. The sequence has been extensively modified by pedogenesis and fluctuating watertables, and contains numerous palaeosols. A spectrum of channel types is evident in the geomorphological expression of the Shepparton Formation and younger fluvial sediments. The older *prior streams* are former, relatively straight, wide and shallow meander belts with a coarse sand bed load, paired sandy levee banks and large meander wavelengths. The channels are associated with an extensive aggrading floodplain. These contrast with the recently abandoned channels, the *ancestral streams*, which tend to be entrenched within the landscape.

The *Coonambidgal Formation* (Qa), represents the alluvial deposition of the modern and ancestral rivers, consisting of unconsolidated grey, red-brown silt, silty clay and poorly sorted sand and gravel. A network of interconnected distributary channels has developed over the flat lying terrain, incised into the older Shepparton Formation fluvial sequence. The distribution of the ancestral streams is generally linked with the modern river system. The meander patterns are similar in sinuosity to those of the modern rivers, but are of much greater size.

A major structural feature, the Cadell Fault, has had a significant influence on the distribution of Cainozoic unconsolidated sediments (figure 2). The trace of a stream channel (Green Gully) is evident traversing across the fault (Pels, 1966). Subsequent reactivation of the fault has tectonically stranded the river channel on the uplifted western block and created ponded drainage on the subsided eastern block. This is reflected in the formation of the Barmah-Millewa Forest and diversion of the Murray River, originally to the northern margins before switching to its present southerly (Barmah Choke) course. Radiocarbon dating suggests the latest phase of fault movement occurred some 20,000 BP (Bowler, 1967).

Deflation of the fluvial sands, particularly from point-bars, scroll bar complexes and the elongate channel sands of the prior streams have resulted in aeolian source-bordering dunes (Qad).

Scattered lacustrine deposits (Ql) are found associated with the major floodplains, particularly in the Kerang area. These typically contain finely laminated to massive grey clay, silty clay, silt, humic clay and palaeosols. Lunettes (Qdl) can occur on the downwind margins of the lakes, sourced from deflation of the lake bed. These are crescentic dunes consisting of well sorted siliceous sand, silty clay, clay pellet aggregates and gypsite. The range of lithologies reflects changes in the hydrological regime of the lake through geological time.

Characteristic aeolian deposits of the Mallee province are evident in the western extremes of the study area. These include the *Molineaux-Lowan Sands* (Qdm) which are irregular to subparabolic, sharp crested densely packed dunes of well-sorted medium to fine frosted quartz sand. In contrast, the *Woorinen Formation* (Qdw) forms discontinuous dunes with subdued flanks separated by broad swales.

1.3) Regional Hydrogeology

The regional groundwater resource is contained in multilayered aquifers within the Cainozoic fluvio-lacustrine sediments (Evans & Kellett, 1989). The confined basal *Renmark Group* aquifer is subdivided into three components (lower, middle and upper) based on lithology, salinity, potentiometry and palynology (Kellett, 1989). However closer to the margins of the Murray Basin, the subdivision becomes less defined. The Renmark Group aquifers tend to be high-yielding with a low salinity groundwater resource in much of the eastern Riverine Plain. Groundwater salinity tends to increase and aquifer yield decrease along the northwesterly flow path within the study area.

The Calivil Formation and the Loxton-Parilla Sands combine to form a regional aquifer system, the *Pliocene Sands* aquifer. Aquifer yields in the Calivil Formation tend to be very high (>50 L/s) in the highland valleys and close to the highland front. However with the general fining of the sediments away from the basin margins, aquifer yield decreases to less than 5 L/s. Therefore, the aquifer is the major productive aquifer in the eastern half of the Riverine Plain.

The salinity/yield characteristics of the Pliocene Sands aquifer (figure 3) show similarities to the underlying upper Renmark Group aquifer indicating a degree of hydraulic connectivity. The northwesterly trend of the ancestral Murray River and the influence of the major rivers on recharge are revealed in the major freshwater plume originating from the southeastern corner of the study area. A similar resource in the northeast of the study area is part of the fan deposits associated with and recharged by the Murrumbidgee River system. Rapid salinity increases in the western margins are mainly due to evaporative concentration and refluxing during times of shallow watertables. Kellett (1989) distinguished two stages in chloride concentration increases along flow lines in the western Riverine Plain. The Moulamein-Mossgeil buffer zone represents the maximum historical extent of up-basin propagation of refluxed salts, with the Balranald-Hatfield discharge zone the production locus of salts by evaporative concentration.

The *Shepparton Formation* is the shallow watertable aquifer for most of the study area. In the western margin, the aquifer thins and the watertable lies in the Parilla Sands. The formation also becomes unsaturated and finally disappears around the margins of Ryan's Hill where low-yielding fractured rock aquifers within the outcropping Palaeozoic granites and metasediments prevail. The Shepparton Formation aquifer is heterogeneous in nature, with discontinuous shoestring sands in a matrix of floodplain silts and clays and is better termed an aquifer-aquitard complex. Groundwater modelling in the Shepparton area concluded that vertical flow dominates lateral movement (Ife, 1988). Lateral movement tends to be local in nature and defined by the distribution of surface hydrological features such as rivers, lakes and supply channels as well as the continuity of the channel sand aquifers.

The Shepparton Formation aquifer has been subdivided into three components (upper, middle and lower) based on lithological and salinity trends (Woolley, 1991; Lawson, 1992). The channel sands appear to mainly occur in the upper (<14-30m) and lower (>25-50m) layers. The finer-grained middle Shepparton appears to be the main barrier for vertical leakage to the underlying Pliocene Sands, resulting in ponding in the upper aquifers and rapid watertable rise.

The broad westerly trend of increasing groundwater salinity is apparent in the Shepparton Formation (figure 4), as in the underlying aquifers. The reactivation of the Cadell Fault has truncated and confined the freshwater plume to the Barmah-Millewa Forest area, creating stagnation and higher salinity on the uplifted western block. The influence of recharge from the Murrumbidgee system is still evident in the northeast corner of the study area.

However, local processes are complicating the salinity distribution. Lithological variation within the channel deposits results in variable flow rates and corresponding differences in the degree of salt flushing. For example, the linear pods of fresher groundwater found within the Berriquin Irrigation District correspond with the prior stream shoestring aquifers. Raising the watertable to within the capillary zone, as evident in the irrigation areas, will initiate evaporation and salt concentration and also remobilise any previous unsaturated-zone salts (Arad & Evans, 1987). This is particularly apparent for the irrigation districts to the east: Coleambally, Denimein and Berriquin, where areas with watertables less than 10-15m depth tend to have groundwater more salty than the regional background..

The general northwesterly trend in groundwater flow is also apparent for the shallow Shepparton Formation aquifer. However, interaction with surface water features and changing land use has created local flow systems that add a level of complexity to the watertable contours.

1.4) Methodology

The specific discharge or flow rate per unit area *v*, through a porous medium is governed by Darcy's Law:

$$v=\frac{Q}{A}=-K\frac{dh}{dl} \tag{1}$$

Where Q is the flow rate (m^3/day), A is area (m^2) and dh (m) is the head loss over distance dl (m). The coefficient K is hydraulic conductivity (m/day) which depends on properties of both the porous medium and the fluid. Accordingly, to calculate vertical leakage rates through the Shepparton Formation aquifer, dh is the head difference between the top of the Shepparton Formation aquifer (ie. the shallow watertable) and at the base (ie. the head in the underlying Pliocene Sands aquifer), and dl is the saturated thickness of the Shepparton Formation. The coefficient K is the vertical hydraulic conductivity (K_v) for the saturated component of the Shepparton Formation.

Therefore, determining the spatial distribution of leakage rates over the study area requires the regionalisation of three parameters: the head difference between the watertable aquifer and the underlying Pliocene Sands, the thickness and the vertical hydraulic conductivity of the saturated Shepparton Formation.

The regional hydrogeology of the study has recently been mapped as part of the 1:250 000 Murray Basin Hydrogeological Map Series (NSW Department Water Resources, 1992; Williams & Woolley, 1992; O'Rorke et al, 1992). The mapping is a cooperative effort between AGSO and the state water agencies, under the auspices of the Murray-Darling Basin Ministerial Council. On each map, the salinity/yield, potentiometry and geometry of the significant regional aquifers are characterised. The cartographic process is based on the Intergraph CAD/CAM facilities at AGSO.

From the Intergraph design files, an ARC/INFO GIS database was constructed for the Deniliquin study area. In addition, primary borehole data was provided by NSW Department Water Resources (NSW DWR) and transferred into an ORACLE database. The regional mapping and borehole record provided the foundation for deriving the required hydrogeological parameters.

On the published map, surfaces such as the distribution of salinity or potentiometry are represented as contours or polygons. To utilise the raster-based functionality of

ARC/INFO these surfaces need to be represented as a regular array. This involved constructing Triangular Irregular Networks (TINs) from the map data, and then sampling the TINs based on a 1km square grid. For example, grids of surfaces representing the watertable, the base of the Shepparton aquifer, the potentiometric surface for the Pliocene Sands aquifer and the surface topography were generated in this way. These ARC/INFO grids can be manipulated using ESRI's grid algebra (ESRI, 1991).

1.4.1) Shepparton Formation Saturated Thickness

The saturated thickness of the Shepparton Formation (figure 5) was simply derived by subtracting the aquifer base grid from the watertable grid. As the land surface is flat-lying (1:2000 gradient) the trends in the saturated thickness reflect the base of the formation. To the east, the Shepparton Formation thins rapidly towards the Palaeozoic outcrops of Ryan's Hill. Thicker sequences are found in channels flanking the structural high, trending towards a local depocentre in the southern central part of the study area. The highest thicknesses define a meandering channel straddling the southern boundary of the study area, reflecting the most sustained course of the ancestral Murray River during the Tertiary. The effect of reactivation of the Cadell Fault on deposition is also apparent. Westwards, the sequence thins as the basal part of the Shepparton Formation is progressively replaced by the upper part of the Parilla Sands. This trend is offset by deposition along the Avoca River system, west of Kerang. Here, the Shepparton Formation is incised into and flanked by outcropping Parilla Sands.

1.4.2) Head Difference

Grids defining the shallow watertable and the potentiometry of the Pliocene Sands were constructed from the groundwater mapping. The residual after subtraction, is the head difference between the top and base of the saturated Shepparton Formation, uncorrected for density effects (figure 6). Negative values indicate that the watertable is higher than the head in the Pliocene Sands aquifer, implying a potential for downwards groundwater movement. This is typical of the eastern half of the study area, particularly in the Berriquin Irrigation District with local extremes of between -10 and -16 metres. These maxima tend to align along the channel sands of the prior streams. In these areas, the high level of accessions to the shallow watertable via rivers, irrigation and poor drainage provides the driving force for the high downward head gradient. The high head difference suggests that local recharge is superimposed onto a regional recharge regime.

In the western half, the direction of the head gradient is less defined, with values ranging from -3 to +7 metres. This reflects the local interplay of lakes, rivers and irrigation areas with the shallow watertable. For example, the Wakool-Kerang area has been recognised as a regional discharge area, suggested by an upwards head gradient from the basal aquifer, the Renmark Group, to the shallow watertable. However, in the Wakool Irrigation District and extending northwards of Moulamein, loading of the shallow aquifer by recharge from irrigation and rivers, has induced potential downward groundwater flow to the Pliocene Sands. The maximum downward head difference is only about -3 metres and flanked by upward flow conditions - the regional discharge regime has been overprinted by a high watertable induced by local recharge. Certainly, the regional upwards flow direction, inhibiting any deep drainage capability into the deepest aquifers, would have contributed to the rapid onset of waterlogging and salinisation at Wakool. In this area, the Pliocene Sands aquifer can act as a groundwater drain, receiving water from the overlying Shepparton Formation and underlying Renmark Group aquifer. However, with piezometric levels for the deeper aquifers rising each year, this situation may easily reverse inducing potential leakage upwards from the Pliocene Sands aquifer.

The complexity of the head difference map reflects the balance between the watertable and the head in the Pliocene Sands aquifer, which is controlled by many variables. The shallow watertable is sensitive to land use and proximity to surface hydrological features. For example, the positive head difference prevailing over the Pericoota State Forest, east of Cohuna, is due to a low watertable. This is maintained by the remnant vegetation efficiently reducing infiltration or acting as a groundwater pump.

The Pliocene Sands potentiometry is influenced by inputs from the overlying Shepparton aquifer and the underlying Renmark Group aquifers, both at a local and regional scale. For example, the positive head difference west of the Cadell Fault is driven by high potentials in the Calivil Formation. The fault is a structural barrier causing rapid thinning of the underlying Renmark Group sediments over the uplifted western block. This constricts the northwesterly groundwater flow, creating hydraulic conditions for upward movement.

1.4.3) Density Corrections of Head Difference

As the head in an aquifer can vary with salinity and temperature, density corrections are required to accurately determine potential flow between aquifers. This involves deriving fresh water and environmental heads from the potentiometry, a concept introduced by Lusczynski (1961). The measurement of water levels in piezometers relates to the *point water head* at the point of entry, say the centre of the screen. This is the water level, referred to a given datum, in a well filled sufficiently with the *groundwater* of the type at the screen centre to balance the existing pressure at this point.

The *fresh water head* at the screen centre is the water level in the well filled with *fresh water* from this point to a level high enough to balance the existing pressure at the screen centre. The column of groundwater in the well above the screen centre is balancing the pressure at the screen centre - the freshwater head is the column of fresh water that would equally balance that pressure.

The *environmental head* at the screen centre is the fresh water head reduced by the amount corresponding to the difference of salt mass in fresh water and that in the *environmental water* between the screen centre and the top of the zone of saturation (the shallow watertable). The environmental water is the groundwater, which can vary in density, found along the vertical between the screen centre and the watertable. The environmental head effectively changes the fresh water column in the well to a water column with a vertical density distribution matching the aquifers found between the watertable and the screen centre, and which equally balances the pressure at the screen centre.

Fresh water heads define hydraulic gradients along a horizontal, while environmental heads define hydraulic gradients along a vertical. Therefore, for this study the density effects on aquifer potentials were corrected by deriving the environmental head difference. The density of the groundwater in each aquifer was calculated from salinity, temperature and pressure data using an iterative FORTRAN based algorithm. This program was written as part of the Murray Basin mapping effort (Tucker & Evans, 1991). The gridded data sets of aquifer salinity and potentiometry were reformatted for use in the program. Average groundwater temperatures of 20°C and 18°C were used for the Shepparton and Pliocene Sands aquifer respectively. In turn, a subsidiary algorithm was used to calculate the environmental head difference, which was reformatted into an ARC/INFO grid for comparison with the other datasets. The theory and methodology of these density corrections are detailed further by Andrew Tucker in Part 2 of this record.

Figure 7 shows the density corrections implicit in using environmental heads for the Shepparton Formation and the Pliocene Sands aquifers. The grid shows the magnitude of the residual between the hydraulic head difference and the environmental head difference. In the eastern half of the study area, density corrections induce a minor change in head difference of generally less than 20cm. As groundwater salinity increase westwards, the salinity contrast between the aquifers also increases. In some areas, density corrections have changed the head difference between the aquifer by over a metre. For example, south of Lake Boga, the salinity contrast has increased the positive head difference by over 2 metres. However, the general comments based on the uncorrected head difference remain valid.

1.4.4) Vertical Hydraulic Conductivity

The grids representing saturated thickness and head difference are simple to derive, based on parameters easily measured or interpreted from boreholes or piezometers. Regionalising the vertical hydraulic conductivity (K_v) for the Shepparton Formation aquifer is a more difficult task.

Estimates of K_v based on long term pump tests are scarce over the study area. The Coleambally Deep Bore Project (Lawson, 1992), to the north of the study area, derived K_v values ranging between 10^{-2} and 10^{-4} m/day for the lower part of the Shepparton Formation aquifer. In this test, some 13200 ML was pumped from the Calivil Formation over 468 days, aimed at monitoring the effect on the shallow watertable. A five-month pumping test was undertaken in the Finley area to quantify sustainable aquifer yield and drainage implications (Bogoda & Lea, 1991). A vertical hydraulic conductivity of 10^{-4} m/day was estimated.

Current groundwater modelling exercises over the area have required regional estimates of vertical hydraulic conductivity for the shallow aquifer. This has been achieved by back-calculating using Darcy's Law with an estimate of recharge or as a logarithmic polynomial function of horizontal hydraulic conductivity (Nolan 1991, Gutteridge Haskins & Davey, 1992).

For this study, the estimate of K_v was based on the lithological descriptions recorded for the boreholes intersecting the entire Shepparton Formation sequence. Within the borehole database the lithological description contains two fields - a code assigned to the major lithology and a brief description of its salient features in terms of grainsize, texture and subordinate lithologies. From this database, some 1300 unique combinations of the major lithology and description fields are recorded for the Shepparton Formation intersected by the boreholes. A vertical hydraulic conductivity value was assigned to each of the 1300 combinations. Table 1 provides a general range of values for the dominant lithologies.

Table 1. Typical K_v values (m/d) assigned to Shepparton Formation lithologies

Lithology	Description	Kv (m/d)
Gravel		1-5
Conglomerate		1-5
Sand	coarse	1
Sand	medium	0.5
Alluvial		0.5
Drift		0.1-1
Sand	fine	0.1
Silt		0.01
Loam		0.01
Coal		0.01
Clay	sandy	0.01
Clay		0.001

These values are consistent with the range of K_v values assigned to lithologies for the MODFLOW-based regional groundwater models being constructed for the Riverine Plain (Kellett, pers. comm.).

By obtaining a weighted average for boreholes intersecting the entire Shepparton Formation sequence, some 220 point estimates of K_v were made over the study area (figure 8). A guide to the reliability of the K_v interpretation can be obtained from the density of the borehole coverage. In some areas, particularly to the west, the borehole coverage is sparse and requires further investigative drilling. The yield characteristics of the shallow aquifer were used to aid interpolation between the borehole estimates. By also overlaying the base Shepparton structural contours, the K_v values could be placed in their geological setting. For example, low K_v values on the eastern down-thrown block of the Cadell Fault correspond to ponded drainage and subsequent deposition of clays and silts. High K_v values are apparent within channels flanking the regional post-Pliocene highs. The highest estimates, near Conargo, appear to have been developed in an alluvial fan complex sourced by these channels. Grainsize and K_v values tend to decrease westwards, away from the basin margins and the sediment source. This trend is offset by deposition of coarser grained material by the Avoca river system.

These K_v estimates are based on the assumption that the fluid has properties identical to fresh water. Modifications were made allowing the effects of variable viscosity using an algorithm based on temperature and salinity (refer Part 2). However, these corrections are insignificant in comparison to the level of uncertainty placed on K_v estimates.

1.5) Derived Leakage Rates for the Shepparton Formation Aquifer

By combining the viscosity-corrected vertical hydraulic conductivity, the environmental head difference and saturated thickness grids using Darcy's Law, a regional estimate of leakage rates through the Shepparton Formation aquifer was derived. The resulting grid incorporates a conversion factor to the units ML/ha/yr (figure 9).

The direction of leakage is governed by the head difference between the watertable and the Pliocene Sands. Negative values show downward flow and recharge conditions for the underlying aquifer. Positive values indicate that the head in the Pliocene Sands aquifer is higher than the watertable level, implying upward flow.

The K_v estimate is the major control on the magnitude of the leakage rate. Extremities in leakage rates in both the downwards and upwards directions require scrutiny in the context of natural resource management. Areas with high negative leakage rates are windows for enhanced recharge into the deeper aquifers, adding to the regional trend of increasing groundwater heads. High positive leakage rates in an area suggest a contribution to shallow watertable rise from groundwater flowing upwards from the deeper aquifer.

1.5.1) Enhanced Recharge into the Pliocene Sands Aquifer

The highest downward leakage rates (>1 ML/ha/yr) are found within and to the north of the Berriquin and Denimein Irrigation Districts (figure 9). Negative or downward leakage requires the shallow watertable to be above the head in the Pliocene Sands. In these areas, a high shallow watertable due to accessions from rivers, lakes, drains and irrigation is the dominant process. Also, high K_v estimates have been derived from boreholes intersecting the Shepparton Formation. These are the target areas where recharge into the underlying Calivil Sands is high and where land use should be scrutinised. Further investigation in these areas is warranted to determine the detailed vertical distribution of aquifers and aquitards within the Shepparton Formation. This recognises that the K_v estimate is a weighted average over the saturated part of the Shepparton Formation sequence only. The distribution of aquitards within the upper Shepparton system, in particular the unsaturated zone needs to be outlined. In some cases there may be a sufficient shallow aquitard cover in the upper Shepparton system to restrict recharge into the significant aquifers in the middle and lower Shepparton Formation.

1.5.2) Influence of 'Deep Lead Pressure'

The maximum upward leakage rates are found north of Conargo, attributed to the high K_v values of the interpreted alluvial fan complex. This area has the highest potential in the study area for rising watertables driven by upwards leakage from the Calivil Sands aquifer. The watertable in this area is currently at a depth of between 15 and 20 metres. Water level monitoring since 1980 at observation bore 36069 shows a 70cm rise in Calivil Formation aquifer pressures and a 20cm rise in Shepparton Formation aquifer water levels.

The direct influence of 'deep lead pressure' or upwards discharge from the Pliocene Sands aquifer would be suspected where shallow watertables overlay areas of positive leakage rates. This situation is prevalent in the western half of the study area, particularly north of Tullakool, the southern margins of the Little Merran Creek water trust and most of the

Deniboota Irrigation District. Upward leakage rates are generally in the order of 0.01-0.05 ML/ha/yr with local maxima to 0.5 ml/ha/yr.

1.5.3) Feasibility of Deep Drainage

Deep drainage, in the sense of induced leakage by sustained pumping from the underlying Pliocene Sands aquifer, offers certain advantages in providing subsurface drainage over the irrigation areas. By using a high-yielding, low salinity aquifer, groundwater can be pumped into the irrigation supply in conjunctive use programs. This offsets the reliance of irrigation on surface water. The regional upward trend in deeper aquifer potentials can also be locally negated. As an example, the long term pumping trial at Coleambally (Lawson, 1992; Lawson & van der Lely, 1992) appeared to have induced an average shallow watertable decline of 0.2m within 2 km of the pumping bore, while supplying 13200 megalitres to the irrigation network. However, analysis of the watertable measurements was complicated by seasonal changes both in climate and land use.

The grid estimate of leakage rates can be used to target possible pumping bores within the Pliocene Sands. The selection criteria for a potential site require hydraulic connectivity between the aquifers (ie high negative leakage rate), a high yielding and low salinity Pliocene Sands aquifer, centred over an area of shallow watertable. Figure 10 highlights potential target areas that fulfil these criteria to various degrees. The local hydrogeological setting around these sites should be investigated in detail. Other factors such as aquifer depth or proximity to infrastructure may also need to be incorporated into a more detailed analysis.

The longevity of pumping would also depend on maintaining a reasonable salinity for the pumped groundwater, to minimise the degree of dilution required for irrigation use. Consequently, this would disadvantage the sites selected for Wakool where the shallow aquifer is more saline.

One of the best sites, where the upper Shepparton aquifer salinity ranges between 500 and 3000 mg/L, corresponds with the site of the Finley pump test (Bogoda & Lea, 1991). Here, pumping from the Calivil aquifer into the irrigation supply was maintained at a rate of 6.45 ML/day for 162 days. The salinity of the pumped groundwater maintained a threshold of 1550-1600 mg/L, invoking a salinity increase in the canal water into which it was discharged from 35 to 50 mg/L. It was concluded that although there was vertical leakage from the overlying Shepparton aquifers, the size and duration of the pump test was not sufficient to significantly lower the shallow watertable. The pump test was part of investigations to outline a suitable water resource for a proposed coal mine and power station at Oaklands, 50 km to the northeast. A battery of production bores extracting up to 50 ML/day, was envisaged for the site (Hoey, pers. comm.).

1.5.4) Leakage Rates over Irrigation Districts

By summing the grid cells, the leakage to (or from) the Pliocene Sands was estimated for each irrigation district. The results are summarised in Table 2. The magnitude of the leakage rates from this study is largely controlled by the estimate of vertical hydraulic conductivity. As K_v can vary over several orders of magnitude and difficult to quantify, the leakage rates given in Table 2 should only be treated as indicative. The mean annual leakage rates per hectare (ML/ha/yr) are only order of magnitude estimates at best.

To place these figures in context, the average annual water consumption on rice for the irrigation districts ranges between 14.5 and 16.4 ML/ha/yr (Gutteridge Haskins & Davey, 1985). It should be noted that although rice is the hydrologically dominant crop, it covers a subordinate area of the irrigation districts. The component that percolates through the root zone has been estimated at 2-3 ML/ha/yr for rice and 0.5-1 ML/ha/yr for perennial pasture (Trewhella, 1989). The mean leakage rate to the Calivil Formation for the Berriquin District (0.3 ML/ha/yr) is comparable to an estimate for the Coleambally District of 0.4-0.5 ML/ha/yr (Trewhella, 1989). The SHE hydrological model over the Berriquin District used a rate of 0.1 ML/ha/yr (29,000 ML/yr) in its calibration (Hoey, pers. comm.).

Table 2: **Total Annual Leakage through Shepparton Formation for Deniliquin Irrigation Districts**

District	Leakage (ML/yr)	Area (km^2)	Mean (ML/ha/yr)
Berriquin[1]	-98600[2]	2903	-0.3
Denimein	-13450	593	-0.2
Wakool	- 6700	2132	-0.03
Tullakool	- 1800	79	-0.2
Total Wakool Region	- 8500	2211	-0.04
Deniboota	+ 1550	1422	+0.01
Moira	+ 650	327	+0.02
West Cadell	+ 30	23	+0.01
Non-Irrigated[3]	+ 110	81	+0.01
Total Cadell Region	+ 2340	1853	+0.01

[1] Area of Berriquin District with underlying Calivil Formation aquifer
[2] Negative values indicate downward leakage to Pliocene Sands aquifer
[3] Non-irrigated area bounded by Murray, Wakool and Edward Rivers and southern margin of study area

1.5.5) Prediction of Future Leakage Rates

Temporal changes in leakage rates are largely controlled by changes in head difference. By adding 6.4 metres to the Pliocene Sands heads, based on an annual projected rise of 20cm/yr, leakage rates 32 years after map compilation (2020) was estimated (figure 11). This is a crude simplification as it assumes a static watertable, which is clearly not the case. However, over the critical areas of shallow watertable in the irrigation areas there would be limited capacity for further rise. Also, there are no density corrections made on the 6.4 metres of increased head which becomes particularly relevant in the western half of the study area.

The outcome of the prediction highlights the sensitivity of the groundwater regime to rising potentials in the deeper aquifers induced by regional clearing of native vegetation. At Wakool, the direction of vertical groundwater flow has switched to upwards, implying a contribution to the watertable by leakage from the underlying Pliocene Sands. The area where upwards leakage is likely to exceed 1 ML/ha/yr has expanded significantly, notably around the margins of the irrigation areas. This has significant salinisation implications. Areas of downwards leakage have correspondingly shrunk to be mainly confined to the eastern irrigation areas - Berriquin, Denimein and Coleambally.

1.6) Conclusions

From the 1:250 000 scale hydrogeological mapping and borehole records and using the raster-based functionality of the ARC/INFO GIS, a regional characterisation of leakage rates through the Shepparton Formation aquifer was compiled. Areas with extremes in leakage values, either downwards or upwards, require scrutiny in the context of land and water management plans.

Leakage within the irrigation districts tended to be downwards, induced by loading of the watertable aquifer from irrigation, rivers or drains. This was particularly apparent in the eastern districts, with Berriquin and Denimein having estimated leakage rates of -0.3 and -0.2 ML/ha/yr respectively. This situation was even evident for the Wakool/Tullakool area with an averaged downward rate of -0.04 ML/ha/yr. This area overlies a regional discharge zone, as defined by potential upward flow from the basal Renmark aquifer. The high heads in the Renmark system coupled with generally low K_v values for the Shepparton Formation would tend to limit any deep drainage capability, bringing on the rapid onset of shallow watertable rise at Wakool. Low upward leakage (+0.01 ML/ha/yr) is apparent over the Deniboota area, perhaps reflecting the lower irrigation intensity and high heads in the Pliocene Sands due to constriction of groundwater flow by the Cadell Fault. On this basis, the possibility of any direct upwards flow due to 'deep lead pressure' contributing to watertable rise relates to Deniboota and other localised areas in the western half of the study area, at this present time. However, the role of upwards leakage in watertable rise will only increase if the current pressure increases in the deeper aquifers continue unabated. The sensitivity of the direction of groundwater leakage to anticipated increases in Pliocene Sands potentials is apparent from figure 11.

By combining the derived leakage rates with depth to watertable and aquifer characteristics, potential sites for testing deep drainage as an option for watertable control in irrigation districts could be located. One of the better targets corresponds to the Finley pump test site. Based on the details of this pump test, the pumping regime to effect deep drainage would have to exceed 6 ML/day (say 30-50 ML/day) over a time scale of years rather than months.

1.7) Further Work

Confidence in estimates of vertical leakage rates depends on a realistic distribution of vertical hydraulic conductivity (K_v). The number of boreholes intersecting the entire Shepparton Formation is limited, particularly in the western half of the study area. Figure 8 shows the areas of data paucity where further investigative drilling is required.

This study deals with the saturated component of the Shepparton Formation. A greater understanding of the Upper Shepparton sequence, particularly the unsaturated zone, would be a useful adjunct. The wealth of shallow borehole data, principally over the irrigation districts, could be used to characterise the sediment distribution for the upper Shepparton. Although this represents a significant resource outlay, a conceptual geological model for the upper Shepparton would be a useful framework for estimates of hydrogeological parameters such as K_v, porosity and storativity.

By using current watertable mapping (post 1988), the estimation of leakage rates can be updated. Also, the use of current 10 or 20-year predictions of the watertable and potentials in the Pliocene Sands would derive a better estimate of the future vertical flow regime in the Shepparton Formation. This would result in greater confidence in the predictions, with minimal effort. The calculation of density corrected head differences between all the regional aquifers (Shepparton, Pliocene Sands and lower, middle and upper Renmark) would give a complete picture of potential vertical groundwater flow.

Part 2: Density and Viscosity Corrections to Groundwater Flow

2.1) Introduction

This section describes the algorithms and software used to apply density corrections to vertical groundwater flow between the Shepparton Formation and the Pliocene Sands aquifer in the irrigation districts around Deniliquin. The ARC/INFO GIS (ESRI, 1991a), and especially the GRID module (ESRI, 1991b), was used for much of the work described. Some software was also developed specifically for the study.

2.2) ARC/INFO Grid Modelling

2.2.1) Overall Functionality

The ARC/INFO GRID module supports manipulation of raster (or grid based) spatial data. Editing, display and analysis of grid data is carried out either in the GRID module or in the ARCPLOT display and plotting module.

2.2.2) Advantages of the Grid Model

Each cell in the grid may have one or several attribute values. A consistent, flexible and powerful grid algebra language is supported by the GRID module, which also allows grids of different resolutions to be accessed simultaneously to derive other grids. Integer, real or character values may be stored as gridded data.

2.2.3) Limitations of the Grid Model

The GRID module does not allow the specification of grids with axes that are not parallel to the axes of the current co-ordinate system. Nor is it possible to specify column and row widths of varying dimensions.

Currently, the version of the GRID module installed at AGSO does not support FORTRAN access to data held in ARC/INFO grid files - this would have been of considerable assistance in the current study. A relatively computationally intensive, iterative algorithm to calculate groundwater density from TDS, temperature and pressure has been implemented and tested as a FORTRAN program (Tucker and Evans, 1991). While it would have been possible to duplicate this algorithm with the ARC/INFO map algebra language, the time required to effect the port and test the program made it preferable to convert the ARC/INFO grids to ASCII files before processing them with the existing version of the program.

The ARC/INFO grid module does support a range of ASCII grid formats - these make data transfer from the internal ARC/INFO grid format to an external program relatively straightforward.

Except for groundwater density calculations, all other derived parameters described in this report were calculated with the ARC/INFO GRID module.

2.2.4) Summary

The ARC/INFO GRID module supports much of the necessary display and analysis functionality required for calculating and viewing groundwater flows in the irrigation districts around Deniliquin. However, it has still been appropriate to perform some grid processing external to ARC/INFO.

2.3) Defining an Appropriate Map Projection

While the scale distortions due to cartographic projections may appear to be small in comparison to the area being modelled, it is appropriate to ensure that the projection specified for the grids within ARC/INFO is as expected, and consistent with accepted cartographic standards.

Generally, spatial analyses are best performed on data that has been projected to an equal area projection (Malling, 1976). However, given that the area covered by the Deniliquin study is relatively small, the Universal Transverse Mercator projection, as used to define the Australian Map Grid (Australian Map Grid Technical Reference Manual, 1972) is quite adequate. Care should be taken to ensure that the appropriate spheroid is used when defining the projection within ARC/INFO, as use of an inappropriate spheroid may result in a 1 kilometre grid cell being mislocated by 10% or 20% of the dimensions of the cell.

2.4) The Variable Density Flow Equations

2.4.1) Calculating the Density of the Groundwater

The density of the groundwater can be determined from temperature, pressure (as a head value) and TDS. The iterative method used is based on that of Kuiper (1985) and Kontis and Mandle (1987), and uses the data of Potter and Brown (1977). The algorithm assumes that the solute in the groundwater sample is composed only of sodium chloride.

For the initial iteration of each density determination, the density of the groundwater sample is set to 1 kg/L. The molality for the first and all successive iterations is then calculated from the following equation (Weiss, 1982):

$$MOL = \frac{TDS \;/\; 1000}{wt \left[\rho - \dfrac{TDS}{1,000,000} \right]} \qquad (2)$$

where MOL = molality of groundwater, mol/kg

TDS = total dissolved solids concentration of the groundwater, mg/L (at 20 °C and standard atmospheric pressure)

wt = gram molecular weight of sodium chloride (58.4428 g/mol)

ρ = density of groundwater (kg/L) (at 20 °C and standard atmospheric pressure)

The density ratio is then calculated (Potter and Brown, 1977, Kuiper, 1985) from:

$$\frac{\rho}{\rho_0} = \frac{1000 + wt\ MOL}{\dfrac{1000}{\rho_w/\rho_0} + A_0\ MOL + B_0\ MOL^{3/2} + C_0\ MOL^2} \qquad (3)$$

where ρ_w = density of pure water at the temperature and pressure of the groundwater sample

A_0,B_0,C_0 are constants for a given temperature, and determined by third order polynomial interpolation of known values at 0, 25, 50 and 75 °C.

ρ_0 = density of pure water at standard temperature and pressure.

The pressure dependent density perturbation is calculated from (Kuiper, 1985):

$$\delta(P,MOL,T) = \begin{cases} \dfrac{a\ MOL + b}{10{,}000{,}000}\ P & ,0 \leq P \leq 10000\text{kPa} \\ \dfrac{a\ MOL + b}{1000} + \dfrac{.84(\ x\ -\ 1\ )\ +\ 3.75}{100{,}000}\left[\dfrac{P}{100} - 100\right] & ,10000 \leq P \leq 50000\text{kPa} \end{cases} \tag{4}$$

where x = temperature / 25, with temperature in degrees Celsius
a = $-.75\ (x - 1) + .25$
b = $3.5\ (x - 1) + 2$
P = pressure, kPa

Pressure in the above equation is calculated from:

$$P = \rho\ g\ l \tag{5}$$

where ρ = density of fluid at the measurement point
g = acceleration due to gravity
l = observed head relative to the measurement point

Because the pressure is density dependant, and the pressure perturbation in density is pressure dependant, the two previous equations are solved iteratively until the density pressure perturbation convergence criterion is satisfied.

When the new density value has been determined (with the pressure perturbation), the molality can then be recalculated with the most recent density value. Density and molality values are calculated iteratively until the density convergence criterion is satisfied.

The algorithm produces accurate results for temperatures in the range 5° C to 75° C, pressures between 0 and 10,000 kPa, and molalities less than 6 mol/kg.

2.4.2) Determining the Dynamic Viscosity of Groundwater

The dynamic viscosity of the groundwater is required to determine the vertical hydraulic conductivity of the aquifer. The dynamic viscosity of groundwater can be calculated from the following equation developed by Weiss (1982) based on the data of Mathews and Russel (1967), and reported in Kontis and Mandle (1988).

$$\mu = \left(\frac{38.3432}{T^{1/2}_{g}} - \frac{14.621}{T^{1/4}_{g}} + 1.481\right)\left(1 + \frac{TDS}{300}\right) \tag{6}$$

where μ = dynamic viscosity in centipoise
T_g = temperature in °F
TDS = total dissolved solids concentration of groundwater, g/L at 20°C and 1 bar

2.4.3) Calculating Effective Vertical Conductivity

The vertical hydraulic conductivity of the Shepparton Formation over the study area was estimated from the lithological descriptions of boreholes. These vertical hydraulic conductivity values were therefore estimates for freshwater, and needed to be modified to allow for the effects of groundwater of variable viscosity. Given that hydraulic conductivity may be calculated from:

$$K = \frac{-k\ \rho\ g}{\mu} \tag{7}$$

where K is the hydraulic conductivity, m/sec
k is the permeability of the substrate, m^2
ρ is density of the groundwater, kg/m^3
g is the acceleration due to gravity, m/sec^2
μ is the dynamic viscosity of the groundwater

Then the hydraulic conductivity estimated for freshwater may be adjusted to allow for the effects of variable viscosity by applying the following equation:

$$K_g = K_f \frac{\mu_f}{\mu_g} \tag{8}$$

where K_f is the hydraulic conductivity of the substrate and freshwater
K_g is the hydraulic conductivity of the substrate and groundwater
μ_f is the dynamic viscosity of freshwater
μ_g is the dynamic viscosity of the groundwater

2.4.4) Determining Environmental and Freshwater Equivalent Heads

The point water head, also referred to as the point source head, is defined as the water level, referred to a given datum, in a well filled sufficiently with the water of the type to balance the existing pressure at that point. Where groundwater is of variable density, it is appropriate to use two additional heads to determine flow rates. Luscynski (1961), has defined freshwater head (also referred to as "equivalent freshwater head") at a point in variable groundwater systems as "the water level in a well filled with freshwater to a level sufficient to balance the existing pressure at the point." Luscynski (1961) also defines the environmental water between a given point in a groundwater system and the top of the zone of saturation to be "the water of constant or variable density occurring in the environment along a vertical between the point and the top of the zone of saturation." The environmental-water head (or environmental head) at a given point in a variable density groundwater system is defined as the "freshwater head reduced by an amount corresponding to the difference of salt mass in freshwater and that in the environmental water between that point and the top of the zone of saturation."

The following relationships therefore exist among the three head definitions:

For point and freshwater heads:

$$\rho_f H_{if} = \rho_i H_{ip} - Z_i (\rho_i - \rho_f) \qquad (9)$$

For environmental and freshwater heads:

$$\rho_f H_{in} = \rho_f H_{if} - (\rho_f - \rho_a) - (Z_i - Z_r) \qquad (10)$$

For point and environmental heads:

$$\rho_f H_{in} = \rho_i H_{ip} - Z_i (\rho_i - \rho_a) - Z_r (\rho_a - \rho_f) \qquad (11)$$

Where ρ_f is the density of freshwater

ρ_i is the density of the water at the measurement point

ρ_a is the average density of the water between the top of the zone of saturation and the measurement point, as defined by:

$$\rho_a = \frac{1}{Z_r - Z_i} \int_{Z_i}^{Z_r} \rho \, dz \qquad (12)$$

H_{if} is the freshwater head at the measurement point

H_{ip} is the point head at the measurement point

H_{in} is the environmental head at the measurement point

Z_i is the elevation of the measurement point with respect the elevation datum

Z_r is the elevation of the top of the saturated zone with respect to the elevation datum

Equivalent freshwater head values can be used to determine flow along a horizontal line in variable density groundwater systems. Environmental head can be used to determine flow along a vertical line in variable density groundwater systems. In groundwater flow systems with densities close to that of freshwater, the three head values at any given point will be very similar. In groundwater flow systems where densities differ considerably from that of freshwater, it is important to use freshwater heads and environmental heads appropriately. Davies (1987) discusses such a situation - his "gravity-related density-dependent flow error term" is due to the use of equivalent freshwater heads to simulate flow in situations where there is a significant vertical flow component. In such circumstances, a combination of freshwater and environmental head should be used to calculate the flow rates. Kuiper (1983, 1985) has presented an algorithm to do this.

2.4.5) Determining Flow Rates

Where groundwater density fluctuations significantly affect flow rates, the groundwater velocities are defined in the directions of the principle axes of an orthogonal co-ordinate system in terms of the freshwater and environmental heads as (Luszynski, 1961):

$$v_x = -K_{xx} \frac{g}{\mu_i} \left[\rho_f \frac{\partial H_{if}}{\partial x} \right] \tag{13}$$

$$v_y = -K_{yy} \frac{g}{\mu_i} \left[\rho_f \frac{\partial H_{if}}{\partial y} \right] \tag{14}$$

$$v_z = -K_{zz} \frac{g}{\mu_i} \left[\rho_f \frac{\partial H_{in}}{\partial z} \right] \tag{15}$$

where	v_x	is the velocity of the fluid in the x direction
	v_y	is the velocity of the fluid in the y direction
	v_z	is the velocity of the fluid in the z direction
	K_{xx}	is the hydraulic conductivity in the x direction
	K_{yy}	is the hydraulic conductivity in the y direction
	K_{zz}	is the hydraulic conductivity in the z direction

These equations assume that the axes of the co-ordinate system coincide with the principle directional permeabilities.

2.5) Significance of Approximations/Assumptions Used in the Estimation of Vertical Flow

The vertical flow rates for the Deniliquin Irrigation study area were calculated from the equations presented in Section 2.4. These calculated flow rates are subject to any uncertainties in the input data, and to the assumptions inherent in the calculation methodology.

When using the strategy described in this document to predict flow rates under future conditions, it must be remembered that the groundwater flow system is dynamic: the head differences used to calculate flow rates will change because of flow through the Shepparton Formation aquifer, and flow rates will then change in response to the new head differences.

For example, a scenario modelled is the system response to an instantaneous rise of 6.4 metres in the head of the Pliocene Sands aquifer. Of course, such an event would also generate a head increase in the Shepparton Formation aquifer and thus affect vertical flow rates. However, for simplicity we have calculated the flow rates using present day heads in the Shepparton Formation aquifer. Also, changes to the horizontal flow regime will significantly alter vertical flow, as will changes in groundwater salinity.

A three-dimensional numerical groundwater model of the Deniliquin Irrigation areas would overcome some problems described in the previous section, but at a far greater cost than the methods adopted for the current investigation. It would be appropriate to link the appropriate Murray Basin regional groundwater model currently being developed to this exercise.

2.6) Results and Discussion

The salinity of the groundwater in the Pliocene Sands and the Shepparton Formation aquifers is depicted in figures 3 and 4 respectively. The saturated thickness of the Shepparton Formation can be seen in figure 5.

The corrected vertical hydraulic conductivity values are shown in figure 8. The greatest absolute difference between corrected and uncorrected vertical hydraulic conductivities occurs in areas where the vertical hydraulic conductivity is greatest. The greatest relative differences between corrected and uncorrected vertical hydraulic conductivity values is in areas where the groundwater salinity is highest. As expected, the corrected vertical hydraulic conductivities are always less than the uncorrected values. The magnitude of the hydraulic conductivity corrections is considerably less than the estimation error of the uncorrected vertical hydraulic conductivity values.

The uncorrected head differences and the environmental head differences across the Shepparton Formation are depicted in figure 7. The largest difference between the uncorrected head differences and environmental head differences can be seen in the western portion of the study area, where the groundwater salinity is significantly greater than the central and eastern portions of the study area.

The changes in vertical hydraulic conductivity due to the increased viscosity of saline groundwater tend to reduce vertical flow, whereas the increased density of the groundwater tends to increase vertical flow. However, the density corrections to the heads are of greater significance in determining flow rates than the viscosity corrections to vertical hydraulic conductivities.

Figure 9 depicts the corrected leakage rates through the Shepparton Formation. For much of the study area, the changes in flow due to variable density groundwater are small. The difference between the corrected and uncorrected leakage rates is greatest towards Wakool, where the differences between uncorrected and corrected head gradients are largest.

Techniques and software have been established that will allow variable density groundwater flow to be estimated with the ARC/INFO GRID module in other regions of the Murray Basin. A library of interface routines to the ARC/INFO GRID data structures would make the application of numerically intensive routines to GRID data considerably easier.

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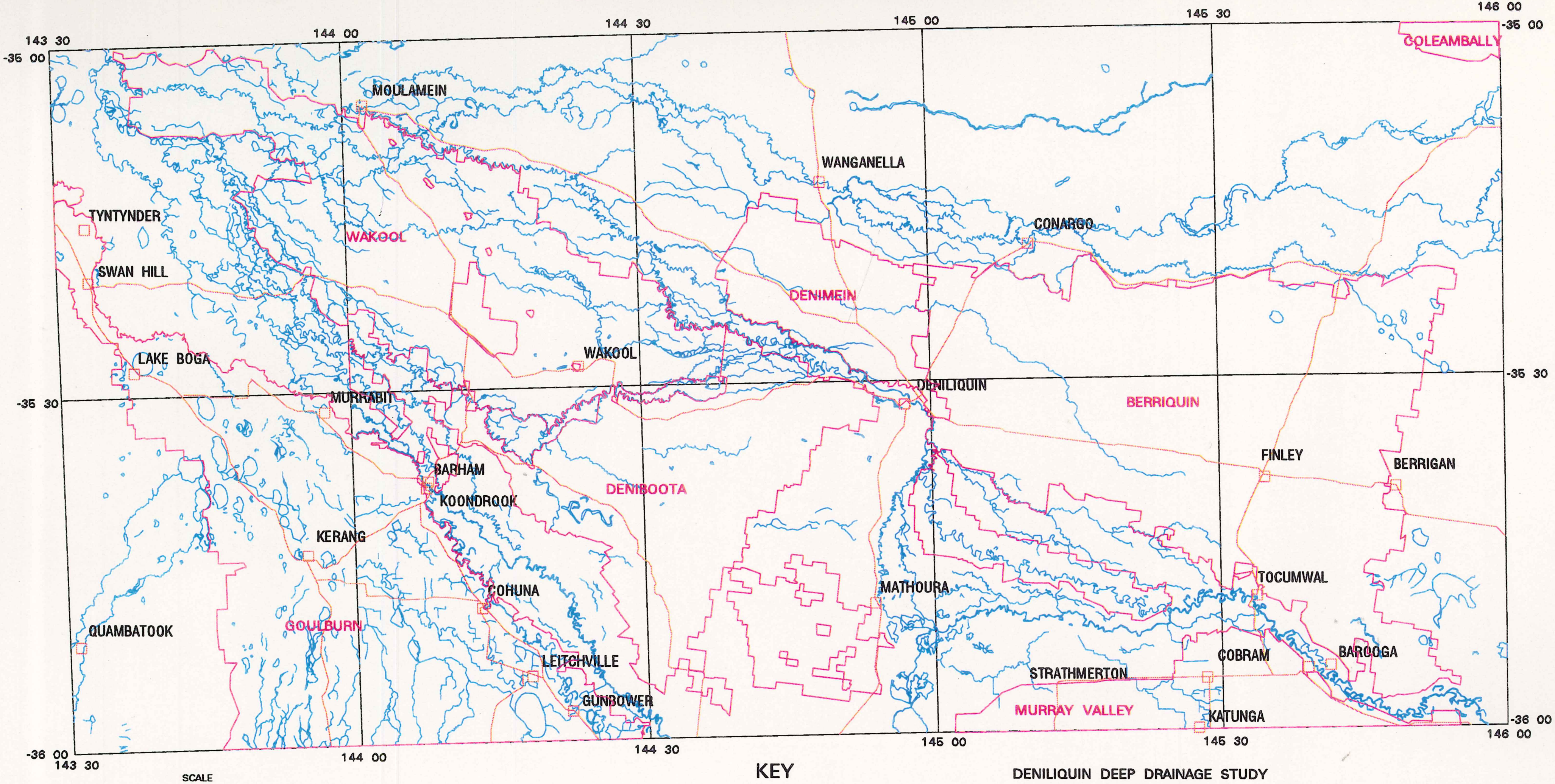
Woolley, D.R., Department of Water Resources, NSW, 1991. Narrandera Hydrogeological Map (1:250 000 scale). *Bureau of Mineral Resources, Geology and Geophysics,* Canberra.

Woolley, D.R. & Williams, R.M., 1978 - Tertiary Stratigraphy and hydrogeology of the eastern part of the Murray Basin, New South Wales. *Symposium on the hydrogeology of the Riverine Plain of southeastern Australia. Aust.Sx.Soil Science*, 45-65.

Figure 1: Deniliquin Study Area



SCALE

0 5 10 15 20 25 km

Transverse Mercator Projection
AMG Zone 55
Australian Map Grid

KEY

- Rivers & Lakes
- Principal Roads
- Irrigation Areas
- □ Towns

DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:
Cultural background for the 1:250 000 scale Murray Basin Hydrogeological Map Series - DENILIQUIN, JERILDERIE and SWAN HILL. Used under agreement with AUSLIG.

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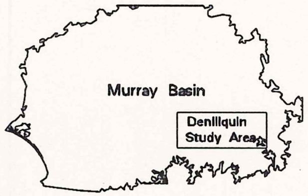
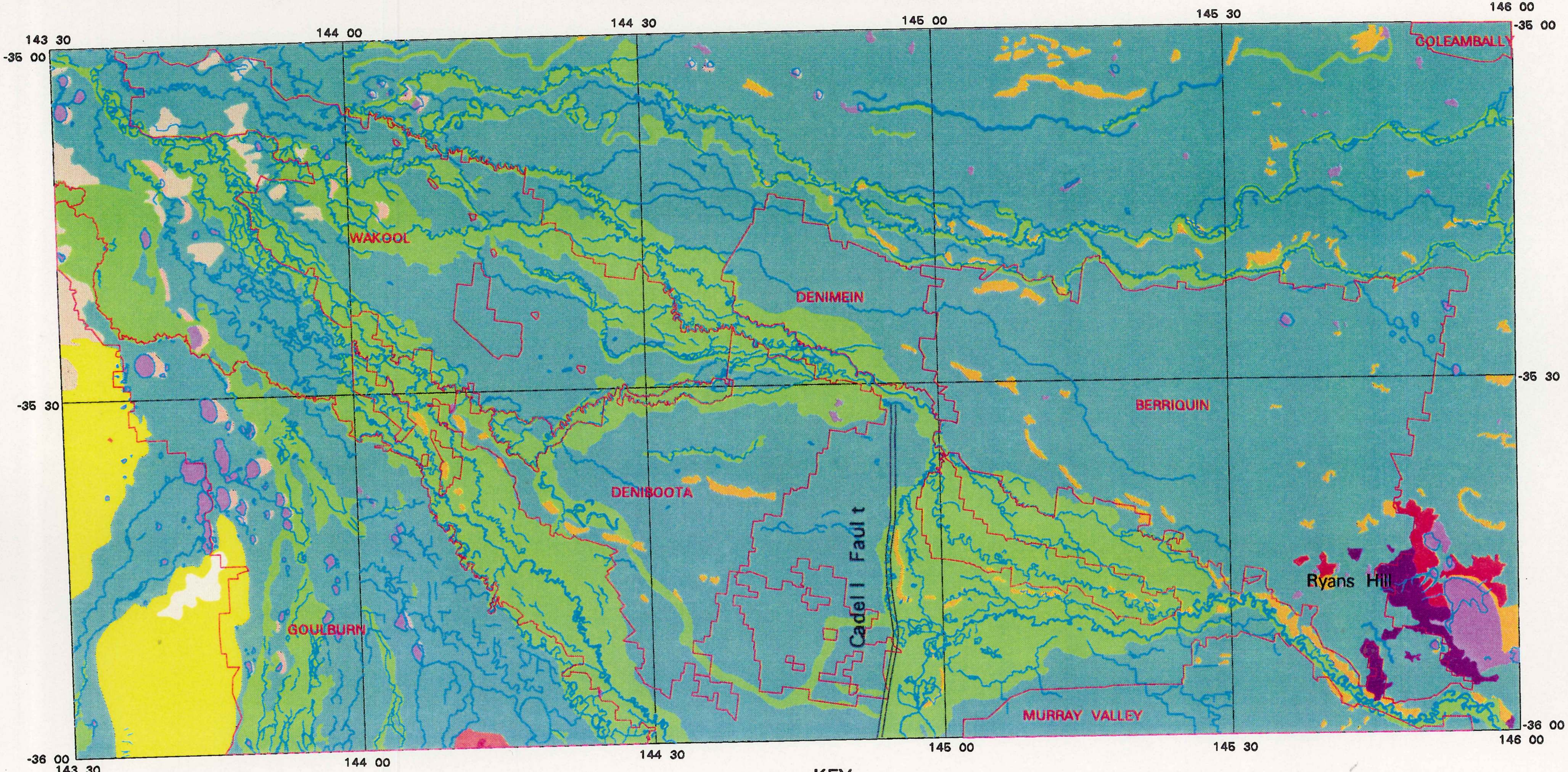


Figure 2: Surface Geology



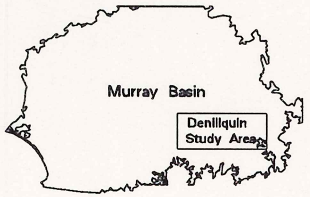
SCALE 1:900 000

0 5 10 15 20 25 km

Transverse Mercator Projection
AMG Zone 55
Australian Map Grid

KEY

- 🟩 Coonambidgal Formation
- 🟧 Fluvial derived aeolian dunes
- ⬜ Molineaux-Lowan Sands
- 🟪 Lacustrine deposits
- ▨ Lunette deposits
- ▨ Woorinen Formation
- ▨ Pooraka Formation
- 🟦 Shepparton Formation
- 🟨 Loxton-Parilla Sands
- 🟥 Siluro-Devonian Granite
- 🟪 Ordovician Metamorphics



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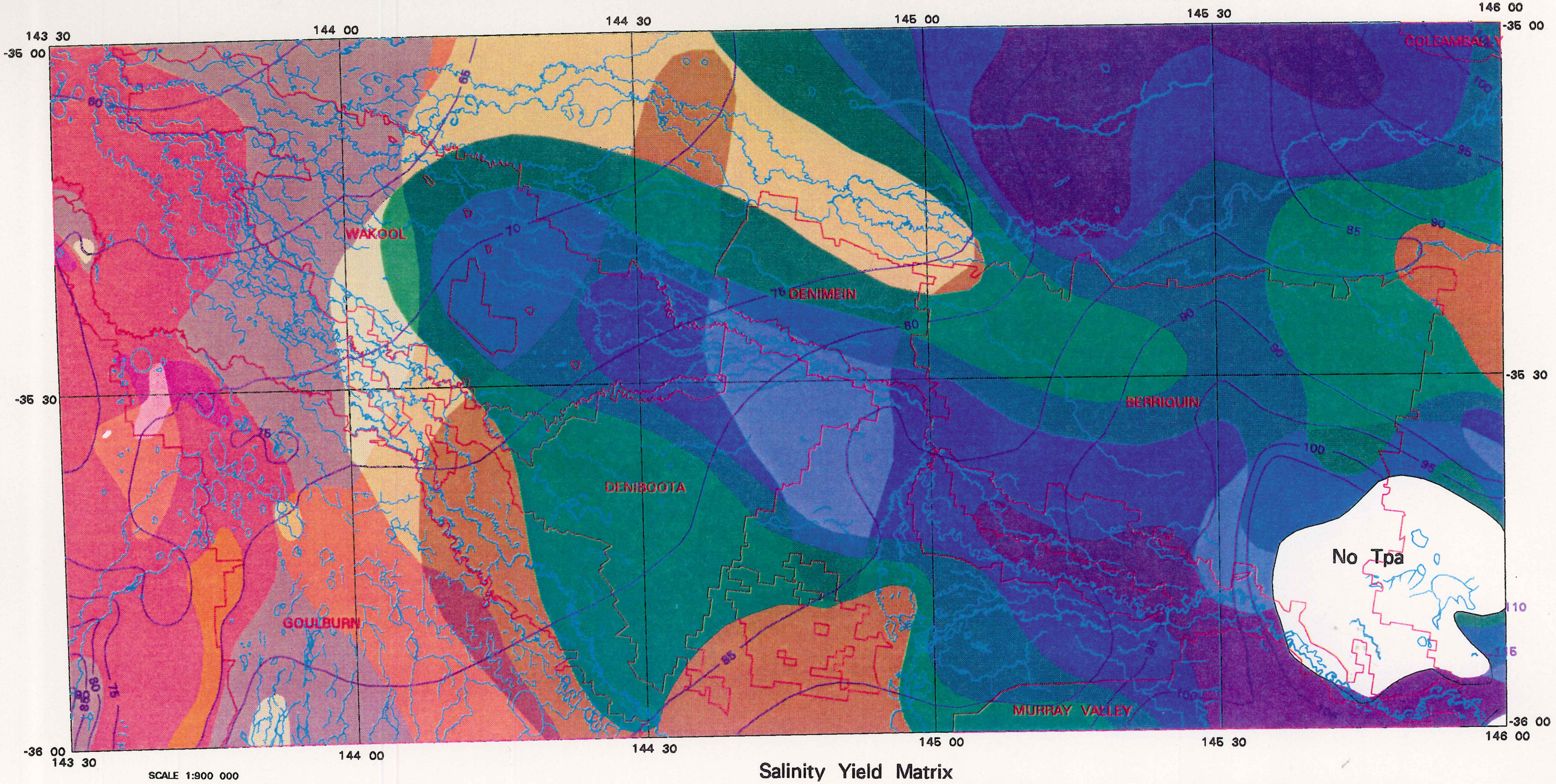
DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:
Surface geology and nomenclature from
Brown, C.M. & Stephenson, A.E.,1985 -
Murray Basin Geological Map
(1:1 000 000 scale) AGSO Canberra.

For SWAN HILL portion, compiled from
Lawrence, C.R., 1974 -
Swan Hill Geological Map
(1:250 000 scale)
Dept of Mines, Victoria

Figure 3: Salinity/Yield & SWL for the Pliocene Sands Aquifer



SCALE 1:900 000

0 5 10 15 20 25 km

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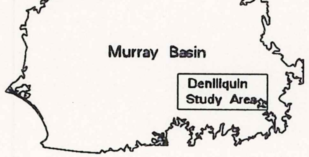
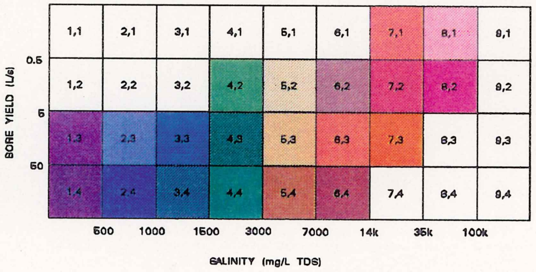


Salinity Yield Matrix



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1,3	2,3	3,3	4,3	5,3	6,3	7,3	8,3	9,3
1,4	2,4	3,4	4,4	5,4	6,4	7,4	8,4	9,4

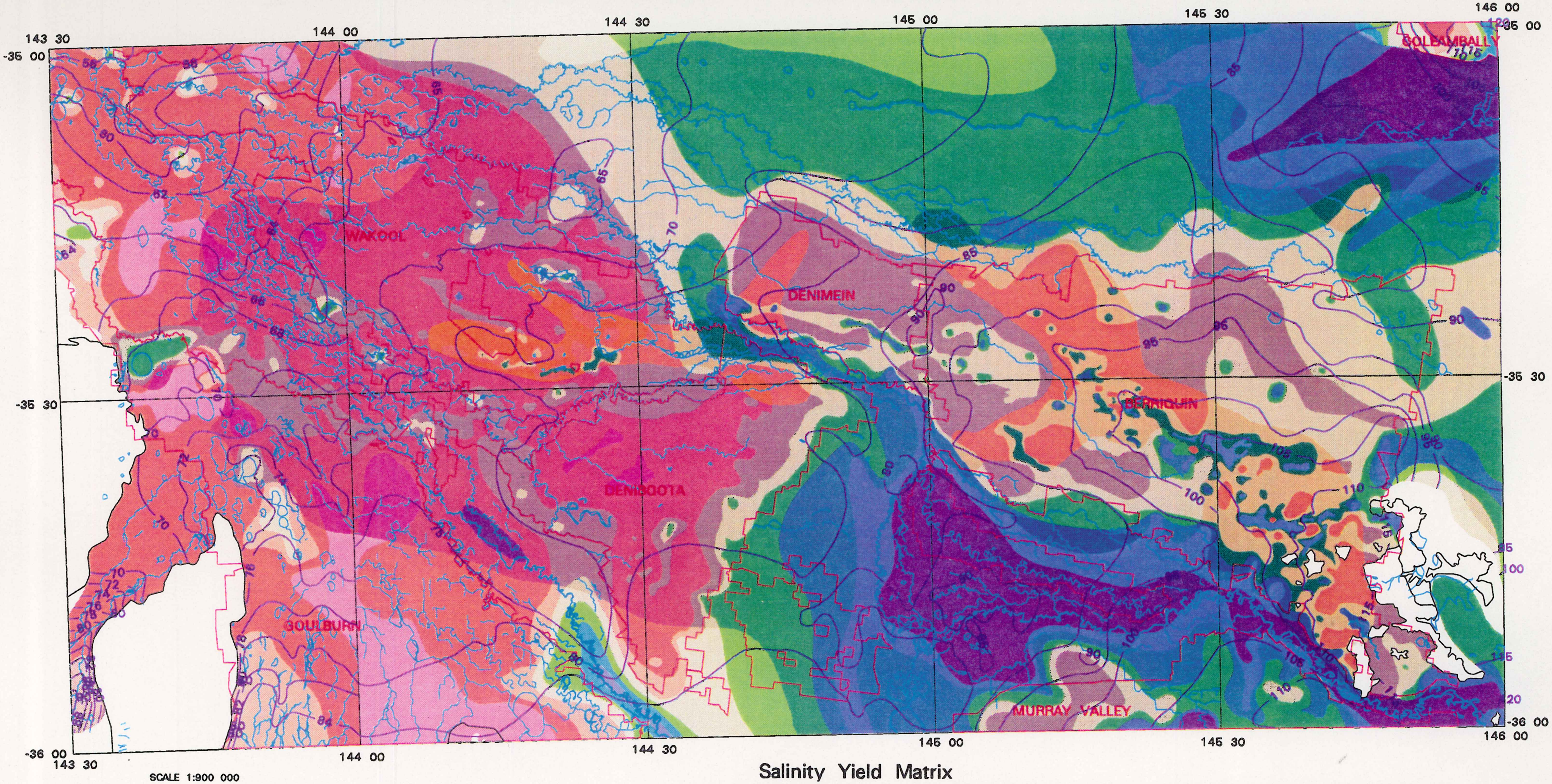
SWL for Pliocene Sands

DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:
Compiled for 1:250 000 Murray Basin Hydrogeological Map Series;

SWAN HILL (O'Rorke, M.E. et al (RWC), 1992)
DENILIQUIN & JERILDERIE (NSW DWR, 1992)

Figure 4: Salinity/Yield & SWL for the Shepparton Formation Aquifer



SCALE 1:900 000

0 5 10 15 20 25 km

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Australian Map Grid

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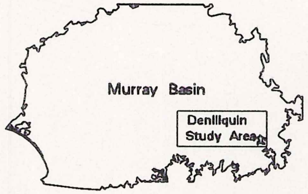
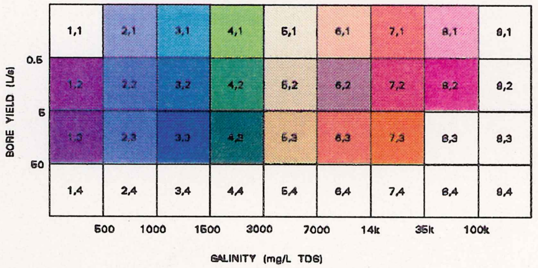


Salinity Yield Matrix



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1,2	2,2	3,2	4,2	5,2	6,2	7,2	8,2	9,2
1,3	2,3	3,3	4,3	5,3	6,3	7,3	8,3	9,3
1,4	2,4	3,4	4,4	5,4	6,4	7,4	8,4	9,4

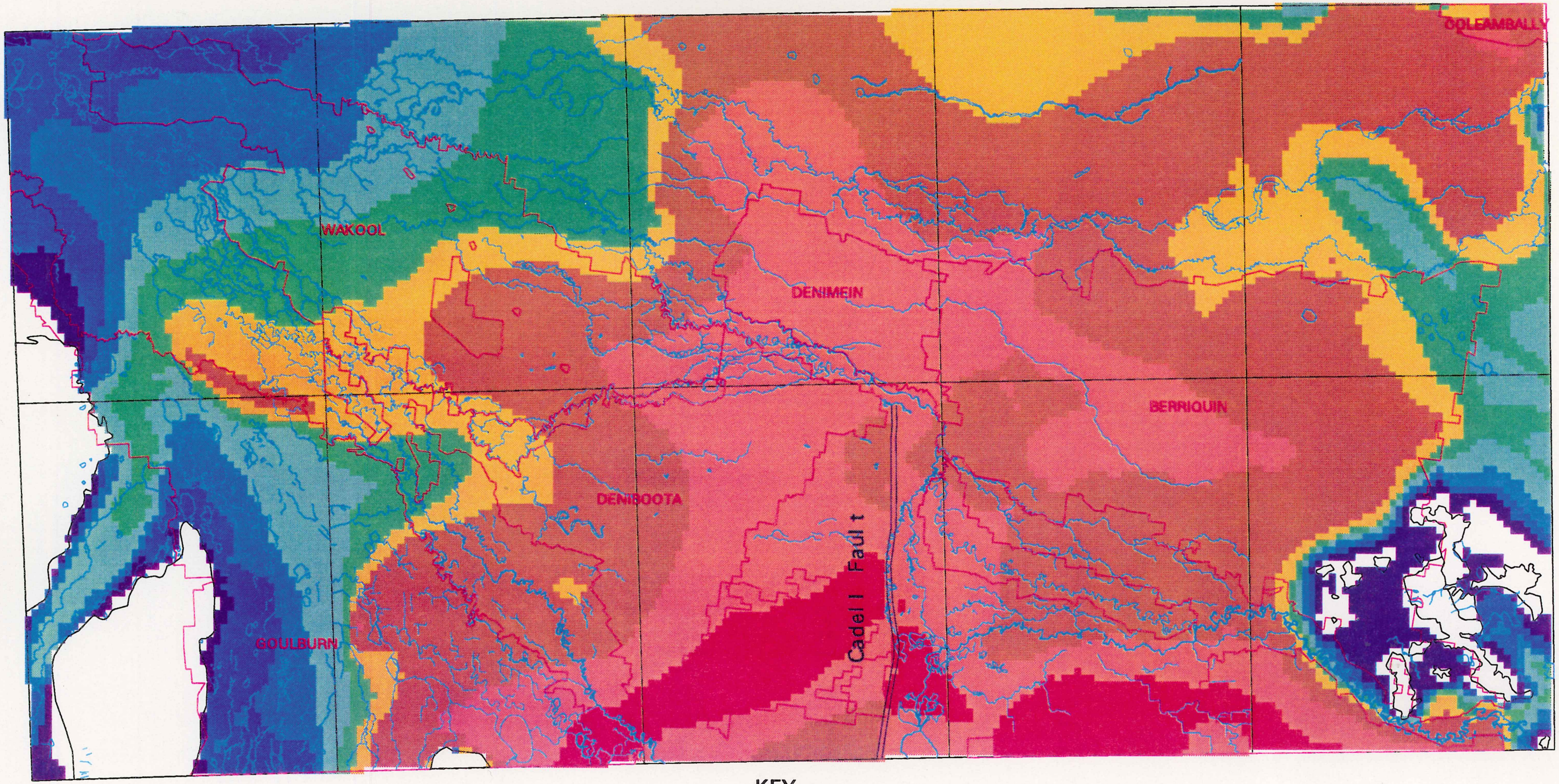
SWL for Shepparton, m AHD

DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:
Compiled for 1:250 000 Murray Basin
Hydrogeological Map Series;

SWAN HILL (O'Rorke, M.E. et al (RWC), 1992)
DENILIQUIN & JERILDERIE (NSW DWR, 1992)

Figure 5: Saturated Thickness of Shepparton Formation



KEY

metres

- 🟪 0-10
- 🟦 10-20
- 🟦 20-30
- 🟦 30-40
- 🟩 40-50
- 🟨 50-60
- 🟧 60-80
- 🟥 80-100
- 🟥 100-120
- 🟥 120-140

SCALE 1:900 000

0 5 10 15 20 25 km

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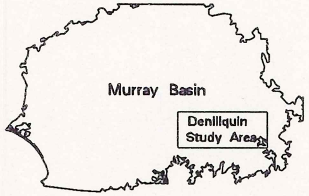
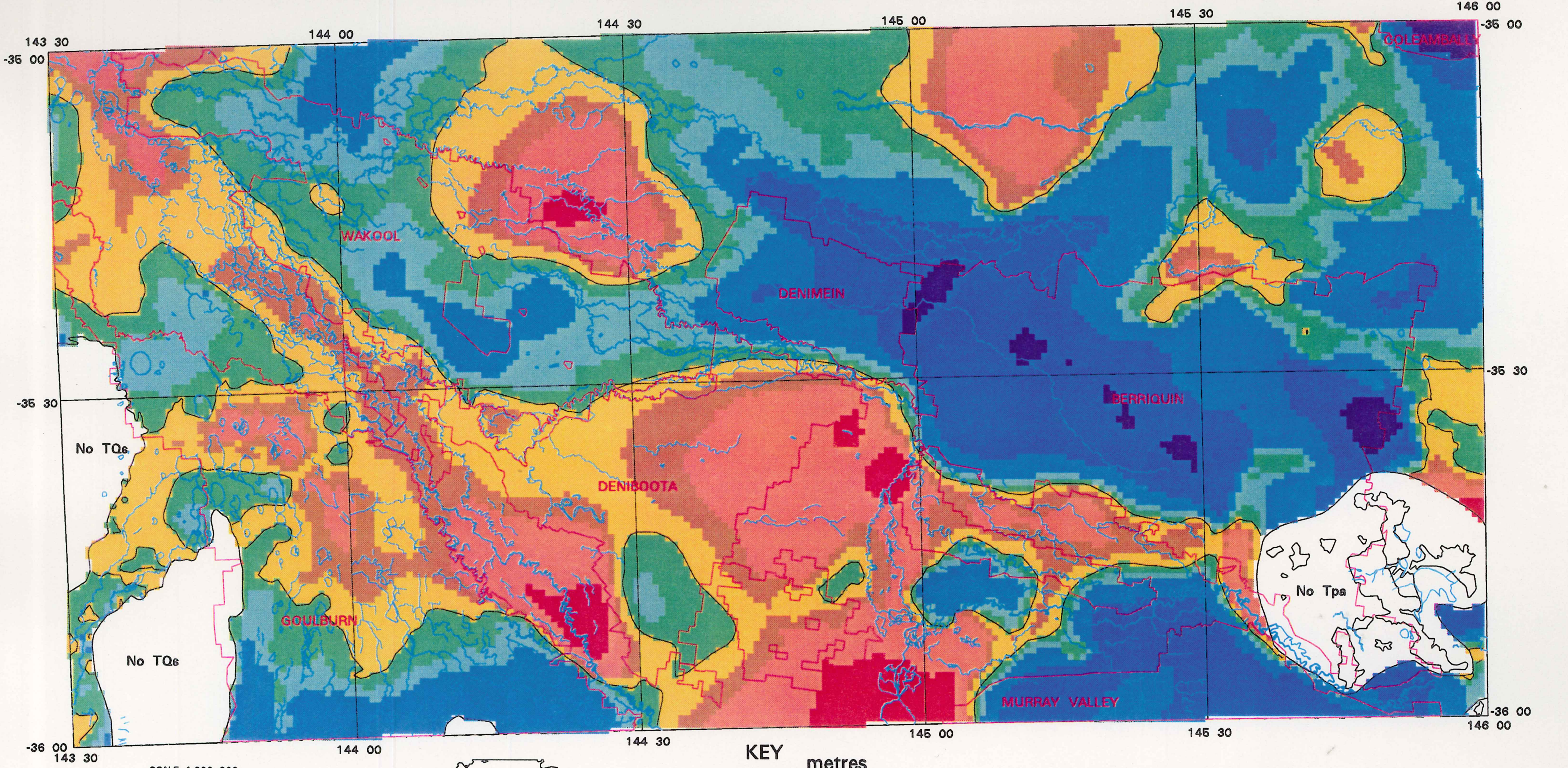


DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:
Watertable and base of Shepparton Formation surfaces reformatted to 1km square grid.
Grid of saturated thickness derived by simple subtraction of these grids.

Figure 6: Uncorrected Head Difference between Shepparton and Pliocene Sands



SCALE 1:900 000

0 5 10 15 20 25 km

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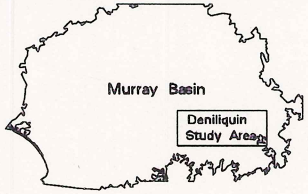


—— Zero head difference contour

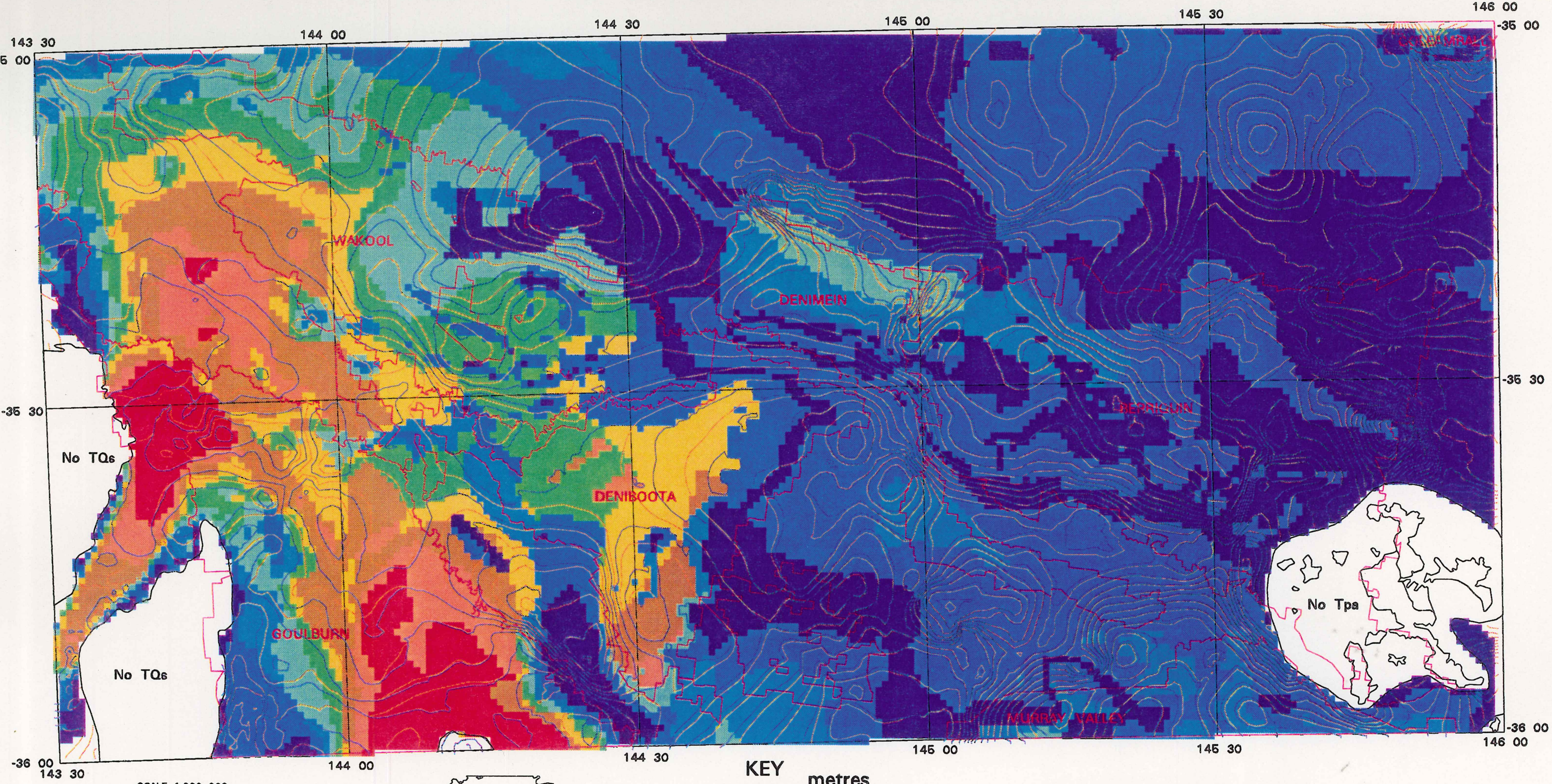
KEY	metres
🟪	< -10
🟦	-10 to -5
🟦	-5 to -2
🟦	-2 to -1
🟩	-1 to 0
🟨	0 to +1
🟧	+1 to +2
🟧	+2 to +5
🟥	+5 to +10
🟥	> +10

DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:
Surfaces representing Standing Water Levels for Shepparton and Pliocene Sands aquifers reformatted to 1km square grid.

Grid of uncorrected head difference derived by simple subtraction of these grids.
Negative values indicates that head in Shepparton (TQs) is higher than head in underlying Pliocene Sands (Tpa) ie. potential downward flow.

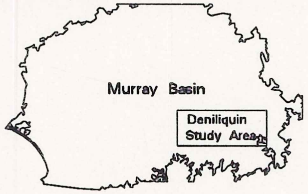
Figure 7: Density Corrections of Head Difference



SCALE 1:900 000

0 5 10 15 20 25 km

Transverse Mercator Projection
AMG Zone 55
Australian Map Grid



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Uncorrected Head Difference, m

Environmental Head Difference, m

KEY

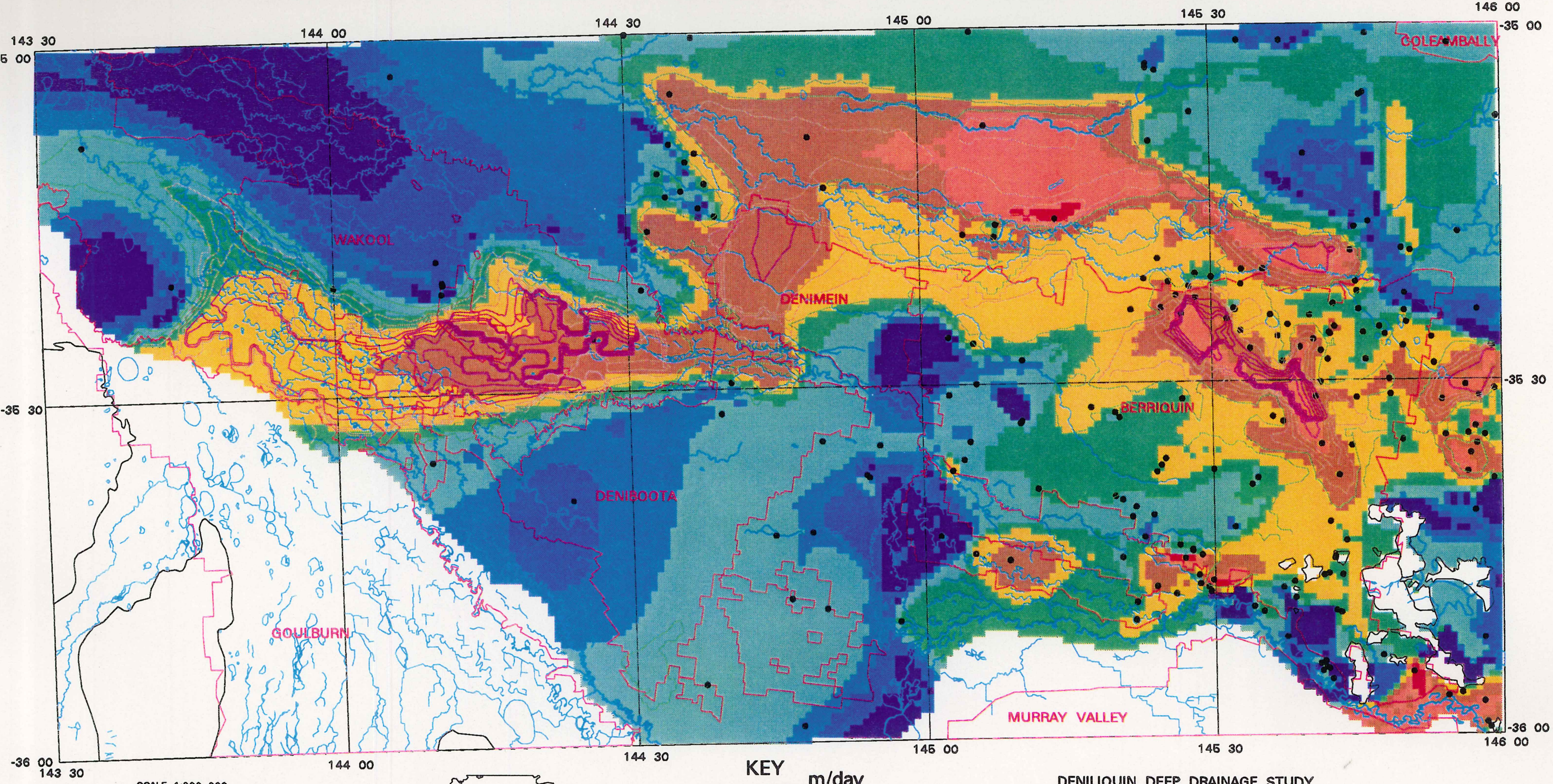
	metres
■	< 0.1
■	0.1 - 0.2
■	0.2 - 0.3
■	0.3 - 0.4
■	0.4 - 0.5
■	0.5 - 0.6
■	0.6 - 0.8
■	0.8 - 1
■	1 - 2
■	> 2

DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:
Uncorrected head difference grid (uchd) calculated by subtracting watertable grid from Pliocene Sands head grid. Environmental head difference grid (ehd) accounts for density effects due to salinity and temperature.

Displayed is the magnitude of the difference between these two grids, showing the effect of increasing aquifer salinities westwards.

Figure 8: Corrected Vertical Hydraulic Conductivity (Kv) for Shepparton Formation aquifer, m/day



SCALE 1:900 000

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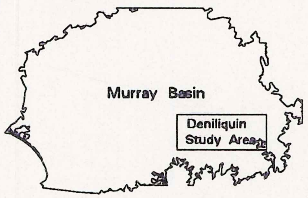


Difference corrected/uncorrected Kv

- —— <0.003 m/day
- —— 0.003 to 0.006 m/day
- —— > 0.006 m/day
- ● Borehole with full TQS sequence

KEY m/day

- <0.001
- 0.001-0.005
- 0.005-0.01
- 0.01-0.05
- 0.05-0.1
- 0.1-0.2
- 0.2-0.5
- 0.5-1.0
- 1.0-1.5
- >1.5

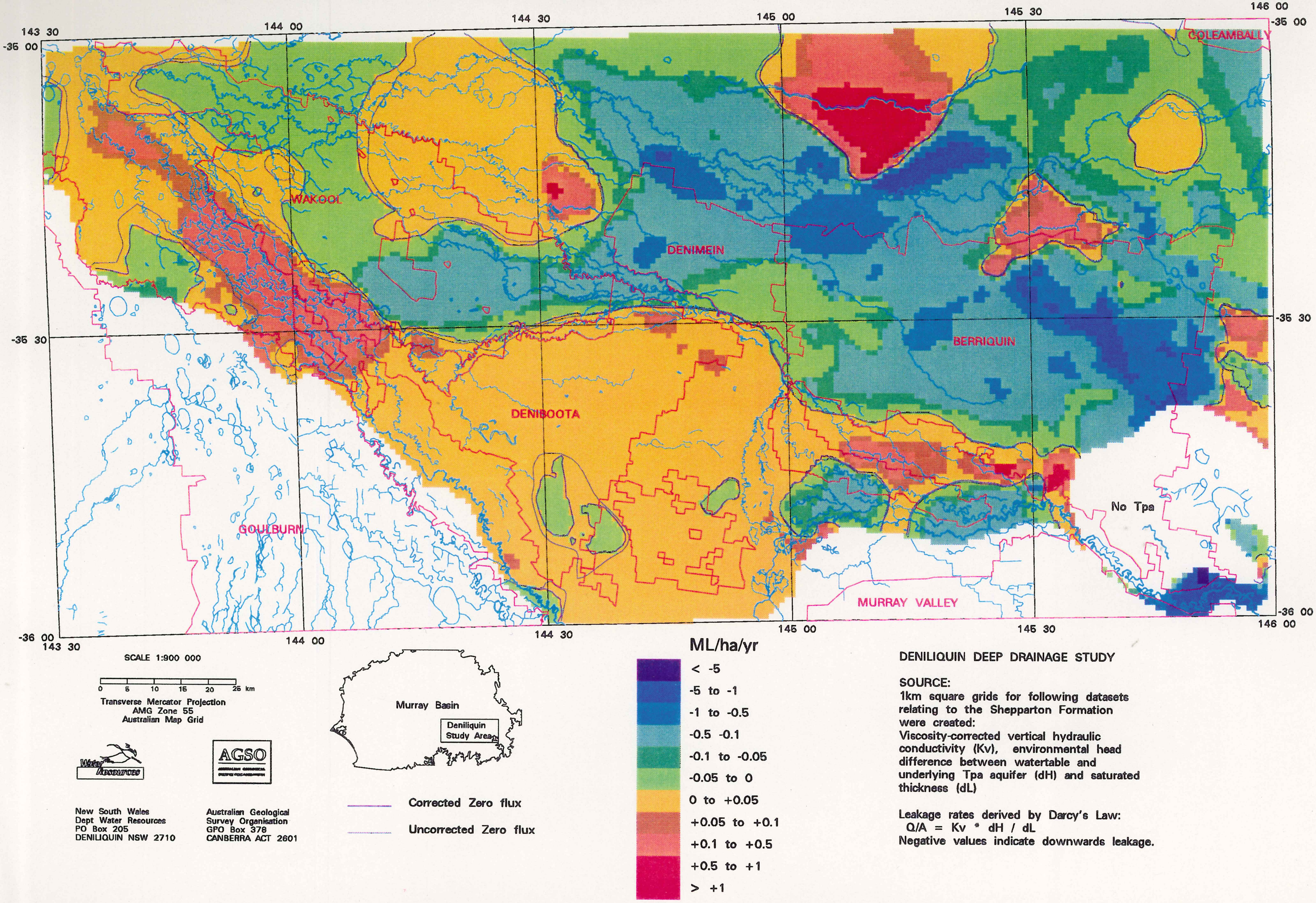
DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:

Lithological data for regional boreholes obtained from NSW DWR. Kv values assigned to lithological descriptions. Interpolation of Kv based on weighted averages for boreholes fully penetrating Shepparton Formation (TQs). Aquifer yield and structural contours were taken into account. Reformatted to 1km square grid.

Contours of density corrections for Kv also displayed.

Figure 9: Corrected Leakage Rates through Shepparton Formation



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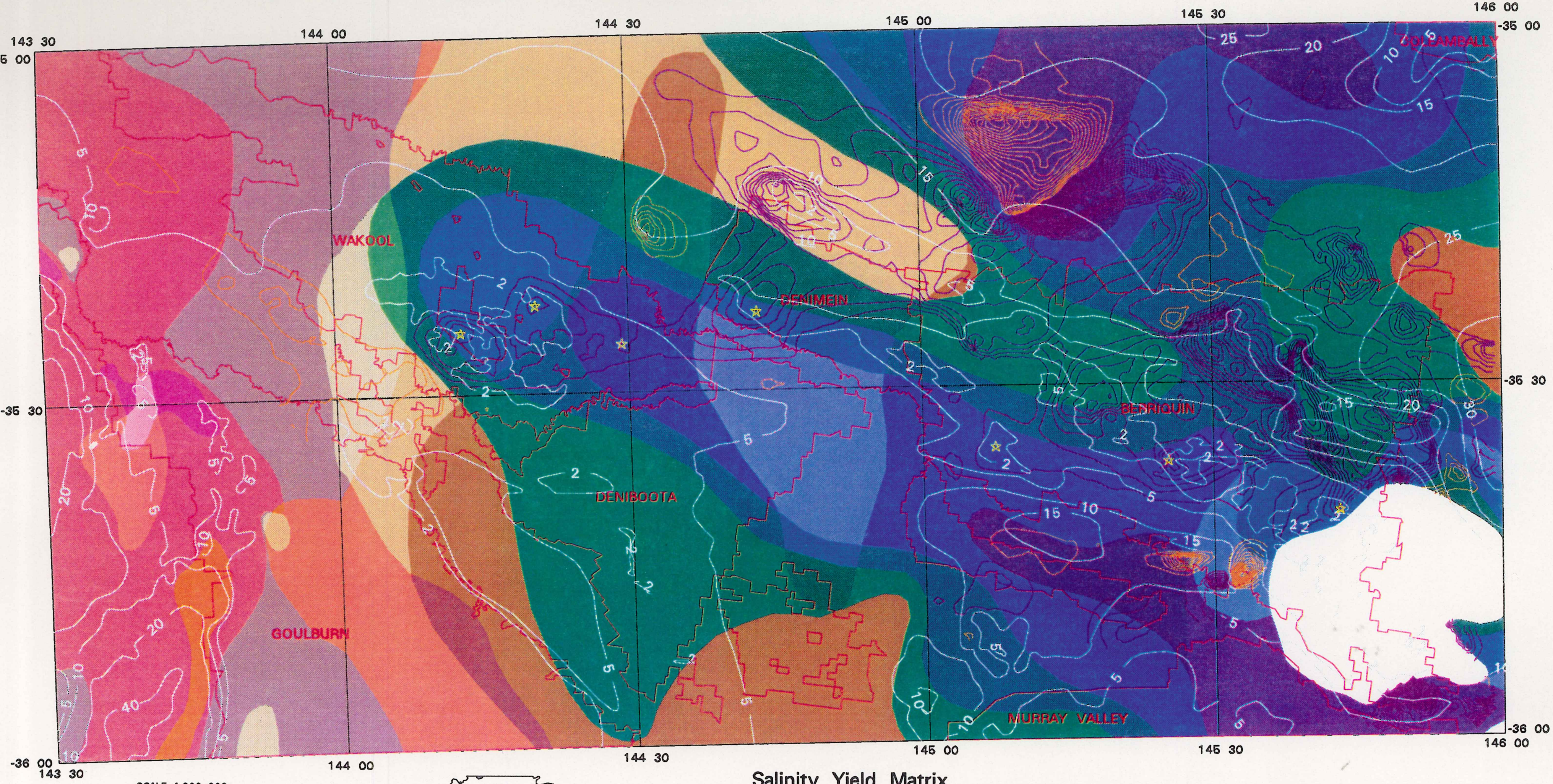
DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:
1km square grids for following datasets relating to the Shepparton Formation were created:
Viscosity-corrected vertical hydraulic conductivity (Kv), environmental head difference between watertable and underlying Tpa aquifer (dH) and saturated thickness (dL)

Leakage rates derived by Darcy's Law:
Q/A = Kv * dH / dL
Negative values indicate downwards leakage.

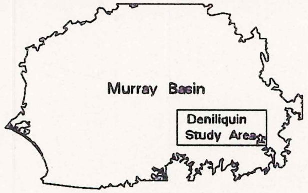
Figure 10: Targeting of Deep Drainage Sites



SCALE 1:900 000

0 5 10 15 20 25 km

Transverse Mercator Projection
AMG Zone 55
Australian Map Grid



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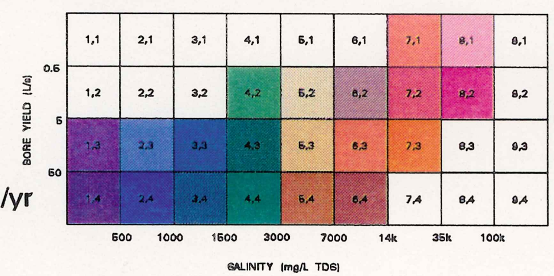
Downward Leakage, ML/ha/yr
Upward Leakage, ML/ha/yr
Depth to watertable, m
Potential bore site

Salinity Yield Matrix



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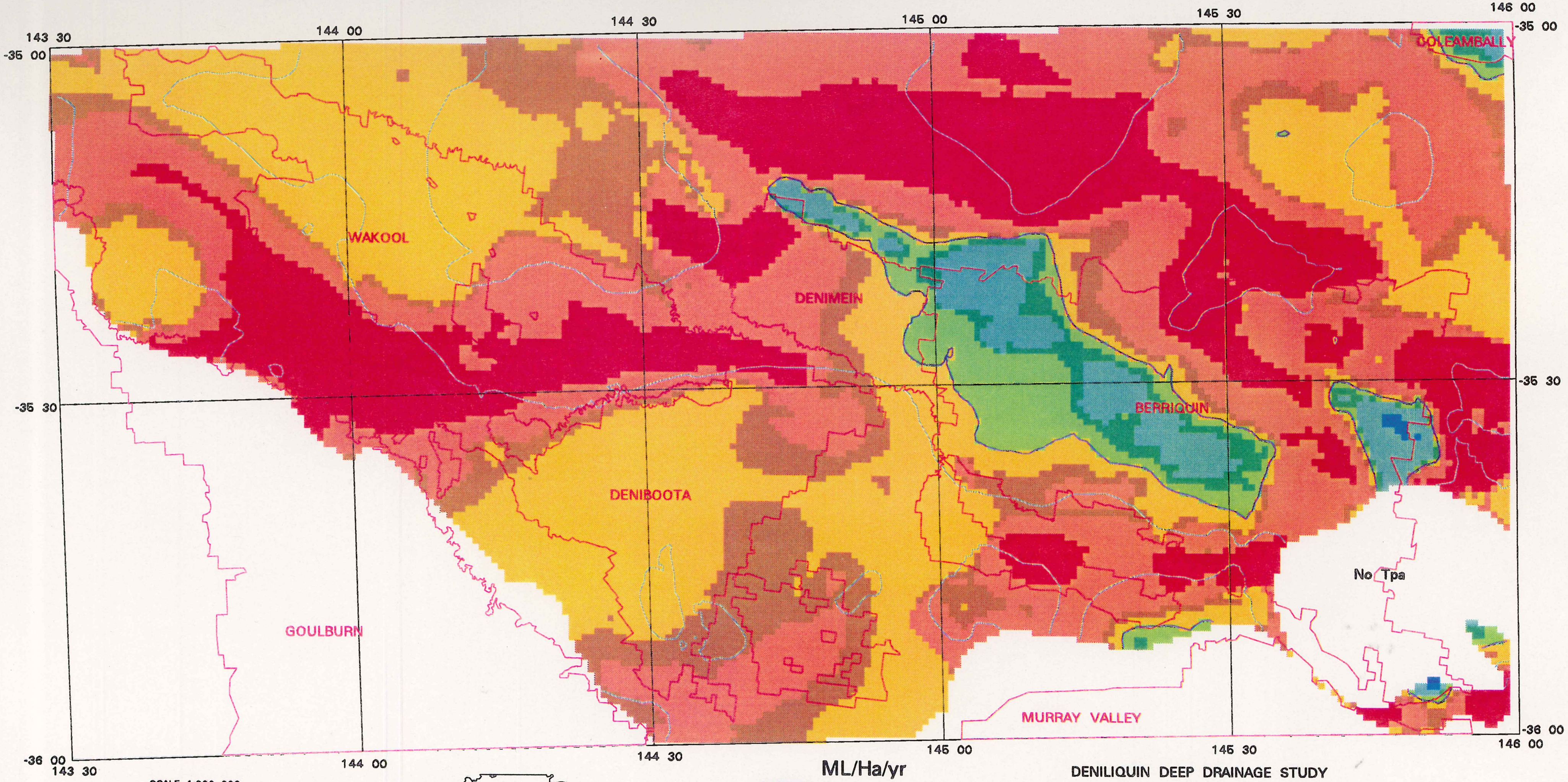
1,3	2,3	3,3	4,3	5,3	6,3	7,3	8,3	9,3
1,4	2,4	3,4	4,4	5,4	6,4	7,4	8,4	9,4

DENILIQUIN DEEP DRAINAGE STUDY

Target areas for high yielding bores in Pliocene Sands aquifer for conjunctive use and deep drainage/ watertable control. Selection criteria based on salinity/yield of aquifer, downward vertical leakage and proximity to shallow watertables.

Figure11: Estimated Leakage Rates through Shepparton Formation by 2020



SCALE 1:900 000

0 5 10 15 20 25 km

Transverse Mercator Projection
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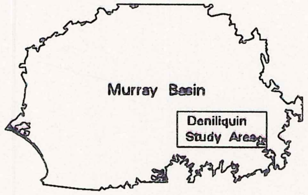

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Zero flux in 1988

Zero flux by 2020

ML/Ha/yr

- < -5
- -5 to -1
- -1 to -0.5
- -0.5 -0.1
- -0.1 to -0.05
- -0.05 to 0
- 0 to +0.05
- +0.05 to +0.1
- +0.1 to +0.5
- +0.5 to +1
- > +1

DENILIQUIN DEEP DRAINAGE STUDY

SOURCE:
1km square grids for following datasets relating to the Shepparton Formation were created:
Viscosity corrected vertical hydraulic conductivity (Kv), environmental head difference between watertable and underlying Tpa aquifer (dH), saturated thickness (dL)

A rise of 6.4m was estimated for the head in the underlying Tpa aquifer over the 32 years following 1988 (20 cm/yr). Leakage rates derived by Darcy's Law:
$Q/A = Kv * (dH + 6.4) / dL$
Negative values imply a greater head in the Shepparton than in the Pliocene Sands ie. potential for downward water movement.