AGSO

THE LAKE TUTCHEWOP, LAKE WILLIAM AND LAKE KELLY SALINE WATER DISPOSAL BASINS, MURRAY BASIN, AUSTRALIA: LITHOSTRATIGRAPHY, HYDRODYNAMICS AND HYDROCHEMISTRY

RECORD 1997/6

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Department of Primary Industries and Energy

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The Lake Tutchewop, Lake William and Lake Kelly Saline Water Disposal Basins, Murray Basin, Australia: Lithostratigraphy, Hydrodynamics, and Hydrochemistry

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CONTENTS

FIGURES

Figure 67 has been omitted from the hardcopy of this record.

TABLES

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SUMMARY

ABSTRACT

Lakes Tutchewop, William and Kelly are disposal basins for a major interception scheme designed to minimise the discharge of salt from Barr Creek into the Murray River.

The use of Lake Tutchewop as a disposal basin since 1968 has created minimal lateral and vertical invasion by surface disposal water into the surrounding groundwater regime. Although lateral gradients indicate a potential for lateral flow of distances up to several hundred metres, both flow rate calculations and geochemical evidence indicate limited lateral movement.

Compared to Lake Tutchewop, the Lake William lacustrine sequence has higher sand content and therefore higher permeability. However, the disposal water can move only relatively small distances laterally because enclosure by the surrounding groundwaters is more effective. These groundwater characteristics result from a combination of lower lake floor elevation and steeper lake margins formed during groundwater-dominated natural conditions, and groundwater mounds superimposed on the natural system by irrigation of the adjacent floodplains. Geochemical evidence is consistent with the hydrodynamic evidence and indicates limited lateral and vertical movement of disposal water movement.

Lake Kelly is intermediate between the other lakes in terms of its natural hydrostratigraphic setting. Currently available hydrodynamic evidence of potential disposal water movement is limited and inconclusive but geochemical evidence indicates limited lateral and vertical movement of disposal water.

SYNOPSIS

General

Lakes Tutchewop, William and Kelly are disposal basins for a major interception scheme designed to minimise the discharge of salt from Barr Creek into the Murray River. This interception scheme is the subject of an ongoing investigation by HydroTechnology (previously Rural Water Corporation now Sinclair Knight Merz) into the current and future impacts of the disposal basins and the future management options for the complex. This report describes AGSO/CSIRO investigations which contribute to this broad aim through a sharp focus on the disposal basins and their immediate surroundings. Specifically, the AGSO/CSIRO work:

(1) Describes the lithostratigraphy of Lakes Tutchewop, William and Kelly; identifies formal stratigraphic units; and provides semi-quantitative information on the porosity in the sequence, and the hydraulic conductivities of various aquifer lithofacies;

(2) Assesses the potential for movement of disposal water into the adjacent groundwater system by determining the direction and magnitude of the lateral and vertical hydraulic gradients within and near the lakes; and

(3) Determines the extent to which disposal waters have moved into the adjacent and underlying groundwater systems by applying geochemical indicators which will distinguish between disposal and natural waters.

Lakes Tutchewop, William and Kelly lie between Swan Hill and Kerang, within a sandy lunette complex which parallels the southwestern flank of the Little Murray River at the terminal end of the Avoca floodplain. The lunette complex lies riverwards, between the Mallee dunefields on the Gregwin and Cannie Ridges.

Until 1968, Lake Tutchewop was a predominantly freshwater terminal lake of the Avoca River system. With the construction of the Number 6/7 irrigation channel *via* Kangaroo Lake to the Little Murray River along the western side of Lake Tutchewop, and the Barr-Creek - Tutchewop drainage channel, Lake Tutchewop has been isolated from the annual Avoca River floods, to become the larger disposal basin for the Barr Creek saline water pumping scheme. Lakes William and Kelly are also disposal basins, linked with the saline-water drainage channel. Formerly, they were isolated salt lakes fed by saline springs, and were regularly harvested for salt.

The lunettes associated with the disposal basin lakes are part of an extensive lunette complex which is presumed to be Pleistocene-Holocene, and overlies the Shepparton Formation. The lacustrine sequence of the Yamba Formation in each of the lakes is comparable. A basal less-permeable unit comprises 0.9 to 1.3 metres of subdued mottled grey bioturbated muds with minor carbonate and ubiquitous traces of gypsum. An upper thinner unit with a more variably-permeable sequence comprises 0.3 to 0.7 metres of sands and sandy mud, commonly biota-rich, calcareous, of variable oxidation states and low in gypsum. This upper unit is absent in Lake William. In Lake Kelly the sequence has earlier localised lunette deposits. Lunette sediments on the eastern margins of all lakes are predominantly clay-pelletal lithofacies with thin interbedded highly-permeable quartz-sand lithofacies.

Porosity in the lacustrine Yamba sediments is predominantly interparticular in the sands, and bioturbation-related in muds.

The physiography of the lake surrounds can be divided into the lunette and floodplain areas. The lunettes are typically dryland-farmed to near the top of the most lakewards crest. This crest is separated from the disposal basin by the steeply-sloping, usually erosion-channelled, face of the lunette. At the base of this slope there is an area of colluvium from the lunette which grades into the rarely-flooded natural lake marginal areas. This area, in turn, grades into the area which is regularly flooded and exposed as the operating levels of the disposal basin fluctuate. Beyond this area is the usually-submerged area of the disposal basin. The floodplain-dominated surrounds are relatively flat areas which at some locations have been disrupted by the channels and levees associated with the irrigation, flood diversion and disposal water engineering works. The floodplain areas are usually sites of active or abandoned irrigation which, at some locations extends or extended to the lake margin. The floodplain-associated lake marginal areas are generally broad and gently-sloping, but in high-energy areas their regular topography can be disrupted by shoals and beach deposits.

Lake Tutchewop

Lithostratigraphic, hydrological and geochemical investigations of Lake Tutchewop are based on four transects which run at approximately right angles to the edge of the disposal basin. The eastern margin transect extends from the usually submerged area of the disposal basin to the dryland farming areas in the lunette; the western margin transect ends near the lake-floodplain boundary close to the artificial surface water systems associated with irrigation channel 6/7 and the Avoca floodwater diversion; the northern transect crosses the northern fringe of the lunette and ends in active irrigation areas to the north-east; and the southern transect ends at the boundary of the lake margin and abandoned irrigation areas on the floodplain to the south-west.

Lithostratigraphic data for Lake Tutchewop show thin continuous cover of two relatively impermeable lacustrine lithofacies (Units 3 &4) below the lake. The underlying Shepparton Formation is of generally lower permeability in the upper 5 metres which isolates the lake from two underlying extensive Shepparton aquifers. An upper silt (up to 5 metres thick) directly overlies a lower sand (a wedge thickening southwards to about 10 metres thick). This lower sand directly overlies the highly permeable Parilla Sand along the eastern margin of Lake Tutchewop. The upper silt has calculated lateral hydraulic conductivities of <2.5 m/day. The lower sand varies from 3 to 4 m/day on the eastern margin to 3 to 9 m/day on the southwestern margin. Below the eastern margin of Lake Tutchewop, the Parilla Sand increases in hydraulic conductivity from values comparable to the overlying Shepparton sand, to 30 m/day at depth.

Vertical hydraulic heads (environmental water heads) on the eastern margin of Lake Tutchewop show a large upwards gradient (e.g. 40 x 10^{-3} m/m) from the Parilla Sand to the overlying Shepparton Formation. Spring activity occurs in the near-surface environments by transmission of groundwater through localised high-permeability vertical conduits. In active or incipient spring zones at the lake margins the vertical gradients are strongly (e.g. 60 x 10^{-3} m/m) or marginally (<4 x 10^{-3} m/m) upwards, respectively. Within the upper Shepparton Formation the very low hydraulic conductivity of the formation clay prevents widespread discharge. Vertical gradients at medium to shallow depths within the Shepparton Formation are usually slightly downwards (e.g. -5 x 10^{-3} m/m) and reflect mainly natural recharge and anthropogenically-influenced surface-water processes. Natural downwards gradients are produced by rainfall recharge of the permeable sediments of the lunette and its colluvial deposits. Artificially-induced downwards gradients are associated with areas of high water level induced by the irrigation to the north, the irrigation drain and Avoca River floodway to the west and, possibly, by the disposal water in Lake Tutchewop.

Lateral hydraulic heads (freshwater heads at constant elevation) at Lake Tutchewop have been measured during a period when operating surface-water levels of the basin were fairly low (68.98 to 69.22 mAHD) compared to the long-term average (69.71 mAHD between July 1987 and April 1995). Gradients were measured at two elevations: (1) at 67.9 mAHD where a combination of natural spring activity overlain by and/or enhanced by recharge from the natural and artificial systems should dominate; and (2) at 64.1 mAHD where the influence of longer-range natural effects should be relatively more important. Under the conditions investigated to date, lateral gradients are, on average, directed towards the disposal basin along all four transects. Detailed measurements along the eastern transect show that in the regularly-flooded area of the lake margin the groundwater heads respond gradually to medium-term changes in the disposal basin heads. Consequently, as basin operating levels decrease, in the regularly-flooded zone there is a slow return towards natural groundwater conditions. After the disposal basin heads reach a minimum and return to higher levels, a temporary minimum in the groundwater heads in the regularly-flooded area is produced by the "lag" induced by slow response time.

Given sufficient time to reach hydrodynamic equilibrium with the surrounding groundwater system, the distance to which the Lake Tutchewop disposal waters could move laterally has been calculated for a reference elevation of 67.9 mAHD. At an operating level equivalent to a freshwater head of 69.5 mAHD, which represents the measurement conditions of this study, the maximum distance the disposal water could move (at 67.9 mAHD) is: (1) to the lunette-colluvium boundary to the east and north-east; (2) to the lake margin-floodplain boundary to the west; and (3) not far beyond the lake margin-floodplain boundary to the south-west. At the long-term average basin freshwater head operating level of 69.9 mAHD the limit of movement (at 67.9 mAHD) is: (1) about 150 m to the east, which is within the lunette; (2) about 400 m to the northeast, which is within the floodplain. To the west, the limit is uncertain because of considerable fluctuations in the heads associated with the irrigation channel/floodway. To the south-west the limit is in the floodplain beyond the measurement limit of 350 m.

The Lake Tutchewop disposal water is unlikely to have flowed laterally to the extent where the long-term hydraulic heads in the disposal basin have reached equilibrium with those in the surrounding groundwater system. Based on a lateral gradient of 6×10^{-3} m/m, an effective porosity of 2% (clay) to 30% (silt), and hydraulic conductivities of 0.001 m/day (clay) to 0.1 m/day (silt) the disposal water would flow laterally about 2 to 20 m in 25 years. Vertical flow rates based on an assumed vertical gradient of -5×10^{-3} m/m, hydraulic conductivities of 0.001 and 0.1 m/day, and a porosity of 5% give depths of 1 and 100m for vertical flow over a period of 25 years.

The best indicators of disposal waters in the phreatic-zone groundwaters beneath and around Lake Tutchewop are deuterium content and major-ion ratios to Br or Mg. Differences between the major-ion ratios of the disposal waters and natural groundwaters are not large but changes with depth can be significant. The deuterium contents are a considerably more sensitive indicator because the δD values of the disposal waters (20 to 30‰) are much higher than those of most of the natural groundwaters (usually < -5‰).

Using major ion ratios, a preliminary scan of 11 sites indicates that disposal waters were present at two, absent at four, and unlikely to be present at five sites. The two sites penetrated by disposal water are near the western margin of the basin in a submerged area of prograding, relatively coarse-grained sediments. At one of these sites the major-ion ratios indicate a simple mixing of disposal water and natural groundwater that extends over the top 2 m of sediment. However, deuterium measurements offer greater resolution and indicate a more complex system involving two types of high-δD water.

Overall, the Lake Tutchewop investigations consistently indicate minimal lateral or vertical movement of surface disposal water into the surrounding and underlying groundwaters. Both simple rate calculations and the absence of geochemical disposal-water signatures in surrounding groundwater are additional indicators of restricted movement, even though lateral gradients indicate a potential for lateral flow into the surrounding groundwaters for distances up to several hundred metres. Data on vertical gradients within the disposal basin are inconclusive but the geochemical evidence suggests that infiltration is limited to an area of the western shore where highly favourable conditions are generated by a combination of high sediment mobility and a tendency to concentrate the coarser sediment fraction near the surface.

Lake William

Lake William has a rounded trapezoidal outline. There is a series of high rounded lunettes to the eastern side with three distinct ridge features. The youngest is the lowest, adjacent to the present shoreline, and may be a modified beach deposit. The lake is entrenched into the surrounding plain with an almost flat lake floor and relatively steep marginal slopes up to the surrounding lunette/floodplain areas.

Lithostratigraphic, hydrological and geochemical investigations of Lake William are based on a single site on the eastern margin and three transects which run at approximately right angles to the north-eastern, western and southern margins of the disposal basin. The north-eastern transect extends from the usually submerged areas of the disposal basin almost to dryland farming areas in the lunette; the western transect extends to an active irrigation area at the lake margin-floodplain boundary; and the southern transect extends across the southern fringe of the lunette into the floodplain.

Three facies are recognized in the lacustrine Yamba Formation at Lake William. The thin basal unit comprises seasonally-laminated lacustrine sediments. The second lacustrine event has produced distinctive evaporitic varve-laminites and cycles of thin basal clay, gradational up to and overlain by carbonate micrite, which grades up to porous sands of gypsum millet-seed crystals. The uppermost event has a uniform sediment with scattered gypsum and halite? poikilotopic crystals, capped by a surface layer of granular euhedral salt cubes and hoppers. Because of the active salt mining in this lake, this upper homogenous unit is probably an artifact of the disturbance by mining.

The porosity in the Yamba Formation is variable, even within one unit at differing locations. The evaporitic laminites of the middle unit and the homogenized sediments of the uppermost unit have high interparticle porosity. The quartz sand lithofacies of the dune/lunettes has the highest interparticle porosity. Predicted k_h of these sands ranges from 3 m/day (medium sand) to 10- 40 m/day (coarse sand). Within the Shepparton Formation the sequence is relatively tight for the upper 12 m.

Vertical hydraulic heads beneath the lunette at the north-eastern margin of Lake William show a small upwards gradient (e.g. 4 x 10^{-3} m/m) from the Parilla Sand to the lower Shepparton Formation but a much higher gradient (e.g. 100 x 10^{-3} m/m) from the lower to the middle of the Shepparton Formation, indicating that the lower Shepparton Formation and the underlying Parilla Sand aquifer do not have greatly differing hydraulic conductivities. The low hydraulic conductivity of the Shepparton Formation clays reduces the upwards gradients within the Shepparton Formation to small but still significantly upwards values (10 x 10^{-3} m/m). This upwards gradient is consistent with a much stronger groundwater influence at Lake William than at Lake Tutchewop, which is consistent with stratigraphic data indicating that the Shepparton surface slopes downwards from Lake Tutchewop to Lake William. This slope may a result of tectonic uplift on the eastern side of Tutchewop? or increased discharge and deflation in the Lake William area.

Lateral hydraulic gradients between Lake William and the adjacent marginal lake environments were calculated for a constant reference elevation of 67.2 mAHD and, for the northern transect, for 61.75 mAHD. During the measurement period basin operating levels of 67.9 to 68.0 mAHD were close to the long-term average of 68.79 mAHD. Under these conditions, gradients along all three transects are lakewards from the lunette and floodplain environments of the hinterland at both reference elevations. The most notable difference between the transects is the much higher gradient towards the lake from the irrigated floodplain areas to the west (17 x 10^{-3} m/m) compared to that from the lunette colluvium on the northeast margin (about 3 x 10^{-3} m/m).

The lateral distances (at 67.2 mAHD) to which the disposal water could move were calculated for an assumed average freshwater-head basin operating-level of 68.5 mAHD; and the actual average freshwater head basin operating level of 69.0 mAHD which prevailed in the period January 1988 to April 1995. At a basin-operating freshwater head of 68.5 mAHD the disposal water should not move more than 10 m beyond the waters edge at any of the measurement locations around the lake. i.e. the disposal water should be contained within the lake and its marginal environments. At the actual freshwater head operating level of 69.0 mAHD the limit of movement is: (1) about 10 m to the west, which is within the lake marginal environments; (2) about 40 m to the south, which is also within the lake marginal environments; and (3) more than 50 m to the north but probably not much further than the colluvium/lunette boundary. Compared to Lake Tutchewop, the disposal waters could move relatively small distances laterally. This limit is partly determined by the close proximity of the active irrigation areas on the western and, to a lesser extent, the southern margins. However, the lower elevation of Lake William and its steeper margins, both of which reflect a more groundwater and deflation-dominated history than that of Lake Tutchewop, are natural features which would favour higher natural groundwater gradients towards the lake.

Salinity is, at best, a general guide to the presence of disposal waters in the groundwaters underlying and surrounding Lake William. The surface water salinity in the disposal basin (125,000 to 298,000 mg/L; October 1993 to August 1994) is influenced not only by seasonally-fluctuating evaporation and operating conditions, but by precipitation and re-solution of the extensive evaporite mineral deposits which are present during periods of low basin operating levels. The highest measured groundwater salinity (250,000 mg/L) within the surface water range and occurs beneath the usually submerged area of the lake. This brine could be disposal water or it could have been emplaced during the recent natural, highly saline phase. Beneath at least two lake marginal sites occurs a paleo-brine of salinity about 100,000 mg/L which may have formed when Lake William was larger and less saline.

Disposal water in the phreatic-zone groundwaters surrounding and underlying Lake William can be identified using ratios of major-ions to Br or Mg which are not affected by the precipitation of gypsum or halite. Deuterium is also an indicator of disposal water but the current best estimate of the average surface water value is -4‰, which makes it a far less sensitive indicator than at Lake Tutchewop (surface waters range 20 to 30‰). Presumably, the difference arises because Lake William sometimes evaporates to dryness and the high-deuterium waters do not accumulate.

Major-ion and δD criteria indicate that a maximum of about 60% disposal water is present between elevations 67.0 and 68.8 mAHD at a marginal site close to the regularly-flooded zone. Strong deviations from the disposal water values occur in the narrow zone of evaporation-affected shallow sediments above this range. Major-ion criteria indicated that disposal water is present at elevations >67.0 mAHD at a usually submerged site, but was either absent or unlikely to be present at two other sites.

The presence of disposal water beneath the disposal basin and at a close marginal site, but not elsewhere, is a pattern common to both the Lake Tutchewop and Lake William disposal basins. At Lake William there is no apparent correlation between high porosity and/or high sand content of the sediments, and the presence of disposal water in the groundwater.

Lake Kelly

Lake Kelly and Lake Little are components of a discharge complex which lies nestled into and east of a north-south regional dune. Within both lake basins, there is at least one additional lunette feature that subdivides the general deflation depression into smaller interconnected basins.

The lithological, hydrological and geochemical investigations of Lakes Kelly and Little are based on four transects, three of which are set at approximately right angles to the edge of the Lake Kelly disposal basin and the fourth at right angles to Lake Little. There is a drill-hole site on the Lake Kelly western margin. The Lake Kelly eastern transect starts in the usually submerged main area of the disposal basin and crosses a sub-basin and a low inter-basin lunette before terminating at the base of the main lunette system; the Lake Kelly northern transect terminates at the inlet channel for the disposal water near the boundary of the floodplain/lake marginal environments The other Lake Kelly transects and the Lake Little transect terminate at the boundary of the lake margin-floodplain environments.

The lacustrine sequence of Lake Kelly has the most complex depositional unit geometry of all the lakes. Within the lake basin, a north-south lunette covers and preserves the deepest and most distinctive evaporitic laminites of the Yamba Formation. These laminites directly overlie a permeable sand stringer within the Shepparton Formation, a probable original spring site that initiated discharge and subsequent deflation of the lake basin. They are comparable with the middle laminated lithofacies in the Lake William sequence and may indicate that Lake Kelly commenced development subsequent to Lake William. These evaporitic laminites have only been observed in one borehole. Elsewhere in the eastern and northern part of the lake, two lacustrine lithofacies are widespread and a pedogenic overprint in the lower unit indicates lacustrine reworking of the underlying Shepparton clays.

The present floor on the western side of Lake Kelly appears to be a deflation surface incised into the Shepparton Formation. It is uncertain how many deflation cycles are preserved in the lunettes of the complex. Within the basinal lunette three erosional events are apparent. In the main eastern lunette, three erosional events coincide with pedogenic overprints. The quartz-sand lunettes flanking the eastern and northeastern margins of the northern part of Lake Kelly may give some indication of timing of the main reworking of regional north-south dunes to the west. There has been recent mobilisation of sands, initially into and across Lake Little, and then into and across Lake Kelly.

Porosities are highly variable in both Shepparton and Yamba Formations and in the lunette deposits. In the high-standing peripheral eastern lunette the deposits are generally porous (interparticle and fenestral porosity). One of the basal fine quartz sands in this lunette has a k_h of 5m/day. In contrast, the low-relief lunette within the basin is relatively impermeable from occlusion of original interparticle porosity by diagenetic gypsum cementation. Within the Yamba lacustrine sequence, the basal mud-dominant unit has characteristically low porosity in contrast to the upper unit, where porosity is much more variable but appears to diminish towards the lake margin. The Shepparton Formation is generally tight with only thin horizons of sands with interparticle porosity. At the northern end of the lake, one very coarse silt interval has a k_h lower than the limit of resolution ($<$ 2.5 m/day).

Vertical hydraulic gradients at a site on the southwest fringe of the lunette are consistent with the Lakes Tutchewop/William data showing high gradients from the Parilla Sand aquifer to the overlying Shepparton Formation clays.

Lateral hydraulic gradients for Lakes Kelly and Little were determined for a reference elevation of 69.9 mAHD. They are based on one set of readings and are indicative of conditions when basin operating levels were lower (70.26 mAHD) than the long-term average (70.56 mAHD). Pronounced overall lakewards gradients are evident for all transects except that at the northern margin. Data from the Lake Kelly northern transect shows the distinctive minimum in the regularly flooded area of the lake margin which is was observed in Lake Tutchewop However, at the Lake Kelly northern margin the lakewards gradient from the edge of the disposal water drainage channel to the minimum in the regularly flooded zone is very low and the head in the disposal basin was higher than that at the landward limit of the transect. The low groundwater head could be caused by the drainage channel which, if it is cut below the water table, may be intercepting some shallow groundwater flowing lakewards from the north.

Lateral movement of the disposal water (at 69.9 mAHD) for an assumed freshwater head basin operating level of 70.2 mAHD should be limited to 10 m from the waters edge. For the actual average freshwater head basin operating level of 70.6 mAHD, the limit of movement to the east is lakewards of the colluvium at the base of the main lunettes, which is <700 m from the disposal basin. Elsewhere, the limit is beyond the landward ends of the transects.

The maximum groundwater salinity encountered near Lake Kelly is 108,000 mg/L, which is close to that of the possible paleo-brine beneath Lake William and similar to the surface disposal water average. Consequently, salinity is not an indicator of the presence of disposal water in the groundwater. Disposal water was identified using major-ion ratios in highly porous upper 0.2m of sediments in a usually submerged site on the eastern margin and in the top 0.25 m of sediment at the site in the regularly flooded area on the eastern margin. It is unlikely to be present at four other sites. This pattern is similar to those observed at Lakes Tutchewop and William.

CONCLUSIONS

- Lakes Tutchewop, Kelly and William are groundwater discharge areas whose natural characteristics have been extensively modified by a combination of their use as disposal basins, irrigation of the surrounding areas, and the installation of drains and channels associated with these activities.

Former characteristics

- The lakes were natural systems whose widely differing ratio of groundwater to surface water input produced a diverse range of lithostratigraphic, hydrodynamic and hydrochemical features.
- Lake Tutchewop was a terminal lake for the Avoca River, a predominantly freshwater system in which the input of saline groundwater springs on the lake margins was overshadowed by discharge from the river. It had the characteristics of surface water-dominated lakes - a circular outline; a relatively high elevation of the lake floor; gently-sloping lake margins because deflation is minimised; and accumulation of sandy shoals on the western margin.
- The natural hydrodynamics of Lake Tutchewop would have been dominated by surface water evaporation except in the localised marginal spring zones where groundwater evaporation and consequent salinity increases were high. The low groundwater evaporation component minimized drawdown of the surrounding groundwater head, and consequently the lake created only a shallow depression in the regional watertable.
- The low surface-water salinities in Lake Tutchewop may have gradually reduced the salinity of the underlying shallow groundwaters by upwards diffusion of salt. In the

vicinity of the spring zones this process would be minimised by the higher salinities of the evaporated spring discharges.

- Lake William contrasted Lake Tutchewop because the ratio of its groundwater to surface-water input was high. Surface water input could have been mainly overflow from a nearby lake through a small channel to the south-west. Groundwater input would have been facilitated by the relatively low elevation of the discharge area, which would have favoured higher artesian heads from the underlying Parilla Sand.
- The saline groundwater-dominated regime of Lake William favoured deflationary processes which would have further lowered the elevation of the lake floor, producing a topographic depression with relatively steep marginal slopes.
- The natural hydrodynamics of Lake William were dominated by groundwater evaporation from springs discharging into the lake and the consequent formation of highly saline surface brines. This groundwater evaporation would have had a significant drawdown effect on the surrounding groundwaters which, combined with the effects of the relatively high topographic slope towards the lake, produced a depression of the regional groundwater heads much greater than that induced by Lake Tutchewop.
- The highly saline brines produced naturally in Lake William resulted in significant downwards movement of salt from the Lake into the underlying groundwater system, either by advection or diffusion.
- Lake Kelly was intermediate between Lakes Tutchewop and William in terms of its ratio of groundwater to surface water. During some periods of its evolution, Lake Kelly may have received floodwaters from the nearby river system.

Post-implementation of Barr Creek Interception Scheme

- In Lake Tutchewop, under present-day conditions the natural hydrodynamic processes remain dominant in the lunette and its colluvial deposits on the eastern margin, and are evident in attenuated form as springs on the western and eastern margins. The artificial hydrodynamic effects of the disposal basin/irrigation systems are most prominent on the western margin where the close proximity of the irrigation channel/Avoca floodway to the lake produces high but variable gradients towards the disposal basin. The effects of the artificial systems probably decrease from the western margin to the north-eastern margin, where active irrigation but not drainage works are involved, and still further to the south-western, where abandoned irrigation areas occur at the lake margin.

- The artificial systems around Lake Tutchewop help reduce the lateral distance to which the disposal waters would have to flow into the surrounding areas to produce hydrodynamic equilibrium but, as expected from the low lakewards hydraulic gradients which were probably associated with the natural system, theoretical distances of the order of hundreds of metres could be involved. The disposal waters probably create significant, but difficult to quantify, vertically-downwards gradients because the upwards gradients from the Parilla Sand aquifer are nullified by the clays of the Shepparton Formation.
- The containment characteristics of Lake Tutchewop, as indicated by the actual movement of disposal waters, are considerably better than those indicated by theoretical flow rate calculations. Both of these are considerably better than the theoretical limit at which hydrodynamic equilibrium with the groundwater regime is reached.

  Calculations based on lateral flow rates indicate the maximum distance the disposal water could have moved during the period of operation of the disposal basin is about 200 m. Hydrochemical indicators suggest that the actual movement is far less than this, and disposal water has moved only into sandy shoals on the western margin.
- In Lake William, under present-day conditions the natural groundwater regime is probably best preserved in the lunette-associated environments on the eastern margin, where vertical gradients are significantly upwards. Artificial systems dominate the hydrodynamics of the western and southern margins, where superimposition of the effects of active irrigation on the natural groundwater heads produce high lateral groundwater heads and a strong lakewards-sloping gradient.
- These high lakewards lateral gradients theoretically confine the disposal waters to within the lake marginal environments. The hydrochemical indicators suggest that actual movement is even less than this, with disposal water being positively identified only in shallow, usually submerged sediments within the basin and in the regularly-flooded marginal areas.
- Data for Lake Kelly are limited but the present-day hydrodynamics are probably intermediate between those of Lakes Tutchewop and William. The hydrodynamics to the north are affected by the channel carrying disposal water to the lake. In contrast to the situation created by the irrigation channel/Avoca floodway on the western margin of Lake Tutchewop, the drainage channel at Lake Kelly intercepts lakewards-moving groundwater and appears to reduce the lateral gradient towards the lake.

- The investigations of Lakes Tutchewop, William and Kelly have defined some of the wide variety of hydrodynamic situations produced at the margins of groundwater discharge complexes as the existing natural hydrodynamics are modified by disposal waters and surrounding irrigation/drainage schemes.
- If containment of the disposal waters is the primary objective, then this may occur most effectively in groundwater-dominated sites such as Lake William. However, resultant rises in the surrounding groundwater heads could be most significant at these sites as the strong drawdown effect of groundwater evaporation is reduced.
- Conversely, if minimising the effects on the surrounding natural groundwater levels is of prime importance, then surface-water dominated discharge complexes such as Lake Tutchewop may be the preferred site.

INTRODUCTION

Background

The Lake Tutchewop area (Figure 1) is the site of a major interception scheme designed to minimise the discharge of salt from Barr Creek into the Murray River. The disposal basins for the scheme are Lakes Tutchewop, William and Kelly, which are located midway between the townships of Kerang and Swan Hill in north-central Victoria. The Lakes form part of the Kerang Lakes system of natural depressions on the flood plains of the Avoca and Loddon Rivers. Since 1968, water has been pumped from Barr Creek *via* a number of artificial channels into Lakes Tutchewop, William and Kelly (HydroTechnology, 1995).

The Tutchewop interception scheme is the subject of an ongoing investigation by Sinclair Knight Merz (formerly HydroTechnology), and funded by the Murray-Darling Basin Commission (MDBC). This report focuses on related investigations carried out mainly by AGSO and CSIRO, with the support of Sinclair Knight Merz. These investigations have provided detailed lithostratigraphic, hydrodynamic and hydrochemical information to serve the dual objectives of: (1) addressing site-specific concerns related to the management of the Tutchewop disposal basins; and (2) helping to develop lithostratigraphic criteria for the prediction of salt movement from disposal basins.

Preparation of this report has involved the use of a number of unpublished preliminary reports prepared by HydroTechnology / Sinclair Knight Merz (e.g. Dimos, 1992; Barnewall and Brinkley, 1993; Harrison, 1993; HydroTechnology, 1994, 1995).

Detailed Objectives of the Study

The general aims of the HydroTechnology (1995) project are to investigate the current and future impacts of the disposal basins on the local and semi-regional groundwater and surface water systems, and to use this information to assess future management options for the disposal complex. The AGSO/CSIRO/ Sinclair Knight Merz investigations described in this report contribute to this broad aim by complementing the

Figure 1. Location and surficial geology of the Tutchewop disposal complex.

semi-regional investigation by HydroTechnology (1994,1995) with information which is mainly sharply focussed on the disposal basins and their immediately underlying and surrounding environments.

The AGSO/CSIRO approach employs detailed lake-marginal transects and:

(1) describes the lithostratigraphy of Lakes Tutchewop, William and Kelly; identifies formal stratigraphic units; and provides semi-quantitative information on the hydraulic conductivities of various aquifer lithofacies;

(2) assesses the potential for movement of disposal water into the adjacent groundwater system by determining the direction and magnitude of the lateral and vertical hydraulic gradients within and near the lakes; and

(3) determines the extent of disposal water migration into the adjacent and underlying groundwater systems using a combination of salinity, water chemistry, and some isotopic signatures.

This primary lithostratigraphic information and hydrodynamic data is used in groundwater models which help predict the nature and extent of future salt movement from the disposal basins (e.g. Simmons and Narayan, in preparation).

The methods used to achieve these aims, and the study sites, are described below.

OUTLINE OF METHODOLOGY

Transects

At various locations around the lakes, short transects were surveyed and established at approximately right angles to the lake shore. To obtain an adequate spatial coverage, the strategy was that each lake should have four transects located approximately midway along the northern, southern, eastern, and western shores. In practice, modification was necessary to account for problems of access (e.g. northeast Lake William), the need to target strongly-contrasting marginal-lake environments (e.g. the Avoca river floodway-influenced eastern shore, and the dryland-farming area west of Lake Tutchewop), and to incorporate existing piezometer nests established by HydroTechnology / Sinclair Knight Merz. Figure 1 shows the resultant array of transects, plus a semi-regional transect established to provide a lithostratigraphic correlation extending across the three lakes.

Drilling and Pore Fluid Sampling/Analysis

Transect sites on the disposal basin margins and permanently-submerged areas were soft and wet, and for this project we used a specially-designed tripod-mounted rig assembled on site, with a hovercraft to transport the rig components. This method is a variation of the penetrometer technique in which steel tubes are hammered into the sediments to 0.4 m depth. The clays of the Shepparton Formation were readily cored by this method. Sediment samples for porewater analyses were obtained from the bottom 0.1m of each core to minimise the possibility of contamination by "float".

A rotary rig was used at several sites to drill to a depth of 10-15m with continuous augering and a retrievable wireline core barrel. Junctions of auger flytes had 'O' ring seals to minimize external water contaminating the core.

Salinity of the pore fluids was determined by optical refractometry using a portion of a small volume of porewater (typically ≤1 ml total) extracted from the sediments using a Manheim press. Cation analysis was by ICP, and ion chromatography was used for anion analysis.

Drillholes were cased as piezometers, and subsequently surveyed relative to the Australian Height Datum (AHD).

Logging

Some 25 boreholes from AGSO, CSIRO & HydroTechnology investigations have been examined and core logged to provide the lithological framework for this work. Log formats are outlined in the Appendix to this report. The logs are presented as figures in Ferguson & Radke (1995).

Estimation of Porosity and Permeability

Porosity abundance and type was qualitatively determined by visual assessment with binocular microscopy. As discussed in drilling methods, core material has come from three drilling methods, each with its own disturbance to sediment texture. The modification of original porosity by drilling artefacts is not consistent. As a generalisation, core material is more compressed by penetrometer coring and more expanded from the augering process. HydroTechnology / Sinclair Knight Merz cuttings are only available as one sample per logged lithostratigraphic interval and it is speculative whether this sample is homogenized from over the whole interval, or is one sampled interval that has been selected to be representative of the whole interval.

Predominant porosity types recognized within these sediments are interparticle (IP), bioturbation (BO), intercrystalline (IC), fracture (FR) and fenestral (FE) types.

Porosity abundance categories have been arbitrarily selected for logging as 20-30%, 10-20%, 2-10%, <2%, and 0%. This reflects expected interparticulate porosity in sands. Although theoretical porosity in clays can be much higher, their effective porosity is very low to non-existent.

Accordingly, being limited to particle-size analysis alone, this study has taken the experimental correlations of particle-size distribution parameters with hydraulic conductivity (Figure 2), as determined by Masch and Denny (1966). This approach has a considerably limited range of reliable prediction, down to approximately 3ϕ MD_{50}, and is only suitable for the higher permeability sands. There is considerable subsequent literature for improved estimation of porosity and permeability from parameters of particle-size distribution, but these require additional bulk properties. Panda and Lake (1994) demonstrate that there is good correlation between parameters of particle-size distribution and permeability. The limit to their approach is at approximately 1 darcy, below which apparently not all pore space of the sediment is supporting flow. They improve on the

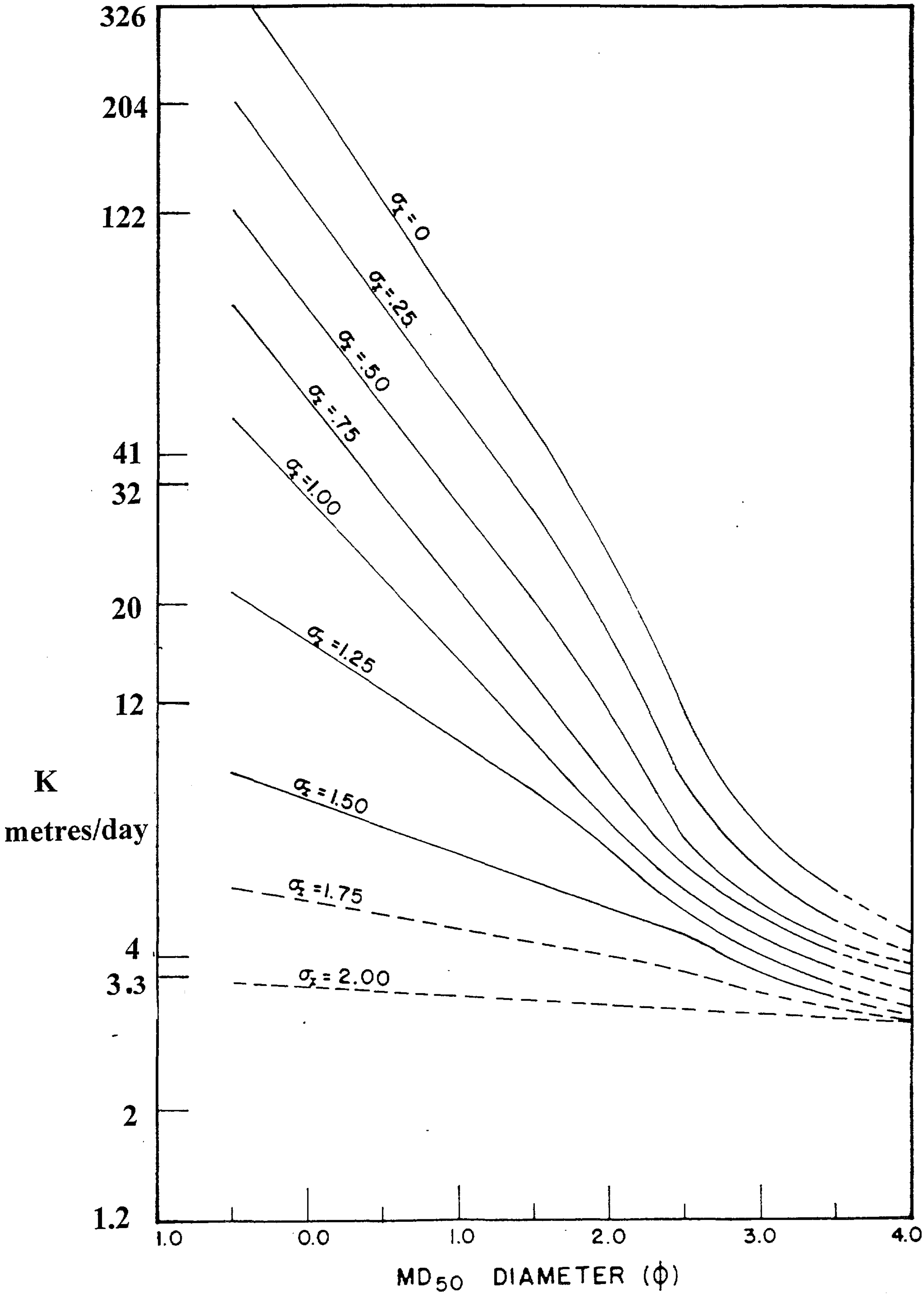


Figure 2. Curves for prediction of hydraulic conductivity. Axis parameters are defined in the text. (after Masch & Denny, 1966).

Carman-Kozeny equation by using the bulk properties of average porosity and tortuosity, as well as including the statistics of particle-size distribution. They used experimental data of Beard and Weyl (1973) who conducted a comprehensive experimental study on the permeability of unconsolidated sand packs, both dry and wet packed.

Particle Size Analysis was conducted on 26 samples of the higher-porosity sands and silts. Particle-size frequency curves are presented in Ferguson & Radke (1995). These characteristics are summarized in Figure 3 .

Predicted hydraulic conductivities, based on this granulometry, are compared in Figure 4. These results are discussed in context with each lake occurrence.

Determination of Hydraulic Heads and Gradients

Lateral and vertical hydraulic gradients associated with groundwater discharge complexes and disposal basins are typically small because of the flat topography. Consequently, the concepts of Lusczynski (1961) and Lusczynski and Swarenski (1966), which involve the separate determination of lateral and vertical gradients, are used to obtain accurate values for the hydraulic heads.

Vertical gradients were obtained from environmental water heads in piezometers set to different depths at the same location. Vertical gradients were difficult to obtain for the lake environments because the limited depth range of the tripod penetrometer-drilling techniques prevented the installation of piezometers at greatly differing depths. As a result, most of the meaningful vertical gradients have been obtained from the rotary-drilled piezometer nests.

Lateral gradients were determined from freshwater heads in piezometers which were set to a constant elevation (Macumber, 1991). In this investigation, minor deviations from constant elevation were corrected by interpolation or extrapolation using vertical gradients estimated from piezometer nests. If there was only one piezometer at the site, then small corrections were approximated by : (1) taking the freshwater head at the standing water level (SWL) in the piezometer as zero, (2) constructing a two-point line representing the change in freshwater head with elevation; and (3) reading the freshwater head at the required elevation from this line.

Identification of Disposal Waters

Identification of disposal water in groundwaters was based on a comparison between the salinity, major ion chemical composition and deuterium isotopic composition of surface disposal waters in the lakes and the composition of the natural groundwaters which surround and underlie the disposal basin.

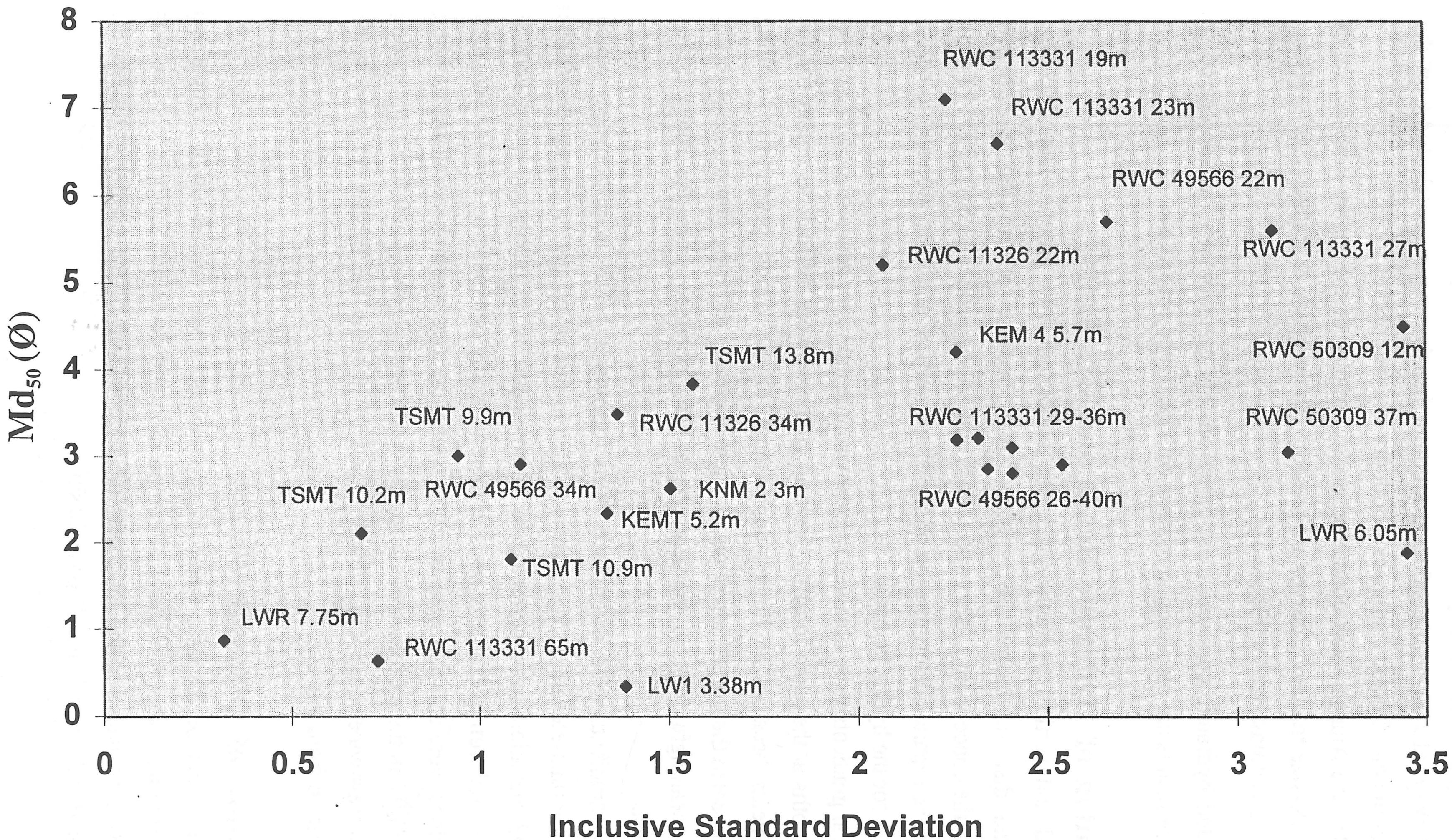


Figure 3. Particle-size characteristics of sands, Yamba & Shepparton Formations, Lake Tutchewop - Lake Kelly area. Axis parameters are defined in the text.

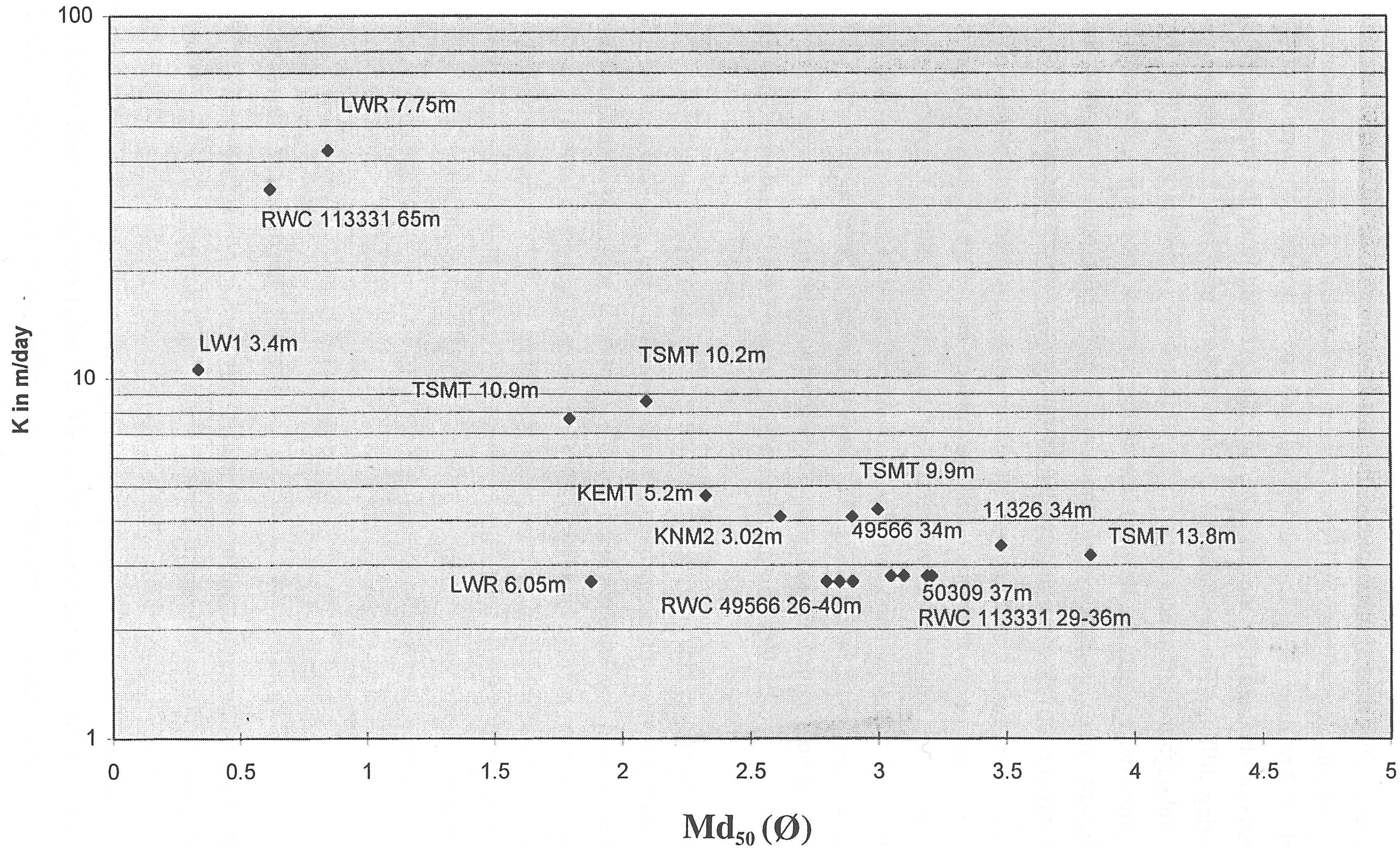


Figure 4. Predicted hydraulic conductivities of sands, Yamba & Shepparton Formations, Lake Tutchewop - Lake Kelly area.

The range and average composition of the surface waters in the lakes was obtained from a series of samples collected by HydroTechnology / Sinclair Knight Merz over the period April 1993 to June 1994. The salinity and major-ion chemical composition of the groundwaters was obtained from the porewater samples extracted from the sediment cores obtained during drilling. The deuterium measurements were made on distillates of wet sediments. Although the differences between the surface disposal waters in the lakes and the natural groundwaters may not be great, the drilling methods used in this investigation (in particular the tripod penetrometer method) are capable of producing accurate and detailed records of relatively small changes in porewater composition with depth.

REGIONAL SETTING

Physiography

The lakes lie within and towards the northern margin of a lunette complex (Macumber, 1968), a belt some 10 kilometres wide, with a northwest-southeast trend of some 40 kilometres that parallels the southwestern side of the Little Murray River between the northern ends of the Mallee dunefields (Cannie and Gregwin Ridges), both present-day exposures of Parilla Sand (Figure 5) . It is most probable that the lunette sands have been derived from these Mallee dunefields. The belt of lakes lie within the terminal region of the Avoca Floodplain, adjacent to a lower Coonambidgal surface on the present Murray River floodplain. Within this lunette complex, each lake has distinct lunettes, some with at least three generations which can be differentiated physiographically.

Additional lunette ridges that do not relate to existing lakes, generally strike NNW-SSE between the lakes, but with irregularities in trend apparently caused by their interaction with lake/lunette processes (Figure 1). The parallelling lunette/dune fields of the area tend to diverge around to the east of existing lakes. If the dune systems are considered to have origins from salinas or from freshwater lakes, then a former Megalake is a possibility. Subsequent active smaller lakes have locally modified the regional trend of these dunes. Lakes Little and Kelly have or are still actively capturing sands from a linear dune to the west, and redistributing this sand to a recent generation of leeward lunettes.

Regional Structural Fabric

Lake Tutchewop overlies the intersection, in the basement, of the Kerang Lakes Trough and the northern end of the Avoca Graben, an area between the Cannie Ridge to the west and Gregwin Ridge to the south (Pratt, 1988). The latter three features have SW-NE trends and the Kerang Lakes Trough is orthogonal at SE to NW alignment although northwest from Kangaroo Lake, the trough arcs north to north-northeast between Lake Tutchewop and Lake William, before arcing to the northwest again. This sinuosity in the

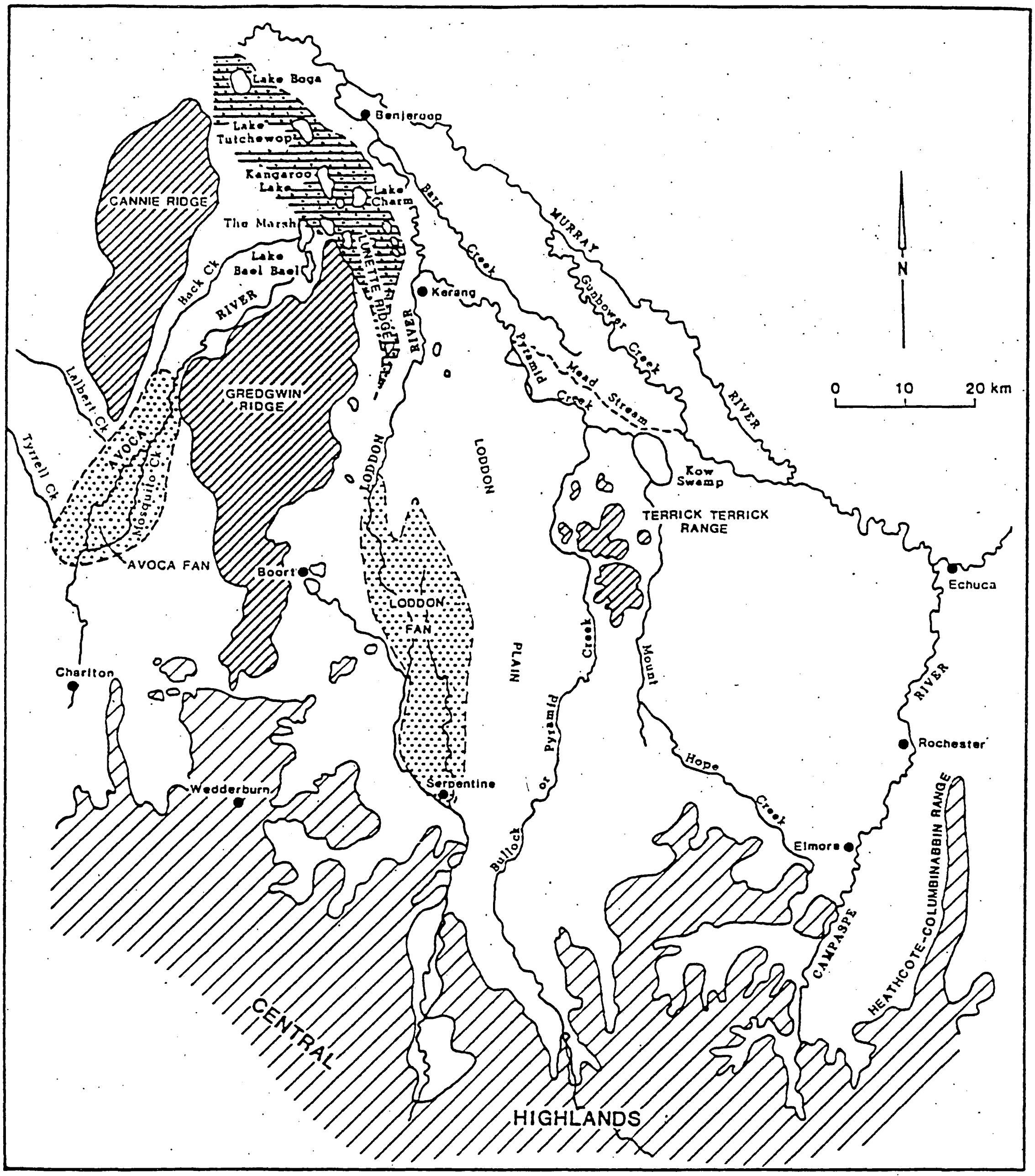


Figure 5. Regional context of Lake Tutchewop, the surrounding lakes and lunette complex in relation to the Avoca River floodplain and mallee dunefields over the Cannie and Gregwin Ridges (after Macumber, 1977).

trough is most probably influenced by the interaction with the Avoca Graben and the Cannie Ridge.

Regional magnetic basement in this area has a NNW-SSE fabric of narrow linear domains as indicated by the total magnetic intensity (TMI) signature (Bureau of Mineral Resources, 1985 ; Brown *et al.*, 1988, Figure 6). Alignment of several groups of lakes: Lake Tutchewop - Kangaroo Lake - Duck Lake - Lake Elizabeth; Third Marsh - The Marsh - Lake Bael Bael; and Third Lake - Middle Lake - Reedy Lake; may reflect subtle surface expression of this magnetic basement fabric.

Lakes Boga, Tutchewop, William, Little and Kelly have a WNW-ESE alignment that is probably indicative of subtle cross-faulting superimposed on the apparent regional fabric. Both the Murray and Little Murray rivers also parallel this trend in the section from opposite Lake Kelly to opposite Lake Boga.

Lakes Tutchewop and Kelly appear to be positioned over the margins of magnetic basement domains, while Lake William appears to be centred over a magnetic domain (Figure 6).

Regional Stratigraphy

Parilla Sand

A blanket of sand and sandstone having a thickness of about 60m covers the whole of the marine Murray Basin. The upper surface of the sandstone forms long prominent ridges trending north-south in Victoria, generally regarded as having been formed as strandlines along a retreating late Tertiary sea (Blackburn, 1962). Ludbrook (1961) described the type section at Loxton, South Australia, as characteristically bright yellow cross-bedded micaceous sands, grits and silty sands deposited in estuarine or shallow water at the end of the Miocene. Firman (1966) split the Loxton Sands into two units, the Lower Beds (estuarine and equivalent to the sands of the Loxton type section) and Upper Beds (fluviolacustrine) with a disconformity in between. Firman also recognized the Parilla Sand, disconformably overlying the Loxton Sands, having a similar lithology (though finer grained) but differing in having little or no cross-bedding. Firman considered the Parilla Sand unit to be fluviolacustrine, and the complete sequence to be Pliocene. Lawrence (1966) defined the Diapur Sandstone and considered it to be a variant of the Loxton Sands. The Diapur Sandstone differed to the Loxton Sands in structure (no strong cross-bedding), lithology (medium to fine-grained, only lightly micaceous sand), and lack of fossils. Lawrence suggested that the lower part of the Diapur Sandstone may have been offshore to

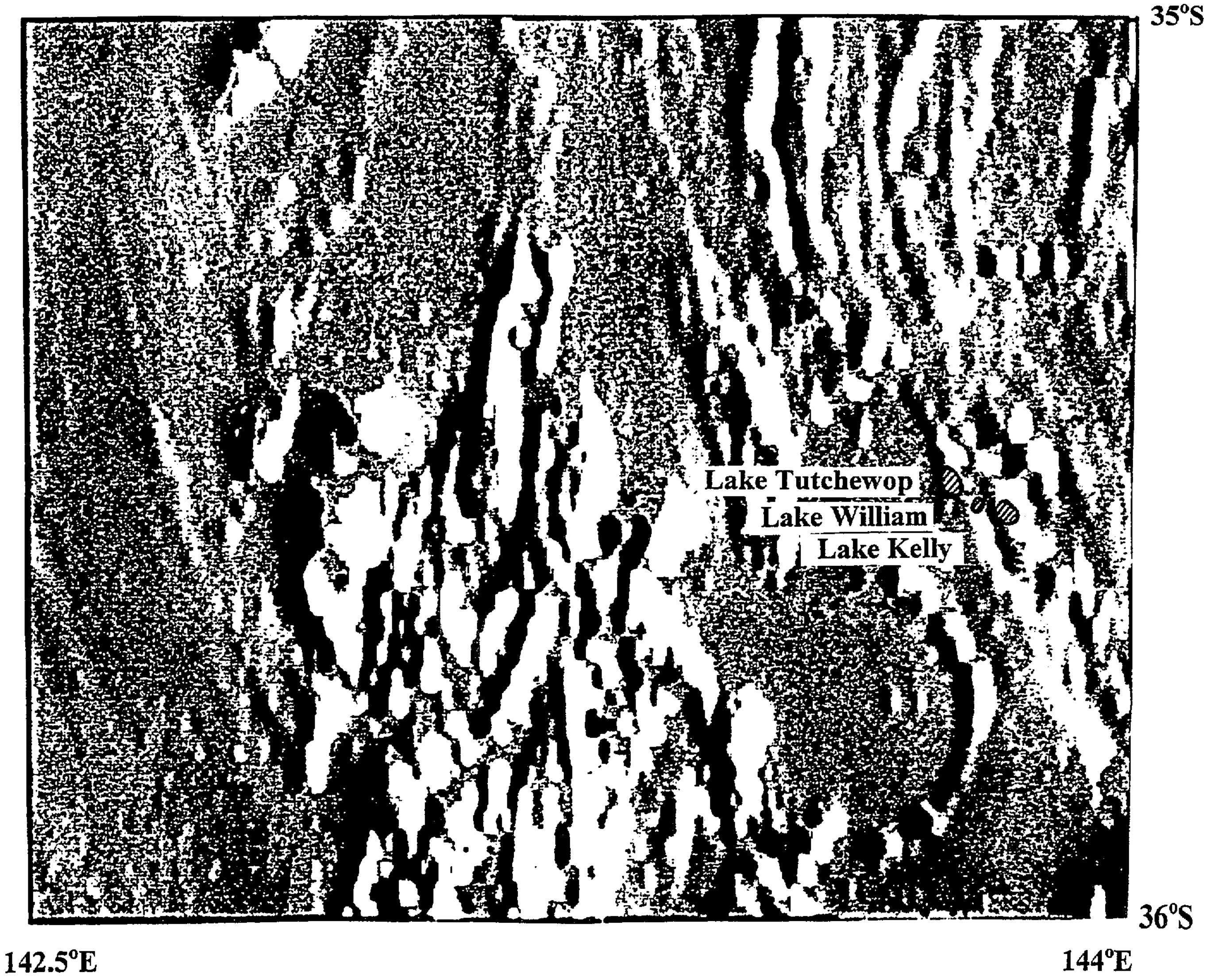


Figure 6. Location of Lakes Tutchewop, William and Kelly over magnetic basement structure (TMI image), Swan Hill 1:250 000.

littoral, and that the upper ridged sands were shoreline deposits. Lawrence subsequently recognized the equivalence with the Parilla Sand .

The Parilla Sand is important in being the down-basin equivalent of the fluviatile Calivil Formation, and because it forms the regional unconfined aquifer throughout northwestern Victoria (Macumber, 1991). From sites at the eastern extent of the Formation, Macumber (1969) found marine fossils at both the base and top of the sequence, and in places strongly cross-bedded, fine to coarse-grained, strongly micaceous sandstone and sandy grit. Upper parts of the unit better fit the description of the Loxton Sands. Macumber (1991) felt it likely that both the Loxton Sands in South Australia and units within the Parilla Sand on the Gregwin Ridge are a distinct lithofacies variant which is found on the basin margins. A further feature at the Gregwin Ridge is the presence of heavy mineral bands up to 1m thick in the Parilla Sand, interpreted as beach placer or shallow marine placer deposits (Macumber, 1969). The monazite in these bands makes these horizons distinctive gamma-ray markers.

At its inland limits below the Loddon Plain, Macumber (1991) subdivides the Parilla Sand into three lithostratigraphic members: the basal Kerang Sand Member, the intermediate Tragowel Member, and the upper Wandella Sandstone.

Kerang Sand Member

The Kerang Sand (Macumber, 1978) is the basal transgressive unit, directly overlying the fluviatile Calivil Formation, or in its absence, the Renmark Group, or on weathered Palaeozoic sediments. It consists of up to 30m of medium- to coarse-grained quartz sand, partially derived from reworking of the underlying Calivil Formation. It is often difficult to distinguish between Calivil Formation and Kerang Sand in the lower Loddon Plain.

Tragowel Member

Beneath the Loddon Plain, the Kerang Sand is overlain by a sequence of white clay and silt, the Tragowel Member (Macumber, 1978). The unit is up to 25m thick, and does not outcrop in Victoria, although similar white clays overlie the Loxton Sands in South Australia.

The Tragowel Member varies from a fine-grained, light grey to white quartz silt, to a silty claystone, in which clean quartz silt is contained in a clay matrix. Passing west under the Gregwin Ridge, the clays pass laterally into micaceous silty sands and sandy silts, with occasional clay bands. They are similar in texture to the overlying Wandella Sandstone but are more uniform, and lacking the cross-bedding.

Wandella Sandstone

This is a fine- to coarse-grained, micaceous sandstone (Macumber, 1978), with minor gravel, and occasional bands of heavy minerals. It outcrops on the Gregwin Ridge where it is fossiliferous and in places shows moderate cross-bedding. Westward of the Loddon Valley, lithologies within the Parilla Sand are more varied and therefore not easily correlated. Variations include sequences consisting of sand and sandstone throughout, sand sequences overlying silts and fine sands, and sequences similar to that of the Loddon Valley where the white clay is centrally placed. Large amounts of iron oxides are a characteristic of the Parilla Sand, probably arising from the remobilization of lateritic ironstones, followed by reprecipitation in the upper recharge parts of the basin from groundwater throughflow (Macumber, 1991).

Pratt (1988) indicates the thickness of Parilla Sand to increase eastwards from just under 50m on the western side of Lake Tutchewop to over 60m at Lake Kelly. In this area, the percentage of sand in the formation is approximately 50%. The upper surface of the Parilla Sand lies between 30 mAHD on the western side of Lake Tutchewop, to 40 mAHD below Lake William. and just over 40 mAHD below Lake Kelly (Pratt, 1988).

Shepparton Formation

Lawrence (1966) defined the Shepparton Formation as being a thick sequence of fluvial and lacustrine sediments overlying the Calivil Formation. The sediments are principally brown and grey mottled clay and silt, with thin beds of fluvial sand - the shoestring sands of the prior streams. The Shepparton Formation is distinguished from the younger Coonambidgal Formation (Lawrence, 1966) by the latter being essentially deposits of existing streams or their recent ancestors in the Murray Basin. On the Loddon Plain, a clear distinction can often be made between a lower sequence of red and light grey clays and an overlapping suite of brown and grey clays, the boundary between the units being generally sharp but becoming less distinct up towards the highlands.

Locally in the buried Powlett Plains valley, very distinct red-brown and light grey clays occupy the same stratigraphic interval as the Parilla Sand immediately to the north where they also onlap the Parilla Sand (Macumber, 1991).

The colour distinction between the red clay and yellow-brown clay is seen by Macumber (1991) as having climatic and environmental significance, with the reddish colours indicating conditions that were conducive to ferruginisation. He makes a tentative correlation between the ferruginizing events on the Loddon Plain and the conditions which led to the silicified and ferruginized Karoonda Surface , developed on the Parilla Sand after its exposure to subaerial weathering (Firman, 1966).

Extensive distributary development prevailed on the Loddon River systems throughout Plio-Pleistocene times, when the Riverine Plain was being systematically aggraded: initially, in response to the marine transgression, and later, as a consequence of climatically controlled cycles of fluvial sedimentation (Lawrence, 1966, Macumber, 1968). As coarser sediments were deposited close to the highlands, there is a gradual fining northward across the Loddon Plain, until a point is reached beyond which stream loads were virtually reduced to suspension load: this allowed a predominantly clay plain to build up (Macumber, 1991).

In the Lake Tutchewop area, the Shepparton Formation has a general thickness of 40m (western side of Lake Tutchewop) to 30m at Lake Kelly. Pratt (1988) indicates that the proportion of sand intervals in the formation decreases eastwards from about 20% at Lake Tutchewop to about 10% at Lake Kelly.

Yamba Formation

The Yamba Formation (Firman, 1973) comprises an association of sediment types deposited in a range of local environments in or adjacent to saline lake complexes. These include successions reflecting seasonal interplay between aeolian, pluvial and groundwater conditions. In detail the successions can vary from one lake setting to another (Brown and Stephenson, 1991).

The formation comprises friable, pale-grey to pale-brown gypsiferous clay, grey pelletal clay, gypsum-quartz sand aggregates and gypsum. At the margins of present day playa lakes and salinas, the upper surface consists of desiccated crusts of fluffy gypsite, halite and gypsum-clay pellets. These desiccated lacustrine sediments merge laterally with pale-cream, pale-brown and white gypsite/quartz sand/soil admixtures of the adjacent lunettes. In modern playas the lake floor sediment comprises an upper layer of black sulphide-rich mud with an ephemeral salt crust. The mineral suite within the mud includes sulphide and gypsum-clay laminites, dolomite, dolomitic clay, and dolomite-cemented sand (Bowler and Teller, 1986). The black muds are mostly underlain by thicker sequences, up to 2-4 metres, of dark grey-blue water-saturated clay with beds of crystalline gypsum mush (Brown and Stephenson, 1991).

Modern and fossil saline lake deposits with associated gypsum and clay pellet sediments are entrenched within the aeolian Mallee landscape and the western margins of the fluvial Riverine Plain.

The Yamba Formation accumulated in salinas within the arid landscape of the Murray Basin. Favourable conditions for this deposition relate to past climatic and lake water-level fluctuations, groundwater/lake-water interactions and consequent variations in salinity. Deposition was predominantly associated with drying phases during transitional wet to arid periods, with inherited high groundwater tables (Bowler and Wasson, 1984). These arid periods were coincident with glacial maxima (Galloway, 1965; Bowler, 1976). Detrital clastic clay sediments were probably deposited in wetter climatic conditions when lakes were deeper and of lower salinities. Evaporation, desiccation and deflation of lake floors were associated with drier windy climates when groundwater discharged into the lakes (Brown and Stephenson, 1991).

Informal Units of the Yamba Formation recognized in the Lake Tutchewop - Lake William - Lake Kelly area

The substrate and perimeter to the lakes comprises a thin veneer of lacustrine sediments (1.5 to 3.5 metres of Yamba Formation), overlying the Shepparton Formation. The distinction between these formations is generally subtle as the lacustrine sediments are derived from the underlying sequence.

The main differences are the evaporites and sparse biota of the Yamba Formation, as compared to the strongly colour-mottled muds of the Shepparton Formation.

Five lithofacies have been differentiated as a result of detailed logging of shallow sequences in the lakes. There is a general correspondence of sequence in each of the lakes and it is probable, although not established, that the lithofacies reflect concurrent and comparable depositional environments in each of the lakes. The lateral distribution of these lithofacies is outlined in Figures 7, 8, 9, 10, 11 and 12.

The following description and discussion of units relate to Lakes Tutchewop, William and Kelly. Lake Little is not discussed due to an absence of drill data.

Unit 1

Location in lake complex: This is the basal facies in Lake William, intersected only in WNMT-BM. It has not been recognized elsewhere in this lake, or in the other lake sequences.

Geometry and thickness: Unit 1 forms a thin lens 0.9 metres thick, probably with a lower-dipping surface, and an upper horizontal surface.

Description: The basal blue-grey (5B5/1) muddy silt has a minor fine quartz sand content, contains faint lamination and hosts indurated calcitic nodules. It grades up through a sandy

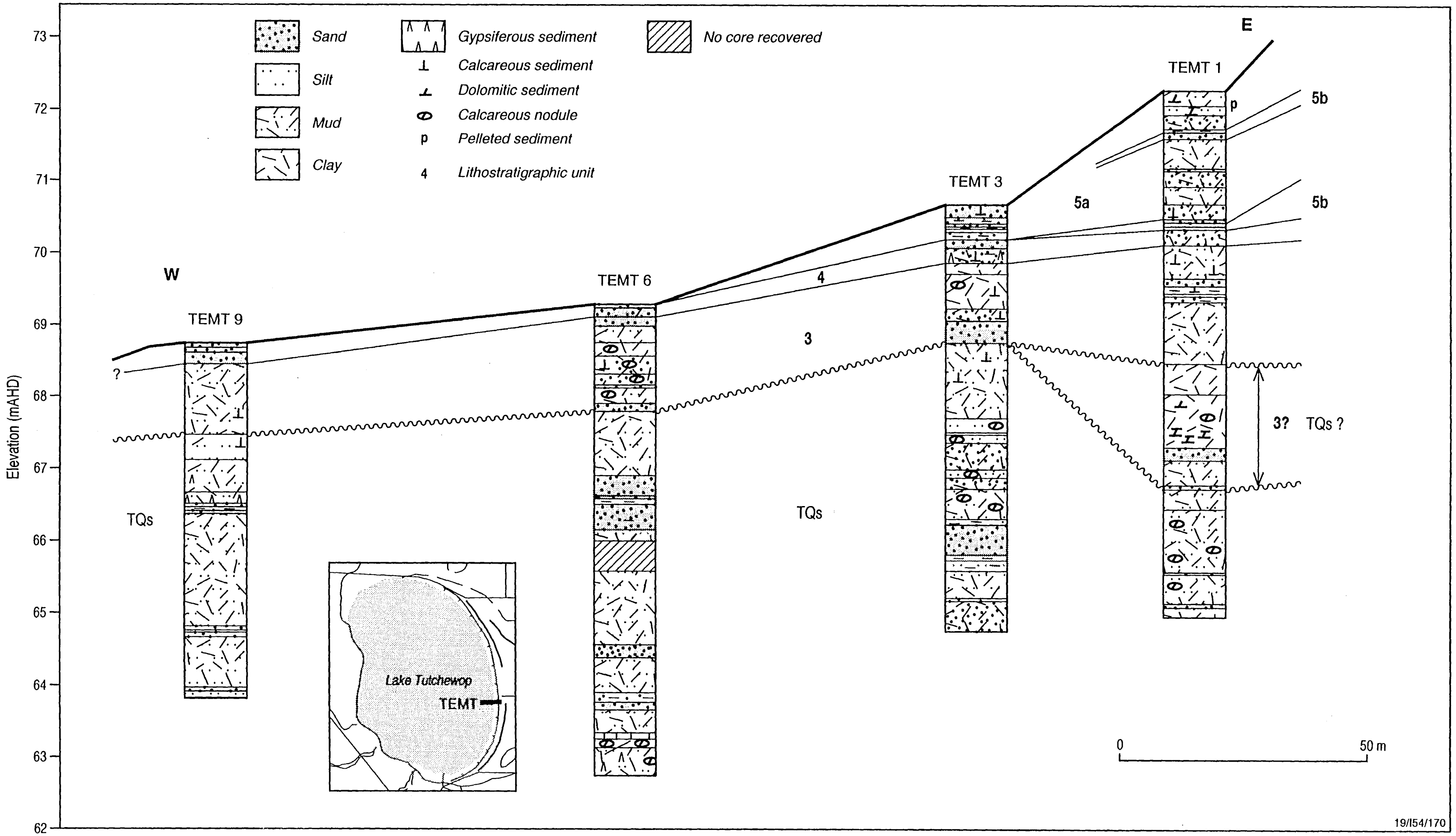


Figure 7. Lithostratigraphy of the Lake Tutchewop eastern transect (TEMT).

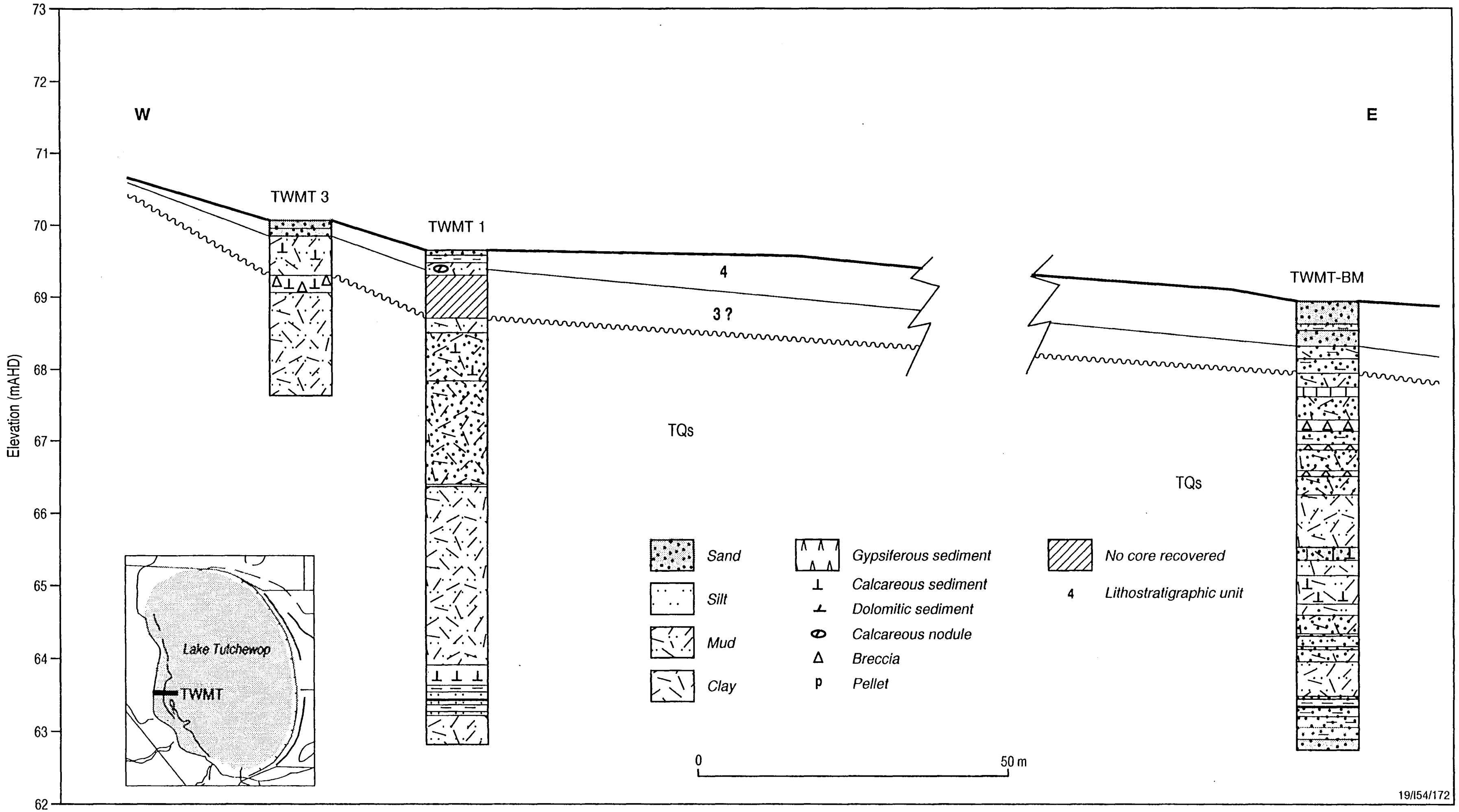


Figure 8. Lithostratigraphy of the Lake Tutchewop western transect (TWMT).

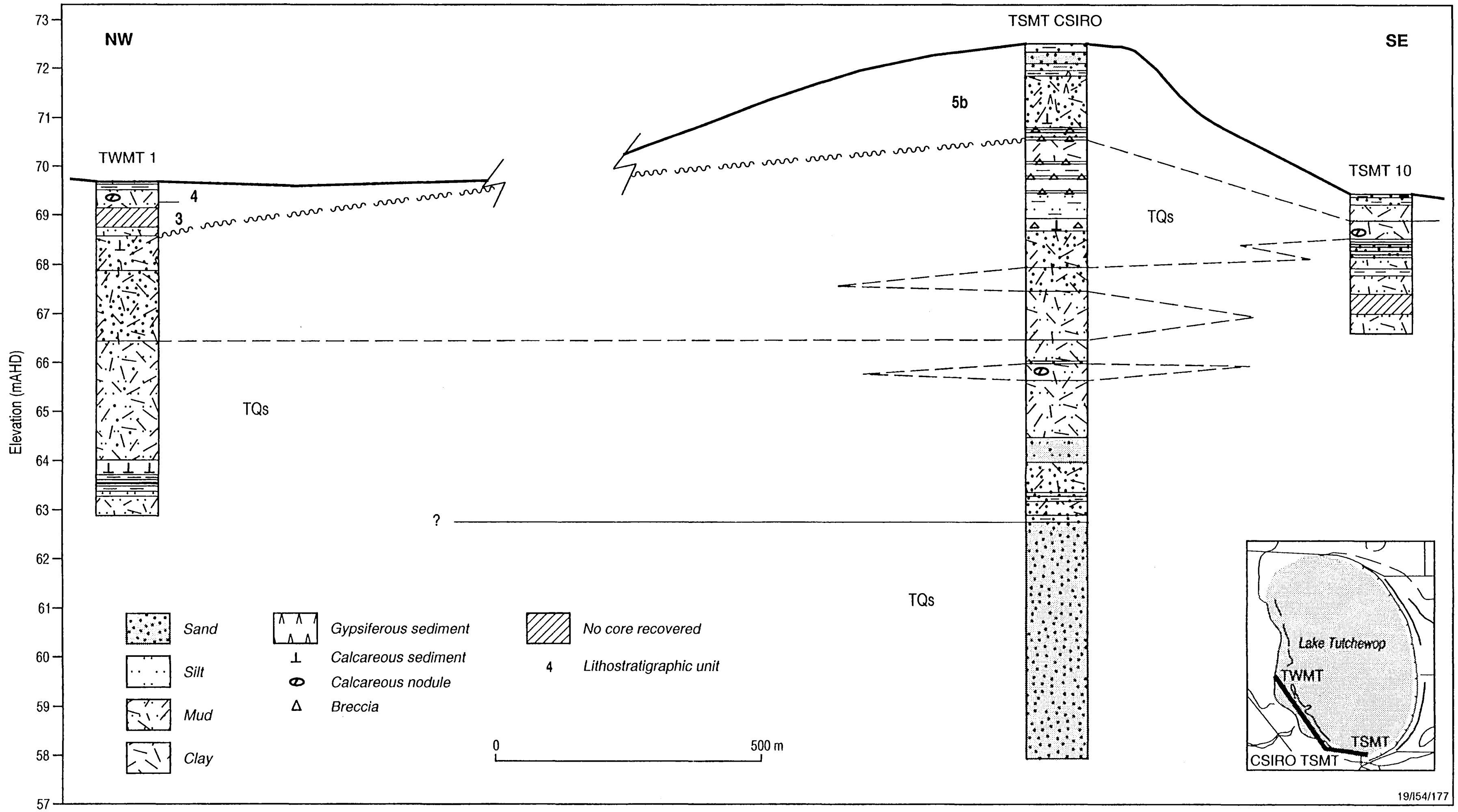


Figure 9. Lithostratigraphy of the Lake Tutchewop southwestern transect (TSMT-TWMT).

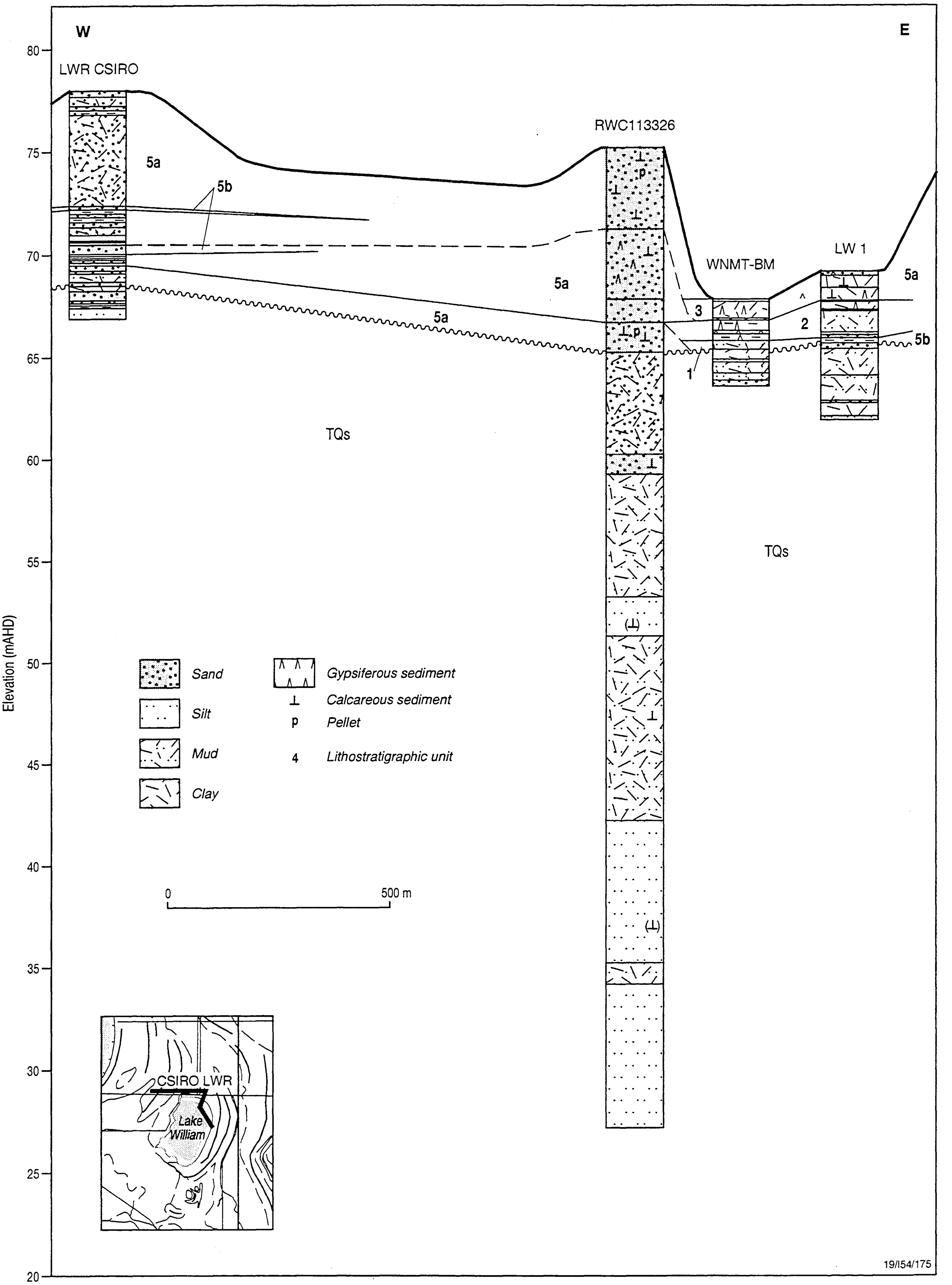


Figure 10. Lithostratigraphy of Lake William.

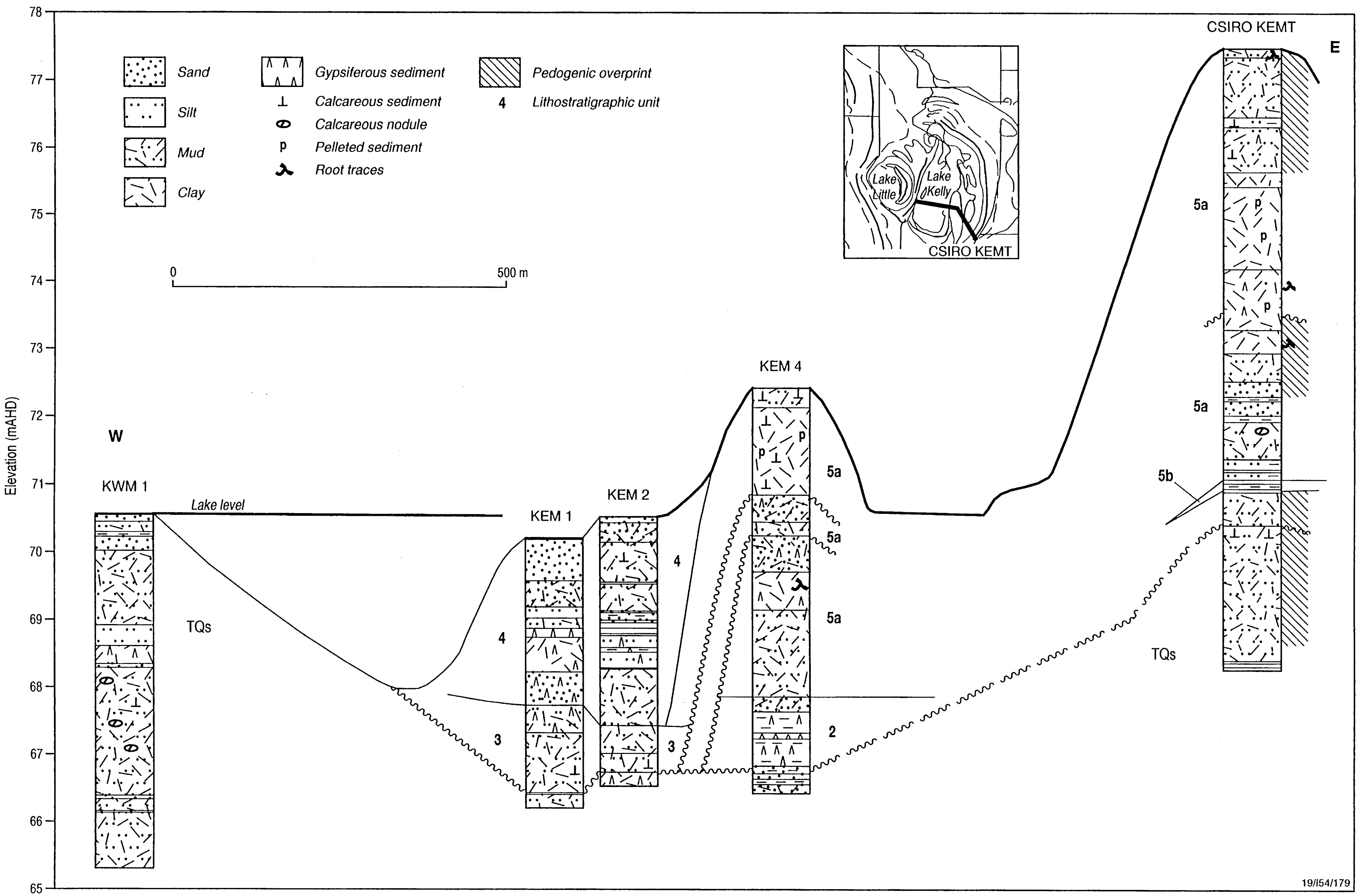


Figure 11. Lithostratigraphy of the Lake Kelly eastern transect (KEMT).

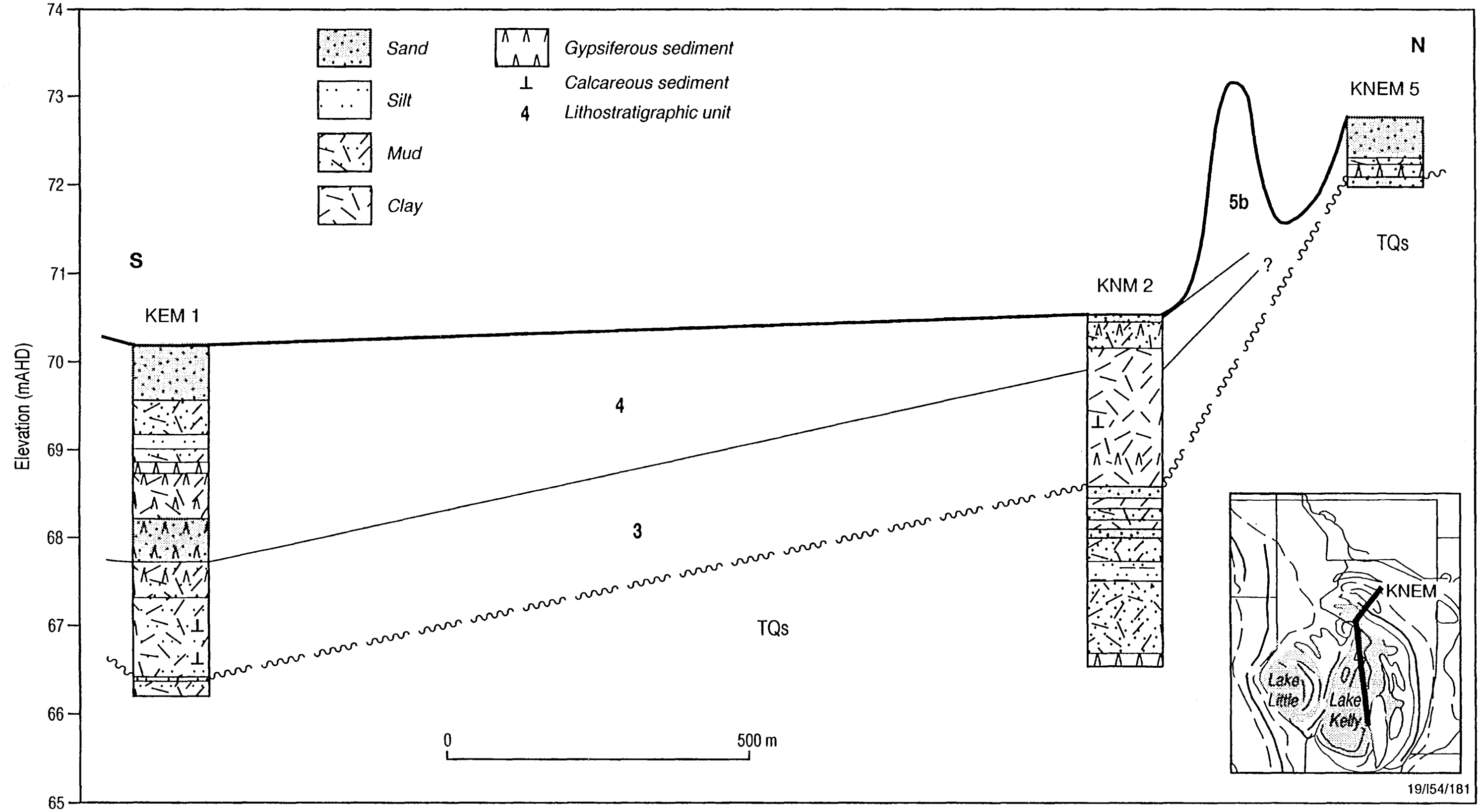


Figure 12. Lithostratigraphy of the Lake Kelly northern transect (KEM 1 - KNMT).

gypsiferous mud to an upper plastic blue grey mud (5B5/1 & N9) with gypsum silt. Some white gypsum laminae occur, the lamination defined by variations in colour and silt content. Distinctive are millimetre-sized black flecks, plant material?, some of these being replaced by sulphides to form indurated platelets. There is minimal porosity as intercrystalline voids in the gypsiferous laminae.

Stratigraphic relationships: Unit 1 overlies the Shepparton Formation with disconformity, and is overlain conformably by Unit 2.

Depositional Environment: Freshwater to hypersaline lacustrine.

Discussion: The scattered presence of gypsum laminae indicates hypersaline, evaporative conditions that probably precipitated lacustrine gypsum varves. The predominance of blue-grey mud, with clay content? and plant material may indicate predominant freshwater conditions that seasonally evaporated to conditions suitable for gypsum precipitation. The presence of sulphide platelets, probable replacements or nucleations on the organic material, may allude to a subsequent diagenetic origin from sulphate reduction which may explain the random preservation of gypsum laminae, as opposed to laterally continuous preservation that would be expected in such evaporitic environments.

Unit 2

Location in lake complex: This distinctive unit is present in the sequences of Lake William (WNMT-BM and LW1) and Lake Kelly (KEM-4). It has not been recognized elsewhere.

Geometry and thickness: A thin tabular unit with about 0.6 m thickness in both lake occurrences. It has probable extensive distribution in Lake William, and in Lake Kelly where it is probably extensive across the eastern side of the discharge basin.

Description: Unit 2 has a striking colour-laminated character; white, blue-green grey, orange grey and yellowish orange (N8, 5B6/1, 10YR5/4). Each lamina comprises a cyclet of basal clay with variegated colour, grading up to dolomitic micrite, to microsucrosic gypsum sand which coarsens up to fine to medium sand-sized millet seed gypsum mush. At least 5 to 6 cycles are recognized.

Stratigraphic relationships: It overlies Unit 1 conformably in Lake William and is overlain by Unit 3. In Lake Kelly, it disconformably overlies a porous sand stringer of the Shepparton Formation, and is overlain directly by compacted mud of a lunette deposit.

Depositional Environment: Seasonal influxes of low-salinity clayey waters evaporated to hypersalinity with resultant evaporite precipitates.

Discussion: In Lake William the unit adjoins a porous beach sand and in Lake Kelly it overlies a sandy stringer. It is probable that these locations were the early saline spring sites of the respective discharge complexes. This lithofacies represents minimal external disturbance or overprint by colluvial wash or river floodwaters.

Unit 3

Location in lake complex: The unit is the most widespread unit in all lakes, and is exposed at the surface of Lake William,

Geometry and thickness: It forms a tabular body draping the underlying surface and is thin in Lake William (0.9 m) and thicker in Lake Kelly where it has a near uniform thickness of 1.2 to 1.3 m where present in the central and northern parts. The lithofacies is absent east of KEM-1 but extends to the northern margin of the lake. At Lake Tutchewop, the unit is about the same thickness of 1.2 m on the eastern margin of the lake, but does not appear to exceed 0.7 m on the western margin.

Description: Characteristic of this unit are its upper and lower disconformable contacts with related pedogenic overprints. Because of a higher impermeable mud content, the oxidation mottling follows bioturbation and is subdued in colour. Medium grey (N5 to N6), olive grey (5Y5/1-6/1), greenish grey (5GY6/1) colours are typical with pale yellow brown (10YR6/2) and greyish orange (10YR6/4) oxidation mottles. The muds commonly have dark medium grey rounded patches that resemble mud lumps. Bioturbation, vertical borings and root traces, are common. Ostracods and oogonia of *Chara* are randomly present. Wood fragments are rare.

The bioturbated muds vary slightly in silt and sand content, and may be calcareous with soft or crumbly micrite patches and laminae. Semi-indurated micritic nodules are stratiform where present. Gypsum is ubiquitous as sucrosic crystalline occlusion of bioturbation porosity, and minor scattered small displacive crystals in the mud.

Stratigraphic relationships: In Lake Kelly and Lake Tutchewop, Unit 3 overlies the Shepparton Formation disconformably. It is generally overlain by Unit 4 disconformably. In Lake William, this lithofacies overlies unit 2 conformably? and is exposed at the surface.

Depositional Environment: Varied lacustral origin, generally with higher input of surrounding Shepparton clay and mud.

Discussion: The unit is the least permeable and least porous of the lacustral lithofacies. Its distinctive character of subdued colours of oxidation mottling, presence of pedal fabrics and tight nature probably result from the exposure and pedogenic overprint prior to the most recent lacustral phase of sedimentation.

The biota, though a minor component, is distinctive and distinguishes this lithofacies from underlying Shepparton sediments.

The sequence in Lake William attributed to this lithofacies is quite distinct from the other lakes. That Lake William has been actively mined, and is more frequently supersaturated with respect to halite, probably accounts for the more homogenized, gypsum-halite rich character.

In the northern part of Lake Kelly it is questionable if this lithofacies is present as the sequence also resembles unoxidized Shepparton muds. However, the underlying Shepparton sequence has a strikingly different degree of oxidation and mottling development which suggests there is a separate overlying unit.

At Lake Tutchewop, the unit is more oxidized and less distinct in overall appearance from the underlying Shepparton Formation. On the western margin, the lithofacies is sandier and silty, has distinct ped development with associated rootlet and bioturbation traces. Carbonate nodules, micritic alternations, and clayey micrite are more abundant than at other locations. On the eastern side of Lake Tutchewop the unit has very close similarity to a weathering profile on Shepparton muds except for the presence of *Chara* oogonia.

Unit 4

Location in lake complex: This unit is extensive over Lake Tutchewop and in the central and northern part of Lake Kelly. The lithofacies is not recognized at Lake William.

Geometry and thickness: Its geometry varies from a thinly-draped tabular body on the eastern margin of Lake Tutchewop (0.3 to 0.4 m thick), to a thin-wedged form on the western side that thickens lakewards to 0.7 m. It is untested whether the unit extends across the entire lake basin. In central Lake Kelly its draping form is more irregular, varying from 2.5 to 3 m thick, with an apparently deflated western extent in the deeper part of the lake, but wedges gradually to the north.

Description: The lithofacies has characteristic higher sand content and associated higher porosity. It has the most abundant biotic remains - ostracods, *Chara* oogonia, small gastropods, plant material and some wood fragments. Colour is variable from light olive grey (5Y7/1-6/1), brown grey (5YR5/1-4/1), medium grey (N5), greenish grey (5GY6/1), to brownish grey (5YR 3/1).

The sediments are predominantly sand, muddy sand, sandy silt, and sandy mud. The sands are commonly in fining-upward cycles with basal medium to coarse quartz that grades to fine to very fine particles. Interparticle porosity is high. The sediment is commonly calcareous, of variable oxidation and pyrite content, and low in gypsum. Ellipsoidal ooids with quarts-sand nuclei are present in the upper sands on the eastern margin of Lake Tutchewop. At Lake Kelly, the lower part of this lithofacies has a significant gypsum content, derived from both lacustrine millet-seed precipitation, as well as early diagenetic discoids, crystals and rosettes.

Stratigraphic relationships: The unit is disconformable over Unit 3, and is exposed at the surface. On the eastern margins of Lakes Kelly and Tutchewop, some lunette sediments form scree wedges over the lithofacies.

Depositional Environment: Lacustrine of variable depositional energy and salinity, the sediments are higher energy deposits than those of Unit 3, as evident in the ooid facies on the eastern shoreline flats of Lake Tutchewop.

Discussion: Variability is more apparent in this lithofacies, although it is comparatively sandier, with common to dominant sands within the sequence. Accordingly, porosity and porosity variations are greater.

Unit 5a

Location in the lake complex: This lithofacies has the most distinctive geomorphic expression as lunettes distributed on the northeastern to southeastern sector of the eastern shoreline of each of the lakes.

Geometry and thickness: The lithofacies forms high deep lenses and aggraded wedges that have curvilinear expression parallelling the lake shoreline. Maximum thickness varies significantly from 4 to 13 metres.

Description: The sediments are generally compact to crumbly with brownish colours; pale yellowish brown (10YR 6/2 - 7/2), moderate yellowish brown (10R6/4, 5YR5/4), moderate brown (5YR6/2), pale brown (5YR4/2), moderate red (5R6/4) and olive grey (5Y6/2). Texturally the muds and sands are packstones and grainstones, with variably-preserved and compacted clay-pellet components. Root traces are prominent, along with some *Chara* oogonia. Pedogenic overprints modify the upper sequences below erosional surfaces, and are evident from fenestral and bioturbation porosity infilled with sucrosic gypsum, as well as increased fracture porosity from pedal development.

At Lake William, millet-seed gypsum is a significant particulate component.

Stratigraphic relationships: It is disconformable on Shepparton Formation or on lacustral lithofacies, and may also interdigitate with any of the lacustral units.

Depositional environment: Intermittent and episodic accumulation occurred from deflation events on the discharge basin. Pellet formation is by salt crystallisation and resultant clay breakup, with aeolian transport of these particles up onto the lunette dune providing rounding of the soft sediment.

Discussion: Lake Tutchewop has had at least three major deflation events as evident in the extended lunette crests to the southeast of the main lunette. At Lake William, three crests are also evident in the dune complex. At Lake Kelly, two pedogenic profiles recognized in the dune indicate at least this number of deflation events. Additionally in the basin, there is a lower but extensive linear lunette deposit intercepted by KEM 4. Possibly three accumulation phases can be distinguished within this lower lunette.

Unit 5b

Location in the lake complex: Within and to the base of the lunettes (Lithofacies unit 5b) there are repeated intervals of this lithofacies.

Geometry and thickness: Unit 5b forms thin lenses and wedges that are totally contained within the lunette. Thickness is variable but thin, generally less than 0.24m.

Description: Well-sorted light-brown (5YR4/6 & 5YR6/2) and light olive-grey (5Y6/1) unconsolidated sands are characteristic, commonly occurring in graded beds that generally coarsen upwards, although some fine upwards. The sand grades from fine to coarse or very coarse to medium, comprising quartz particles that are variably milky, clear, pink, or red. Small amounts of rounded opaque minerals are also present. Interparticle porosity is very high, with only minor occlusion by calcite or gypsum.

Stratigraphic relationships: Unit 5b is most likely to be disconformable over Shepparton or lacustral deposits, but may also be conformable within lunettes (Unit 5a).

Depositional environment: During high-water stands in the lakes, wave-sorted sands accumulated on the leeward shoreline. These shoreline deposits may then be remobilized or reworked by aeolian action to accumulate against an existing lunette.

Discussion: The coarsening-upward cycles seen in CSIRO KEMT are probable remnants of surface winnowing by winds to leave the coarser lag. Each occurrence of this lithofacies varies in bedding and grading characteristics, suggesting a variety of processes and their influence on the characteristics of the sand.

Summary of Lithofacies Distribution

Five lithofacies (Units 1 to 5) overlie the regional Shepparton Formation; four lacustrine and one lunette unit are recognized within and adjacent to the three lakes. The lower two lithofacies comprise sediments of distinctive evaporitic cycles and occur juxtaposed only in Lake William. Lake Kelly has Unit 2 evaporitic laminites in a localised part of the complex. The upper two lacustrine lithofacies (Units 3&4) are more widespread. Unit 3 occurs in all lakes. It is the least permeable unit and comprises darker colour-mottled bioturbated muds which superficially resemble Shepparton muds but have a distinguishing *Chara* and ostracod content. The uppermost lacustrine Unit 4 comprises sand, muddy sand, sandy silt, and sandy mud, has the greatest and most varied porosity, and is present in Lakes Kelly and Tutchewop. Lunette sediments, both clay pelletal (Unit 5a) and highly permeable quartz sand (Unit 5b) rim the eastern margins of all lakes.

THE DISPOSAL BASINS

LAKE TUTCHEWOP

The investigations of Lake Tutchewop are based on four transects which run at approximately right angles to the edge of the disposal basin (Figure 13) and a semi-regional transect which relates the natural topography of Lakes Tutchewop, William, Little and Kelly (Figure 14). The western transect at Lake Tutchewop starts at a usually submerged site in the disposal basin and extends across the lake marginal areas to near the artificial surface water systems associated with irrigation channel 6/7 and the Avoca floodwater diversion (Figure 15a). The eastern margin transect extends from the usually submerged area of the disposal basin across the lake marginal areas and the colluvium at the base of the lunette, and terminates at the margin of the dryland farming areas on the lunette (Figure 15b). The northern transect (Figure 16a) starts in the regularly-flooded area of the lake margin, crosses the northern fringe of the lunette and ends in active irrigation areas on the floodplain to the north-east. The southern transect extends landwards to the boundary between and the lake marginal areas and abandoned irrigation areas on the floodplain to the south-west (Figure 16b) .

Geomorphology

The Lake has a simple ovoid outline and symmetrical lake floor geometry. It has a smooth arcuate convex eastern shoreline rimmed by a high continuous lunette (up to 82 m AHD) (Figure 13). The eastern margin reflects a classic wave-dominant form, smoothed by longshore drift whereas the western shoreline is more irregular with a slight western concavity and a linear WSW component. Second-order low-relief irregularities are a feature of this side of the lake; small islands, peninsulas and embayments. Lake bathymetry indicates a near flat-bottomed shallow basin with steeper slopes around the

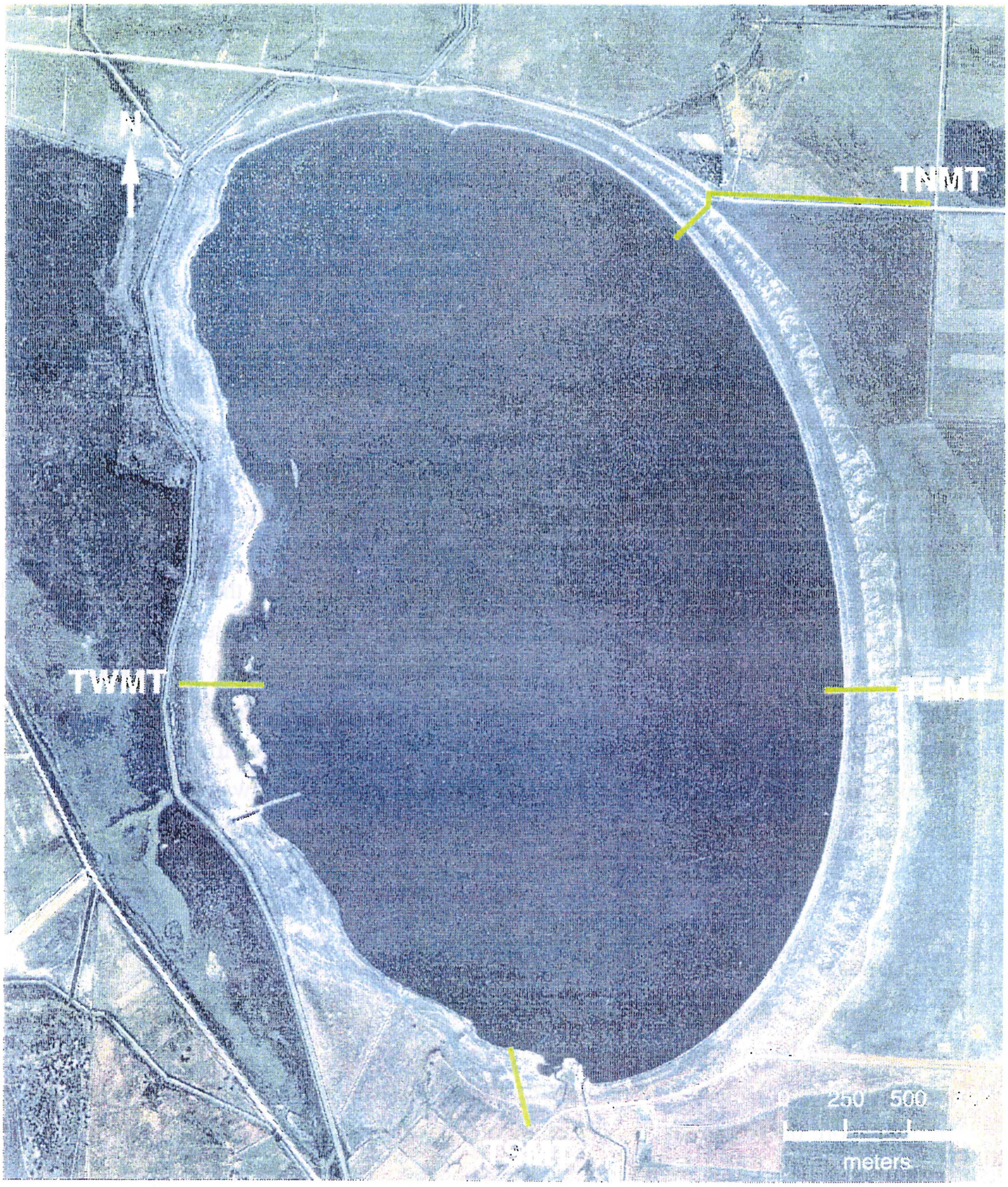


Figure 13 Locations of transects at Lake Tutchewop.

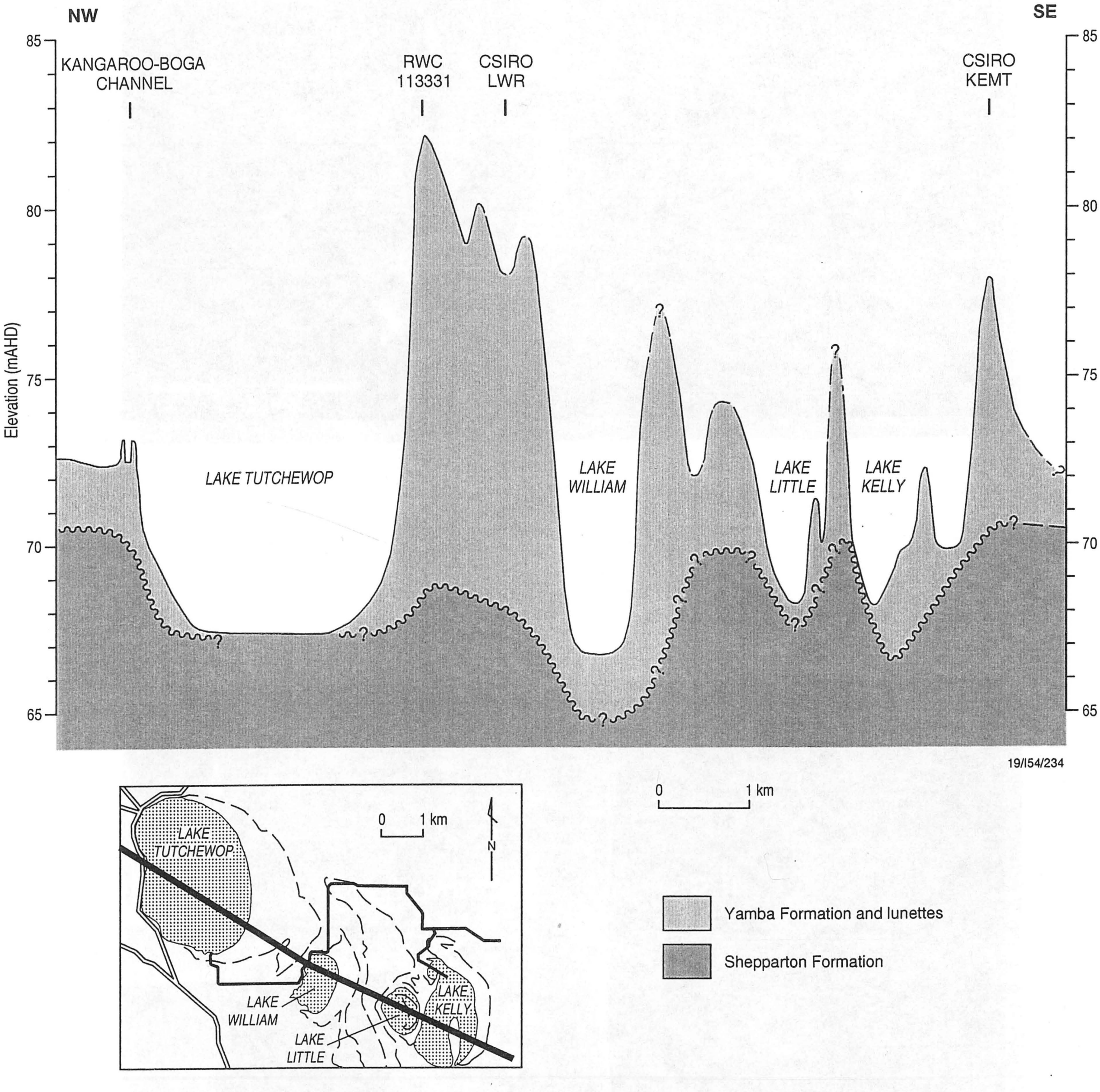
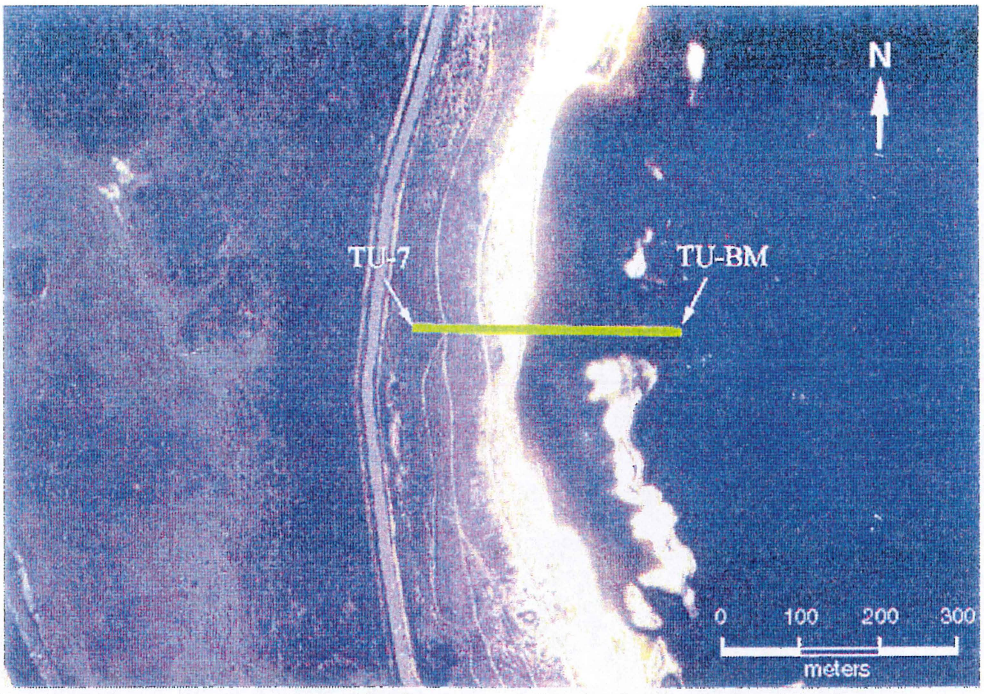


Figure 14. Natural topography of Lakes Tutchewop, William, Little and Kelly.



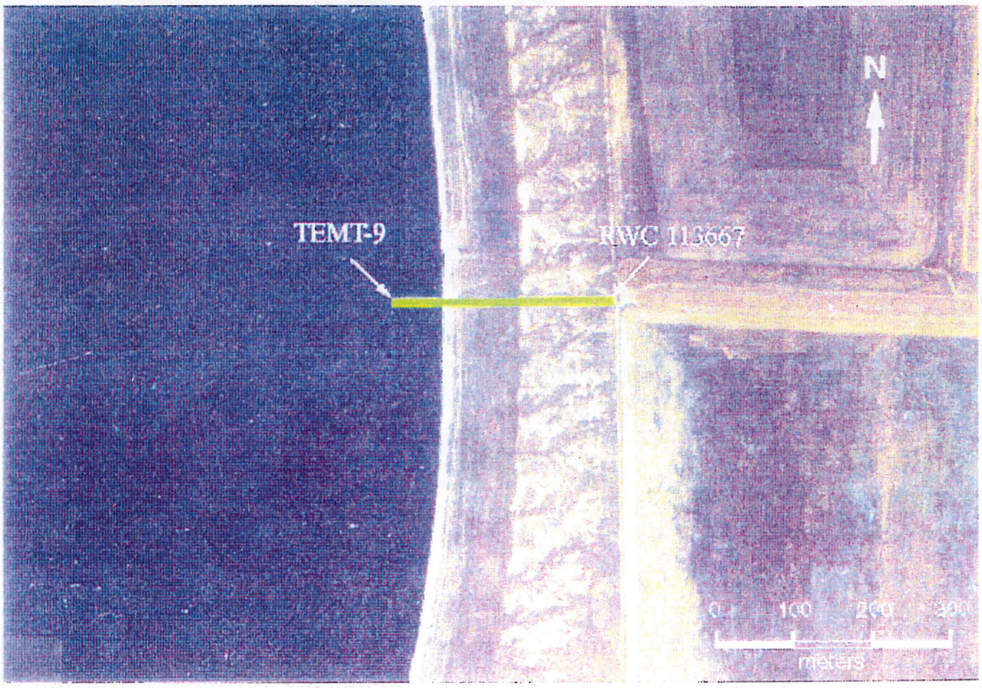


Figure 15. Locations of transects on (a) the western (TWMT) and (b) the eastern margin (TEMT) of Lake Tutchewop.

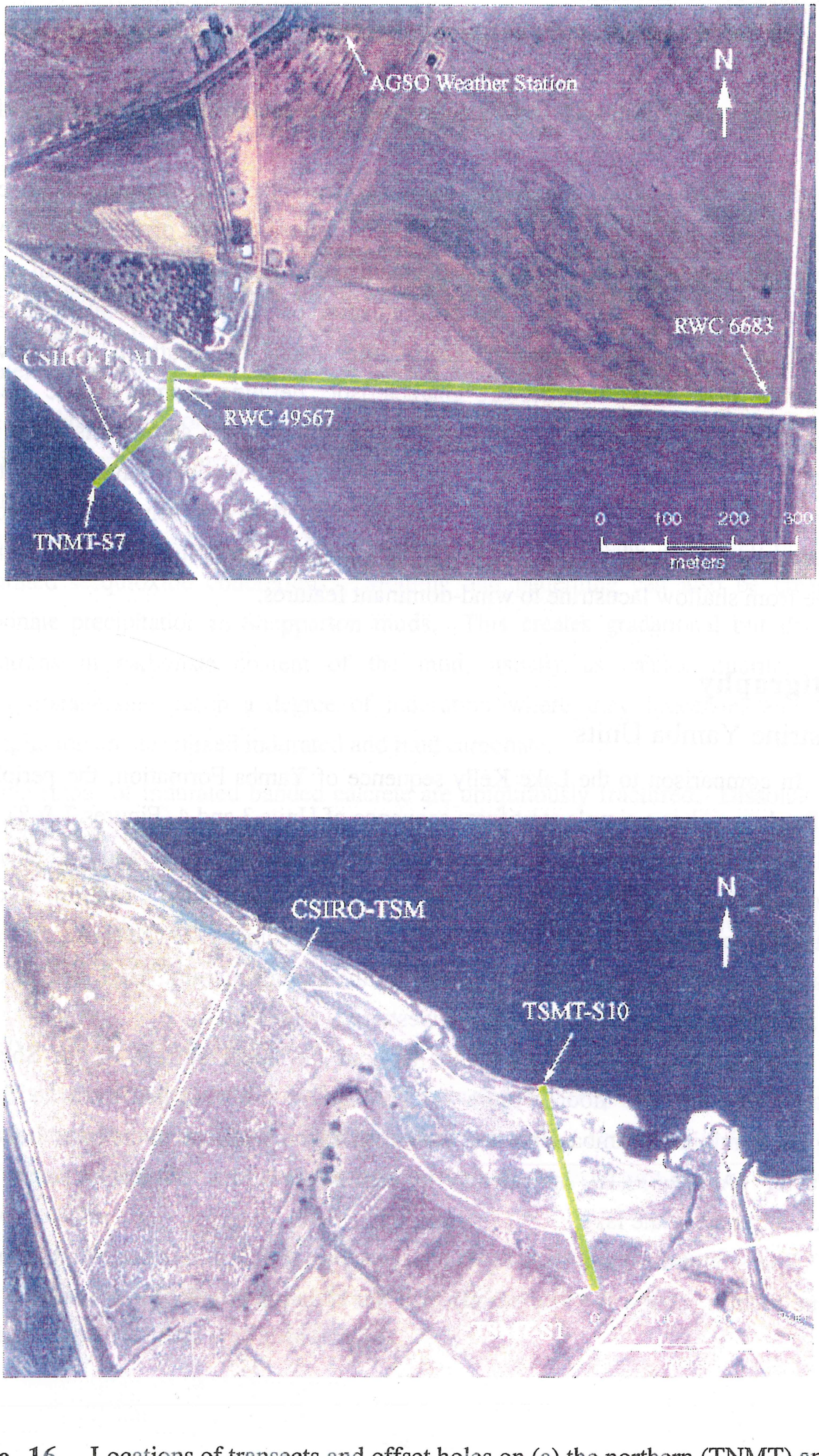


Figure 16. Locations of transects and offset holes on (a) the northern (TNMT) and (b) the southern (TSMT) margin of Lake Tutchewop.

perimeter (Figure 14). The deepest part of the lake (67.2m AHD) lies close to the steeper eastern slope of the lake floor.

The more irregular bathymetry and shoreline on the western side is a direct reflection of the reduced wave-modification of deltaic sediments from the Avoca River outfall (Figure 15a). In east-west section, the western lake margin has aggradational wedges of lacustrine sediment, contrasting with the eastern margin where depositional units have a draped and gradual thickening landwards from the lake margin. This contrast reflects the differing processes of accumulation on opposite sides of the lake. The west margin appears to have some influx of sediment from the Avoca River outfall which is redistributed by longshore drift. The accumulation of scattered low-relief shoals has produced the more irregular western lake margin. Along the southern to southwestern sector subtle beach dune benches are characteristic, defining a small deltaic area from another pre-existing outfall of the Avoca River. In this southern sector, this shoreline has wave-dominant features, sediment has aggraded and been sorted by wave activity to form low-relief beach berms. On the eastern side, relatively finer sediment has been mobilized off-lake and upslope to the footslopes of the main lunette. There appears to be a continuum upslope from shallow lacustrine to wind-dominant features.

Stratigraphy

Lacustrine Yamba Units

In comparison to the Lake Kelly sequence of Yamba Formation, the periphery of Lake Tutchewop has a simple stratiform sequence of Units 3 and 4 (Figures 7 & 8). Unit 3 directly overlies a shallow basin surface of the Shepparton Formation, and is thinner on the western side (0.5 to 0.75m thick), and thicker on the eastern side (1 to 1.5m thick). In contrast, the overlying Unit 4 has a thicker wedge geometry to the west (0 to 0.6m) compared to a thinner (0.2 to 0.5m) veneer on the eastern margin. Here lunette deposits (Unit 5a) have prograded downslope and westwards over Unit 4.

On the basis of similar elevations of both the upper surface of the Shepparton Formation and the lake floor (Figure 14), it is most probable that the lake floor has negligible or minimal Yamba deposits that thicken on the perimeter of the lake. Lake coring by Taylor (Appendix II) indicates a minimum of 0.15m Yamba sequence in the southeastern part of the lake.

Porosity of the Yamba sequence is extremely variable within both Units 3 and 4. In any one section, Unit 4 is more porous than the underlying unit. On the eastern margin, overlying lunette sediments are more porous except in the basal zone which has higher pore occlusion by reprecipitated gypsum.

Shepparton Formation

The formation comprises a relatively monotonous alternation of colour-mottled muds and minor sands and silts of variable porosity (Figures 7,8,9).

In the top 7 metres of the Shepparton Formation, there is significant lateral variability of porosity which is predominantly bioturbation porosity in the muds, with more consistent interparticle porosity in the minor silt and sand lenses.

Diagenetic features in the Shepparton Formation are strongly influenced by porosity and water movement. Most apparent are the following.

- The oxidation of porous conduits through low permeability sediments, especially vertically-oriented permeable channels such as bioturbation and fracturing. Oxidation mottling creates distinctive colour patterns that reflect water movement. Iron sesquioxide precipitation may be localized enough to create spherical or tubular indurated sesquioxide concretions. Mottling and patterning can also be created by carbonate precipitation in Shepparton muds. This creates gradational but distinctive variations in carbonate content of the mud, usually as calcitic micrite. Some concretionary sites reach a degree of induration where they brecciate, and further precipitation creates mixed indurated and mud carbonate.
- Thin horizons of indurated banded calcrete are ubiquitously fractured. Dissolution and reprecipitation features are common in these thin intervals, and modified breccia permeability is maintained.
- In muds and clays, distinct vertical sesquioxide mottling is present below and close to permeable horizons.

Porosity & Permeability

The lacustrine sequence is highly variable in porosity (Figures 17,18 & 19), but as a generalisation, the lower Unit 3 is tighter. The most porous sediments in this lithofacies appear to be on the outermost lake margins, as well as on the basin-side of the western sediment wedge.

Unit 4 has a greater proportion of sands and associated higher interparticle porosity.

The shallow Shepparton Formation has wide variability of porosity in various intervals as apparent in the west-east transect.

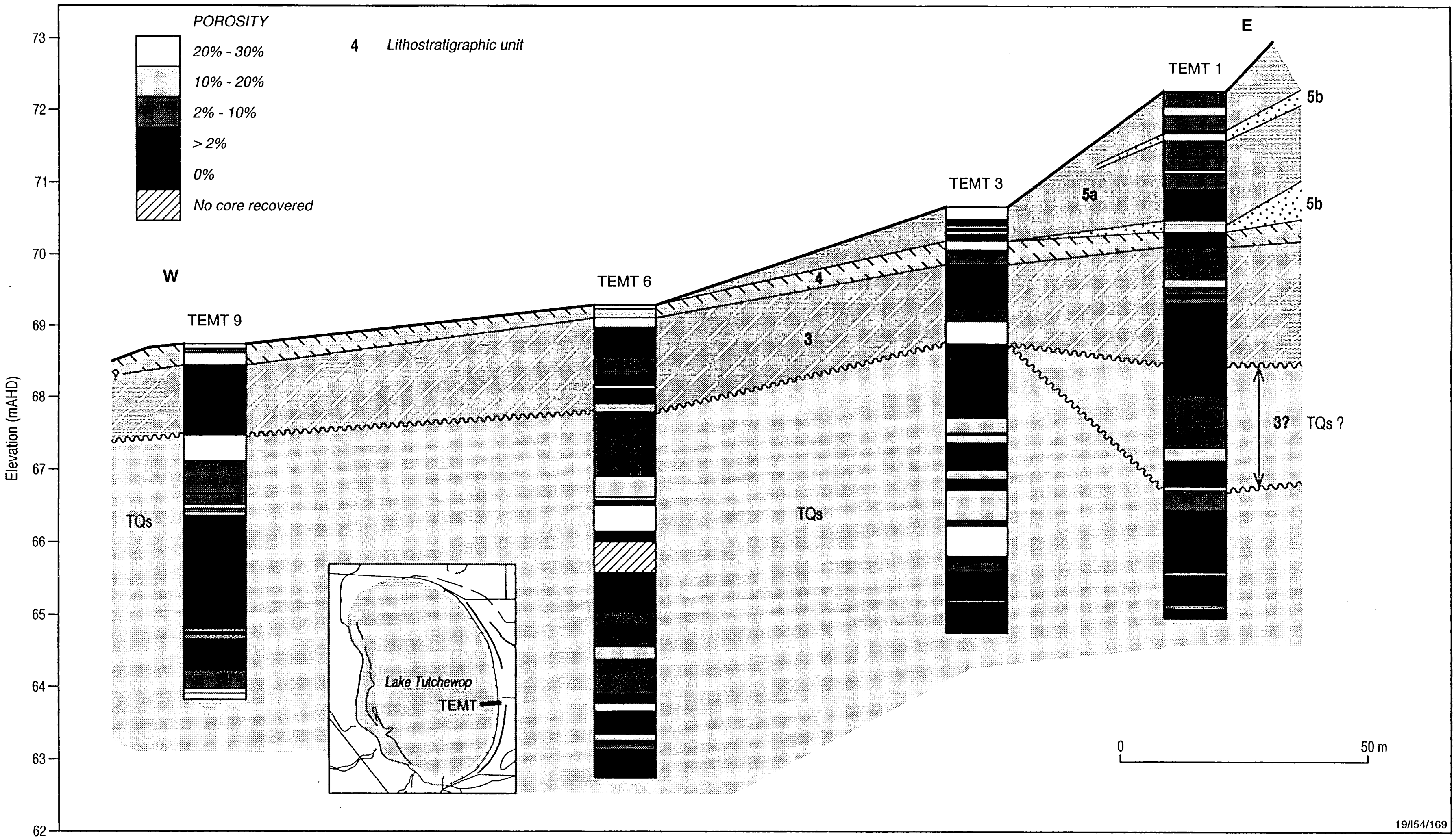


Figure 17. Porosity distribution in the Lake Tutchewop eastern transect (TEMT).

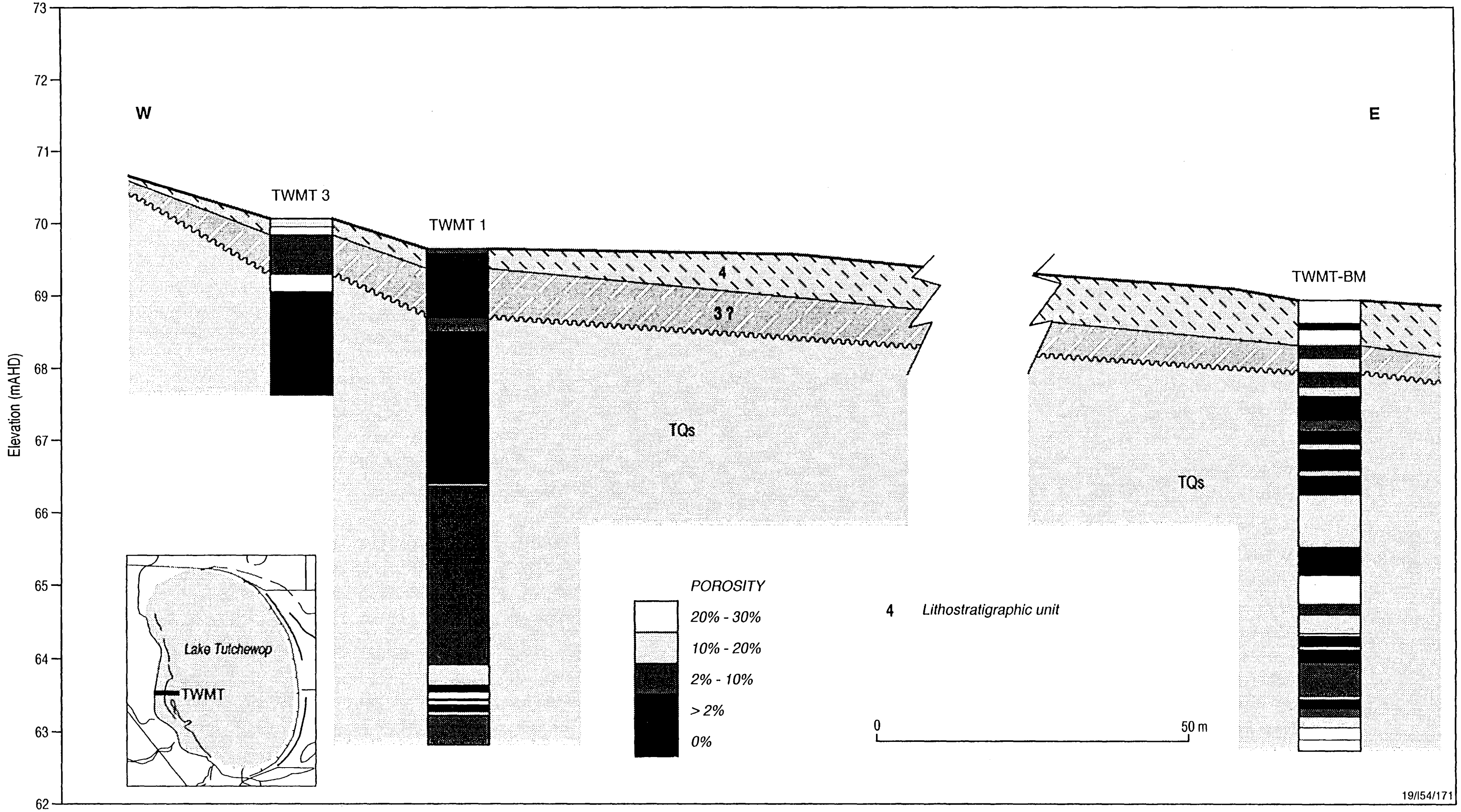


Figure 18. Porosity distribution in the Lake Tutchewop western transect (TWMT).

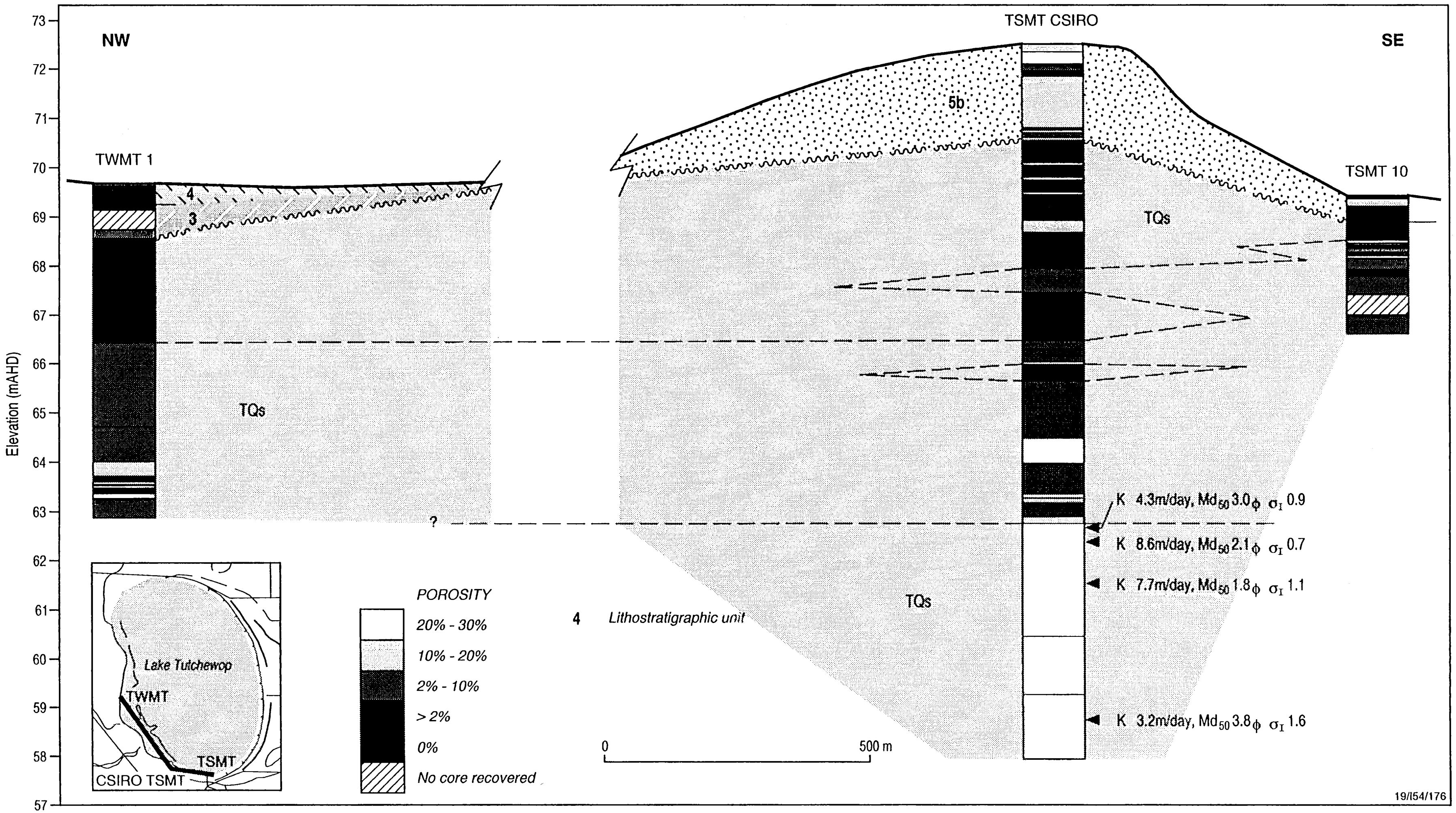


Figure 19. Porosity distribution in the Lake Tutchewop southwestern transect (TSMT-TWMT).

Deeper aquifers below Lake Tutchewop

Within the Shepparton Formation which is generally tight but with variable porosity distribution, two extensive aquifers have been identified from regional drilling; an upper silt that lies 5m below the lake floor, and a lower sand which is approximately 10m below the lake floor. The Parilla Sand directly underlies this sand body on the eastern side of the lake (Figure 20).

Both the silt and sand aquifers slope gently eastwards below Lake Tutchewop. The underlying sand has a 4m fall in its upper surface below the lake, while the silt unit thickens eastward and its upper surface slopes very gently (1m fall) in that direction.

Along the north-south axis of the lake, the lower sand body thins significantly northwards with a related slope down in its upper surface, and the silt thickens northwards with a gentle rise in its upper surface. On the northeastern corner of the lake, both the sand (k_h 3-4 m/day) and silt bodies (k_h <2.5 m/day) plunge westwards below the lake.

These changes of depths and thickness can be interpreted to have resulted from both differential tectonic movement with greater subsidence below the eastern side of the lake, and resultant facies variations of the outfall of the Avoca fluvial system. The sand aquifer intercepted in CSIRO-TSMT is thickest and highest on the south-southwestern side of the lake.

This observed facies distribution is in accordance with east side down rotational movement of fault blocks if they coincide with boundaries of basement magnetic domains (Figure 6).

Potential and Actual Movement of Disposal Water

Information on the movement of disposal water into the surrounding and underlying groundwater systems has been obtained from hydraulic gradient, hydraulic conductivity and hydrochemical data by three methods:

(1) By calculating the theoretical maximum distances to which the disposal water could flow. This approach could only be applied to lateral movement because the information on vertical movement is inadequate. The theoretical maximum distance is here defined as the lateral distance at 67.9 mAHD between the edge of the disposal basin and the point in the surrounding area at which the freshwater head in the disposal basin is equal to the freshwater head in the surrounding groundwaters.

(2) By combining estimates of the hydraulic conductivity and the porosity with the magnitude of the lateral heads to calculate the distances to which the disposal waters should

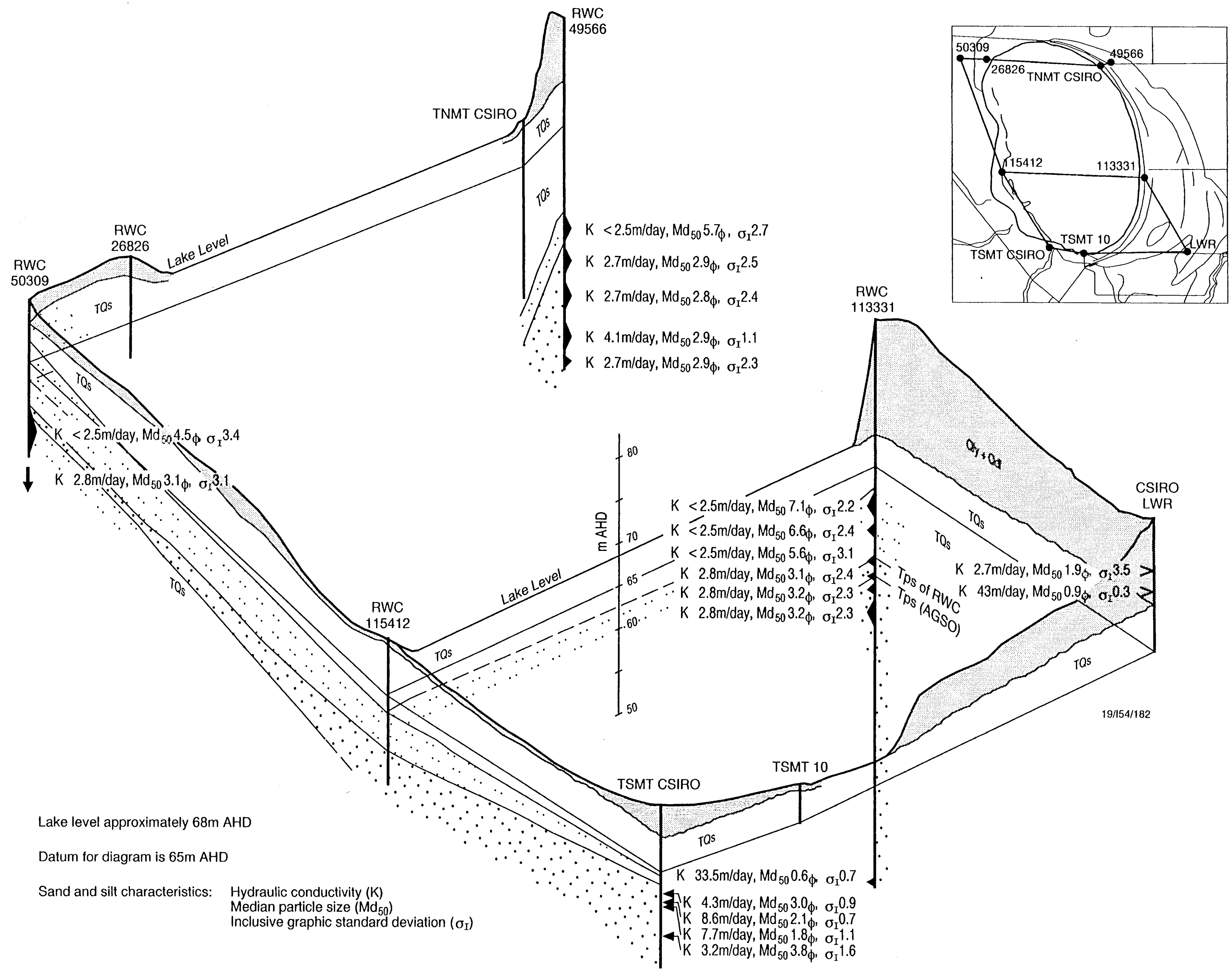


Figure 20. Lithofacies and permeability of the Shepparton Formation and upper Parilla Sand, Lake Tutchewop.

have moved in 25 years, which approximates the time the basin has been in operation. This approach is also limited to lateral movement because of inadequate data.

(3) By using hydrochemical indicators to determine the actual, present-day, distribution of disposal water in the groundwaters.

Hydraulic Gradients

The following information is based on three sets of piezometer measurements made between August and November 1994, when the disposal basin operating surface water levels were in the range 68.98 to 69.22 mAHD. This range is significantly lower than the mean water level of 69.71 mAHD at which the basin operated during the period July 1987 to April 1995 (Sinclair Knight Merz, pers. comm., 1996).

Vertical Gradients

Vertical hydraulic gradients were measured on piezometer nests sited on the eastern (TEMT; Figure 15b) and western (TWMT; Figure 15a) transects.

The piezometer nest on the lunette at the landward end of transect TEMT extends into the underlying Parilla Sand (Figure 21). At this location there is a strong upwards gradient from the Parilla Sand to the Shepparton Formation (e.g. 40×10^{-3} m/m; Table 1). Within the clays of the upper Shepparton Formation, at elevations between about 15 and 65 mAHD, gradients are much smaller and downwards (e.g. -3 to -4×10^{-3} m/m; Table 1).

Gradients within or between the Yamba and Shepparton Formations were measured at the other piezometer nests on the TEMT/TWMT transects. In these formations, a small downwards gradient (-5×10^{-3} m/m; Table 1) is evident near the irrigation channel/Avoca River floodway diversion in the lake marginal areas to the west. (Figure 15a; site TU-7; Figure 22). Elsewhere, gradients are within conservative estimates of the detection limit, but they are consistent with generally slightly downwards gradients in the shallow sediments. Exceptions occur on the western lake margin, where a strong upwards gradient (60×10^{-3} m/m; Table 1) occurs within an area of saline (110,000 mg/L) groundwater discharge. There may be an incipient spring zone in a similar position on the eastern margin, although the slightly upwards gradient is within the detection limit (site RWC, TEMT; Table 1).

Lateral Gradients

Lateral gradients between Lake Tutchewop and the adjacent marginal lake environments were measured in greatest detail along the eastern margin transect (TEMT),

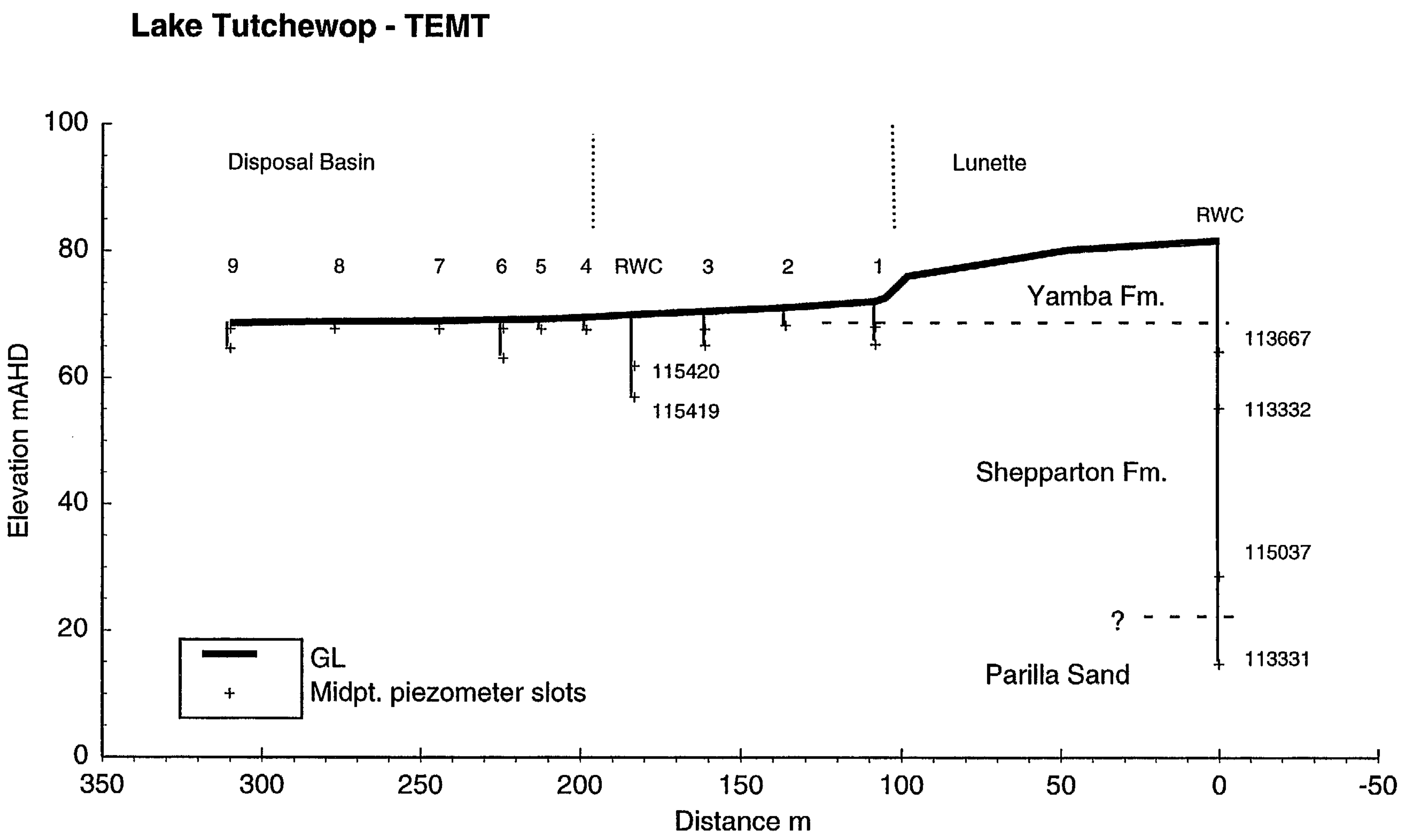


Figure 21. Lake Tutchewop eastern margin transect (TEMT); topography, drill-hole and piezometer sites.

Table 1. Vertical Hydraulic Gradients - Lake Tutchewop

	April	*August*	*October*	*Range*	*Average*	*Detection Limit*
TEMT						
	-3	n.d.	n.d.	---	-3	+/- 2
Lunette	-6	-4	-3	-3 to -6	-4	+/- 1
Parilla Sand	+40	+40	+40	---	+40	+/- 1
1	n.d.	-7	0	-7 to 0	-3.5	+/- 7
3	n.d	-8	-4	-4 to -8	- 6	+/- 8
RWC	n.d.	n.d	+1	---	+1	+/- 4
6	n.d.	-2	-2	---	-2	+/- 4
Disposal Basin BM	n.d.	-3	+3	-3 to +3	0	+/- 6
TWMT						
	-7	-5	-3	-3 to -7	-5	+/- 3
TU-7	-2	0	-3	-3 to 0	-2	+/- 4
TU 1/2	+ 70	+70	+40	+40 to +70	+60	+/-5
Disposal Basin - BM	n.d.	-10	+3	-10 To +3	-3	+/- 4

Piezometers are in Shepparton Fm. unless otherwise stated.
n.d. = not determined
Gradients are in (m/m)*10^3

Midpt. piezometer slots (schematic)

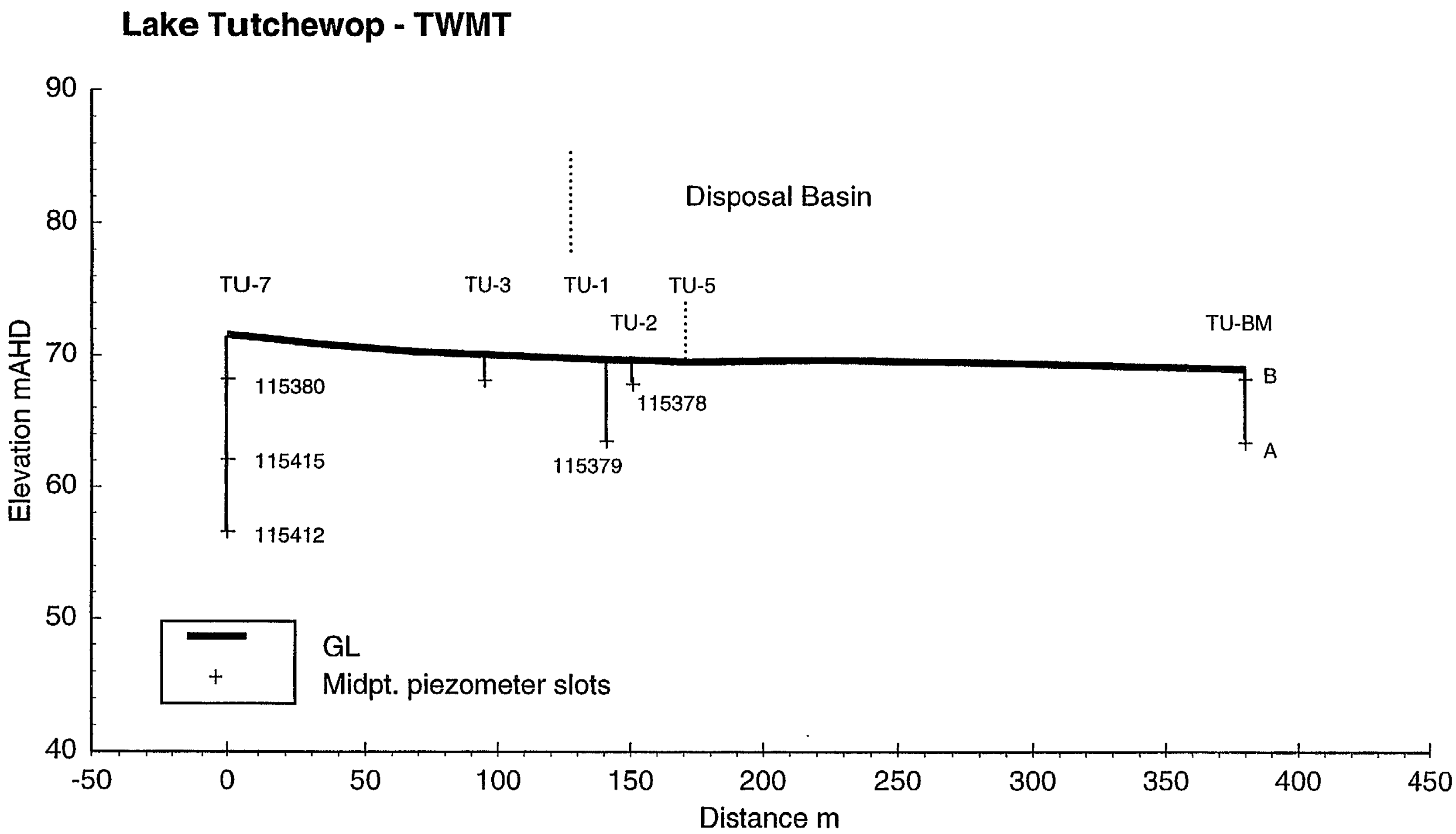


Figure 22. Lake Tutchewop western margin transect (TWMT); topography, drill-hole and piezometer sites.

and in some detail on the western margin (TWMT), and northern margin (TNMT; Figure 16a) transects. A two-piezometer system was used to give an indication of the gradient at the southern margin (TSMT; Figure 16b).

Selection of elevations for the calculation of lateral freshwater heads

All references to lateral heads are horizontal freshwater heads which were calculated (see Appendix I) from the equations of Lusczynski (1961) and Lusczynski & Swarenski (1966). Two constant elevations were chosen for Lake Tutchewop. Most calculations were for a 67.9 mAHD elevation which is within the clayey areas of Shepparton Formation as identified in this investigation. This corresponds to the "Upper" Shepparton Formation aquifer as defined by HydroTechnology (1994). Lateral heads at this elevation should mainly reflect a combination of natural and anthropogenic shallow-groundwater processes and spring activity, which could have deeper sources. Some lateral heads were calculated for an elevation of 64.1 mAHD, which is within or close to the Shepparton silt aquifer which underlies the clays. Heads at this lower elevation should be more strongly influenced by natural processes.

Eastern Margin Transect (TEMT)

The eastern transect at Lake Tutchewop extends from a usually submerged location within the basin across the part of the lake margin regularly flooded by disposal water, across the usually exposed lake margin environment, through the colluvium at the base of the lunette to the crest of the adjacent lunette (Figures 15b &21).

Lateral gradients (at 67.9 mAHD) are strongly lakewards from the lunette to the boundary of the lunette and the colluvial zone, and moderately lakewards across the colluvial zone and the exposed lake margin. The best-defined lateral head profile along the transect occurred at the lowest of the observed disposal basin operating levels (Figure 23). This profile has a pronounced "ledge" near the centre of the exposed lake margin. Together with the observation that the vertical head may be slightly upwards in this area (Table 1), this indicates incipient spring activity on the lake margin.

Lakewards of the spring-influenced zone, lateral heads in the regularly flooded and usually submerged areas are strongly dependent on the disposal basin operating level and the gradients may be landwards or lakewards (Figure 23). During low basin operating levels the lateral heads decrease sharply from the area of spring activity towards the regularly flooded area, reaching a minimum before increasing towards the usually submerged area. This minimum in the lateral heads is present in attenuated form at the intermediate disposal basin operating level but is not observed under the highest basin operating level (Figure 23).

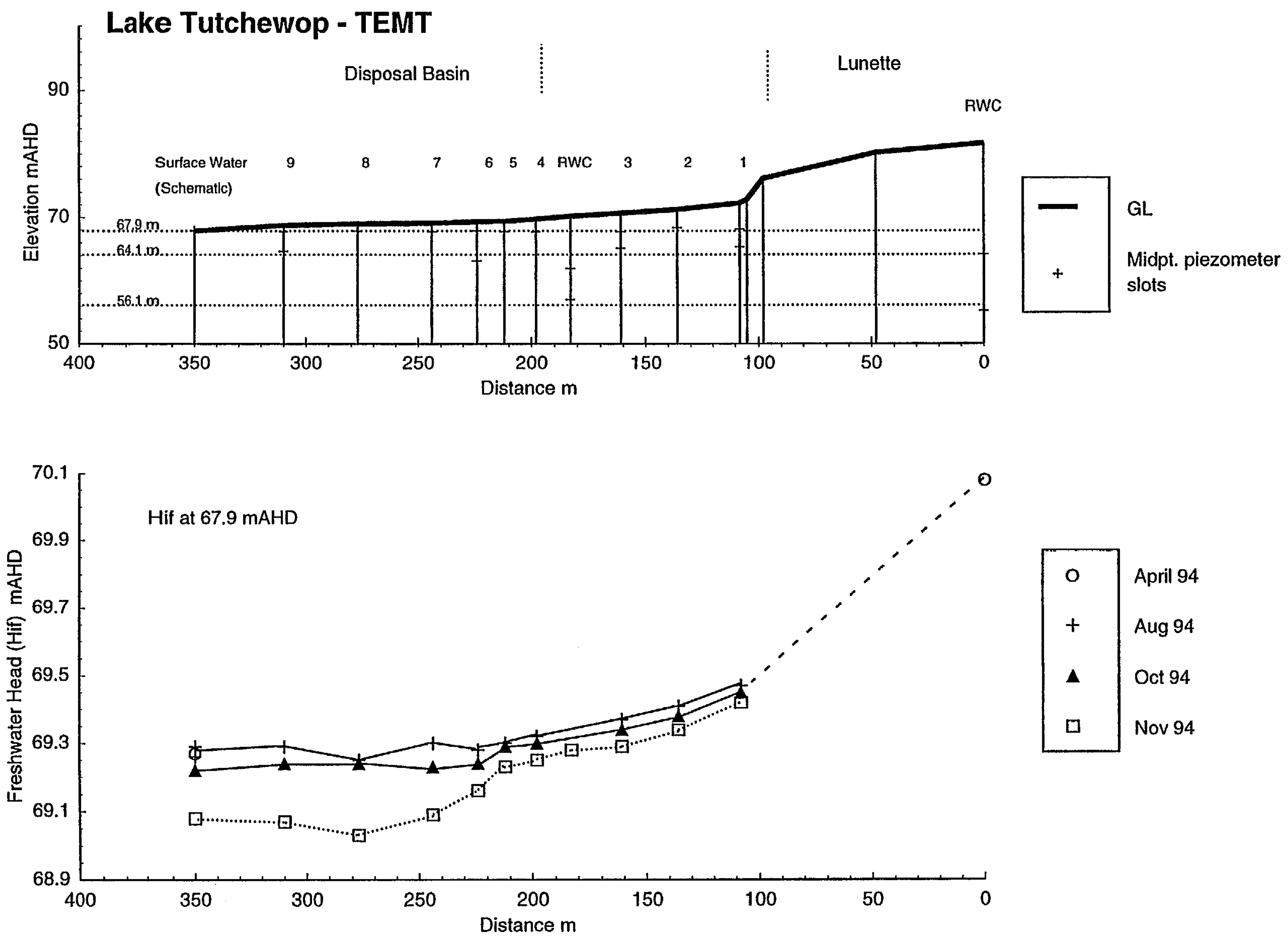


Figure 23. Lake Tutchewop eastern margin transect (TEMT); lateral (freshwater) heads at 67.9 mAHD.

Lateral heads deeper in the Shepparton Formation (at 64.1 mAHD) indicate an overall gradient from the lunette to the disposal basin. There is a "mound" in the profile in the exposed lake margin, which reinforces the other indications of an incipient spring zone in this area (Figure 24).

Western Margin Transect (TWMT)

The Lake Tutchewop western transect (Figures 15a & 22) extends from a submerged site (TWMT-BM) in the disposal basin to a site (TU-7) on the lake margin near the irrigation channel/Avoca River floodwater diversion. The lake margin is relatively wide and gently sloping in this area but, as described previously, there is an accumulation of low-relief sand shoals in this area which disrupts the topography of the regularly flooded areas of the lake margins and the nearby submerged areas.

The lateral heads at an elevation of 67.9 mAHD (Figure 25) at the landward end of the transect are strongly influenced by the adjacent irrigation channel/Avoca River diversion. During the measurement period these lateral heads were initially very high, but progressively decreased, presumably in response to decreases in the water levels in the irrigation channel/floodway. Even at the lowest lateral heads, the gradients were, overall, towards the disposal basin.

Highly saline groundwaters emerge as springs at the surface of the exposed lake margin. Consistent with this observation, the lateral heads at an elevation of 64.1 mAHD (Figure 25) indicate a groundwater "mound" and the vertical gradients are strongly upwards.

Northern Margin Transect (TNMT)

The Lake Tutchewop northern transect (Figure 16a) extends from the regularly flooded area of the lake margin across the northern fringe of the lunette and ends at a shallow piezometer (RWC 6683) located on irrigated areas of the floodplain about 1 km from the lake.

The lateral heads at an elevation of 67.9 mAHD (Figure 26) have a similar profile to that of the eastern transect in that the general gradient is towards the lake and, under some conditions, there is a minimum in the lateral heads in the regularly flooded area. The presence of this minimum is consistent with the observation by Dimos (1992) of a gradient landwards from the disposal basin to the HydroTechnology piezometer at the lake margin. The present work suggests that the landwards gradients associated with the regularly flooded areas are localised and transient.

Southern Margin Transect (TSMT)

The southern transect (Figure 16b) extends lakewards from the junction of the lake margin and formerly irrigated, now disused, flat areas of the adjacent floodplain. Under the

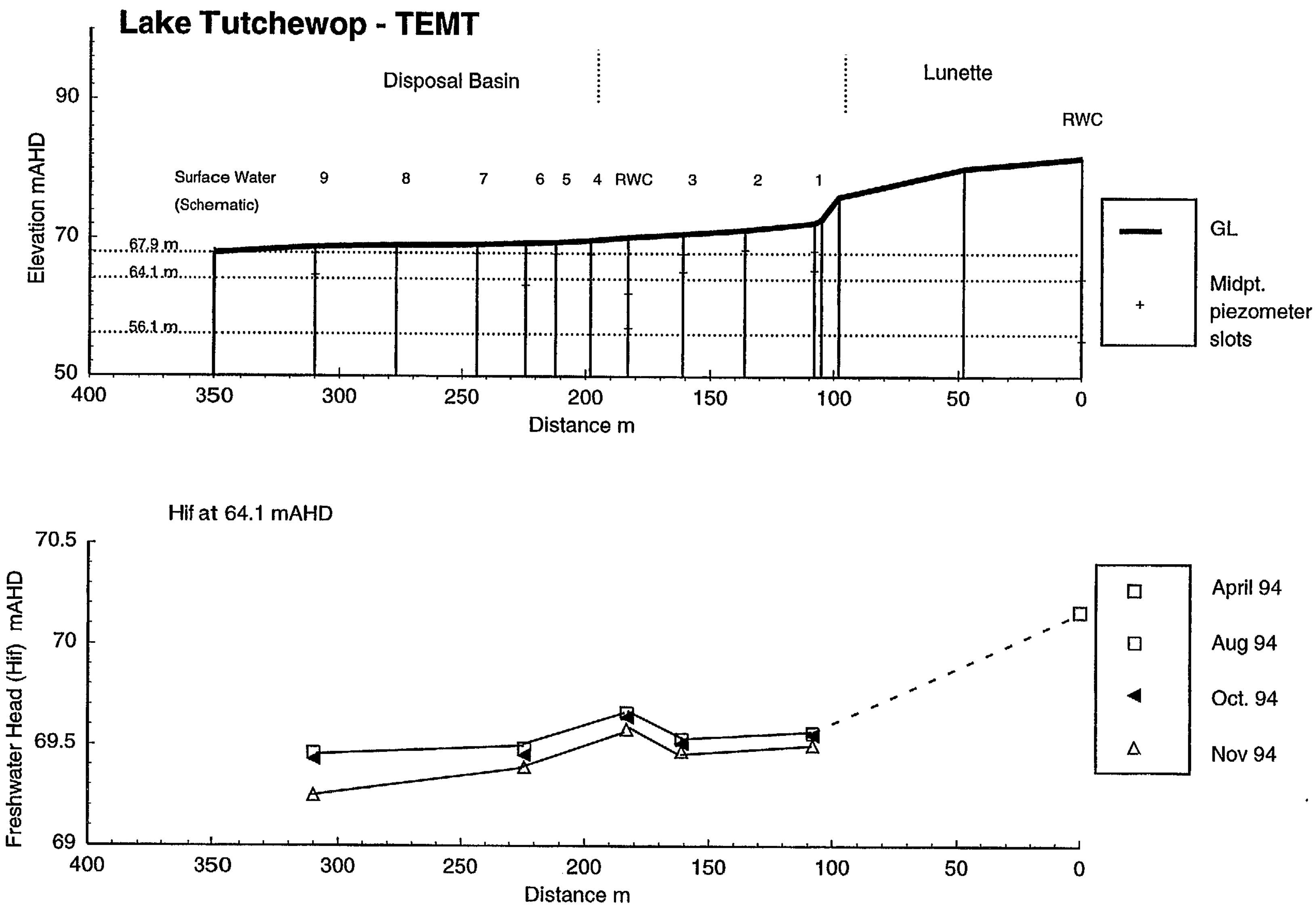


Figure 24. Lake Tutchewop eastern margin transect (TEMT); lateral (freshwater) heads at 64.1 mAHD.

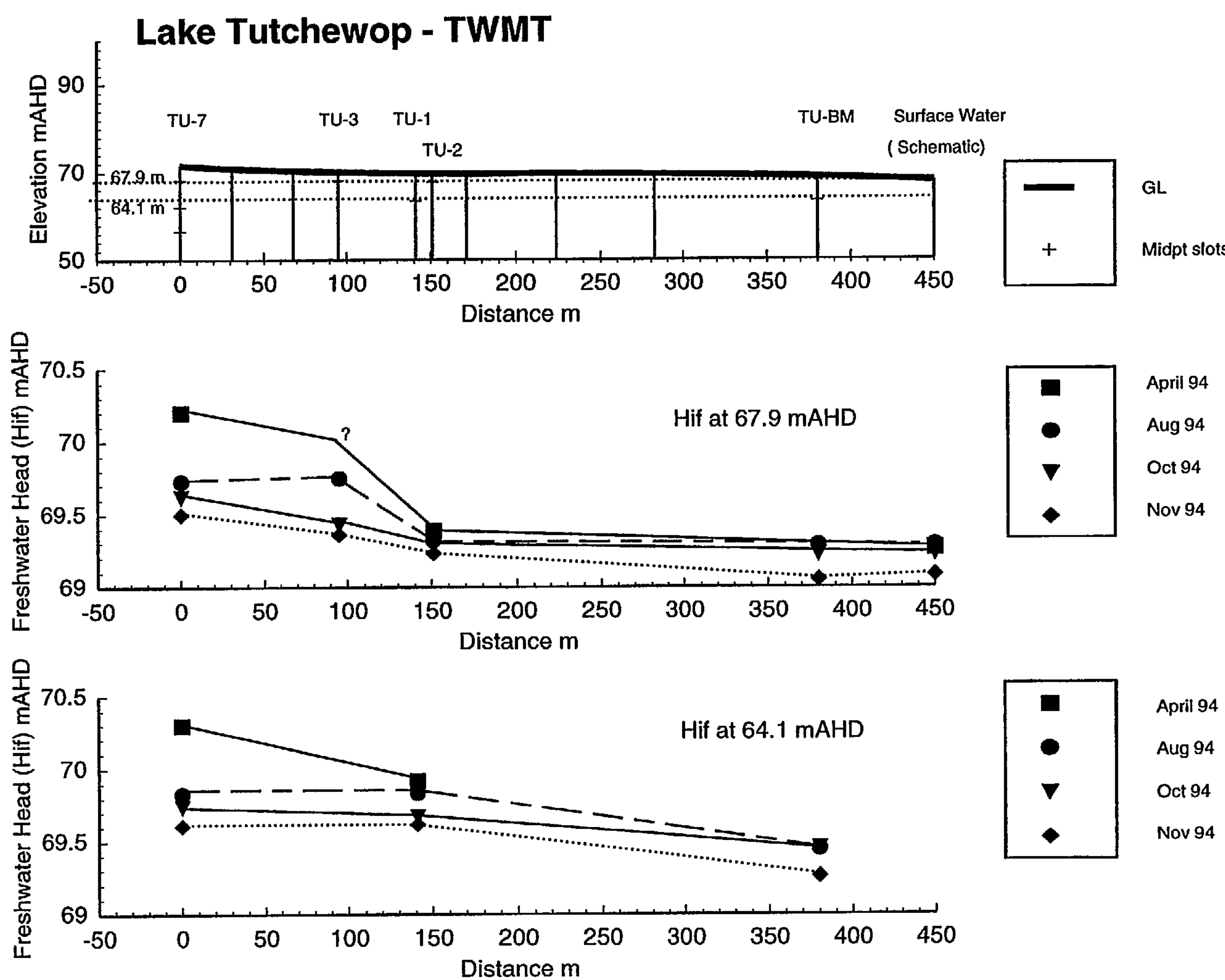


Figure 25. Lake Tutchewop western margin transect (TWMT); lateral (freshwater) heads at 67.9 mAHD and 64.1 mAHD.

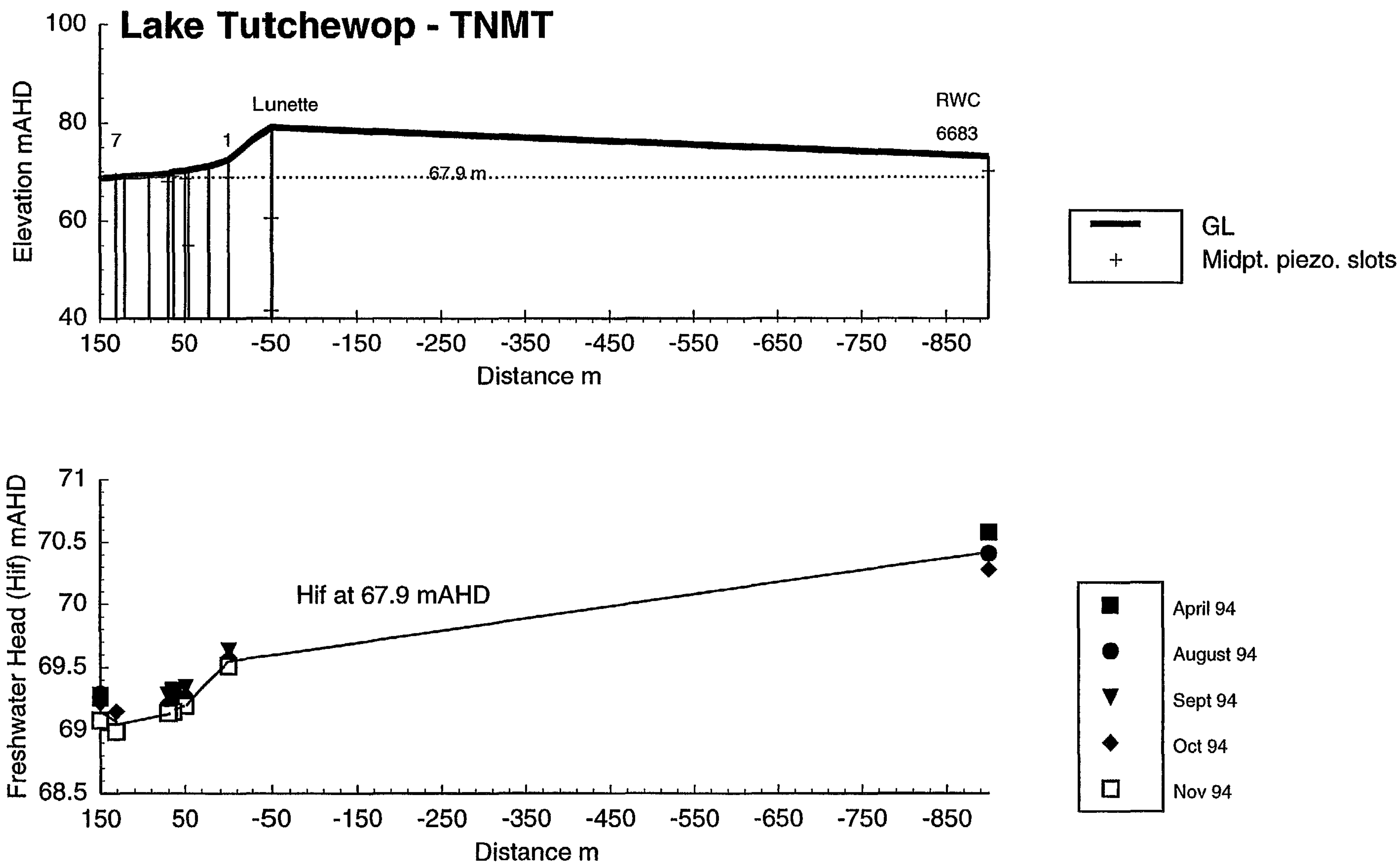


Figure 26. Lake Tutchewop northern margin transect (TNMT) and adjacent hinterland; lateral (freshwater) heads at 67.9 mAHD.

measurement conditions the hydraulic gradient at 67.9 mAHD slopes towards the disposal basin.

Potential Limits of Lateral Movement of Disposal Water

The theoretical maximum distances to which the disposal water could move laterally at an elevation 67.9 mAHD were calculated for two disposal basin operating levels. The two basin operating levels (recalculated to lateral heads) are:

(1) an assumed lateral head of 69.5 mAHD; and

(2) the actual average lateral head basin operating level of 69.9 mAHD which prevailed in the period January 1988 to April 1995 (calculated from data provided by Sinclair Knight Merz, 1996).

The lateral heads in the surrounding groundwater systems used for the calculation were obtained by averaging the available piezometer measurements (usually 3 in the period August to November, 1994; Table 2).

The theoretical distance that the disposal water could flow was obtained by interpolating between adjacent piezometers to find the distance at which the basin operating heads and the groundwater heads would be equal.

At a lateral head operating level of 69.5 mAHD (Table 2), the disposal water should be not move laterally beyond:

(1) the colluvial slope environments to the east and north

(2) the exposed lake margin environments to the west

(3) slightly landwards of the flood-plain/lake margin boundary to the south.

At the actual freshwater head operating level of 69.9 mAHD, the limit of lateral movement is:

(1) about 150 m to the east, which is within the lunette;

(2) about 400 m to the north-east, which it is in the floodplain;

(3) probably more than 120m to the west, depending strongly on the water levels in the irrigation channel/floodway systems;

(3) beyond 350m, which is clearly in the floodplain.

Rates of Lateral Movement of Disposal Water

The lateral groundwater gradients along the transects can be combined with estimates of the hydraulic conductivity and porosity to calculate the distances to which the disposal water should have flowed during the time the disposal basin has been in operation.

Table 2. Possible Extent of Lateral Flow from the Lake Tutchewop Disposal Basin into the Surrounding Groundwater System

Location		Freshwater Head at 67.9 mAHD *Range* (Time period,1994))	*Average* (No. of readings)	*Maximum Extent of Lateral Flow (m)*	*Maximum Extent of Lateral Flow (m)*
Disposal Basin Operating Level		(Jan 88 to April 95)	69.9 (weekly)	at 69.5 (assumed)	at 69.9 (actual)
TEMT	113667	(1 reading April)	70.08 (1)		
	1	69.42 to 69.47(Aug to Nov)	69.45 (3)	100 (base lunette)	150 (within lunette)
TWMT	TU-3	69.36 to 69.75 (Aug to Nov)	69.51 (3)		
	TU-7	69.5 to 69.73 (Aug to Nov)	69.62 (3)	70 (centre lake margin)	> 120 (hinterland)
TNMT	S1	69.51 to 69.63 (Sept-Nov)	69.57(3)		
		70.28-70.41 (Aug-Oct)	70.34(2)	90 (base lunette)	400 (hinterland)
TSMT	S10	69.06 to 69.26(Aug-Nov)	69.18 (3)		
	S1	69.44 to 69.59 (Aug-Nov)	69.52 (3)	350 (hinterland near margin)	> 350 (hinterland)

For this calculation, the time of operation has been taken as 25 years, and the lateral hydraulic conductivity as 0.01 m/day. The hydraulic conductivity figure is the middle of the range of 0.001 to 0.01 m/day proposed by HydroTechnology (1994) as representative of the upper 5 m of silts and clays of the Shepparton Formation.

The magnitude of the lateral gradient will vary with the distance from the disposal basin. It will be at its maximum between the disposal basin and the minimum in the lateral heads in the regularly-flooded area and, from there, decrease away from the lake. For these 'first order calculations" no attempt has been made to calculate a weighted average lateral head from the disposal basin to a point in the surrounding groundwater system. The gradient has been taken simply as the difference between the long-term disposal basin lateral head of 69.9 mAHD and the average of the three lateral head measurements at the chosen location in the surrounding groundwater system.

In the worst scenario, the rate would be greatest in the hypothetical and temporary disequilibrium situation of maximum disposal-basin level and minimum head in the regularly-flooded area. Under such conditions, the flow rate from the disposal basin into the regularly-flooded margin would be about 3m/25 years [assuming the gradient operates over a distance of 25 m then, (69.9-69.0)/25 x 0.01 = 0.00036 m/day]. The distance the water would flow in this time can be estimated by dividing this Darcy velocity by the porosity (taken as 0.05), to give a distance of 60 m.

A more realistic scenario involves the rate of flow from the disposal basin to a point about 100m beyond the margin of the lake and disposal basin. Under these conditions, and using values for hydraulic conductivity intermediate between silt and clay, the Darcy velocity would be about 0.5 m/25 years [(69.9-69.3)/100 x 0.01 = 0.00006 m/day]. The distance travelled would be about 10 m. Considering the sediment variability between silt and clay in the upper 5m of Shepparton Formation, with lateral hydraulic conductivities of 0.1 and 0.001 m/day respectively (based on slug tests by HydroTechnology, 1994), and assuming respective effective porosities of 0.3 and 0.02, then the distance invaded would range from about 20 m in silt down to 2 m in silt.

Hydrochemical Identification of Disposal Waters

Three chemical indicators were tested for detecting disposal water in the groundwater regime below and surrounding Lake Tutchewop. These utilised differences in (1) salinity; (2) ratios of the major ions to Br and to Mg; and (3) D/H ratios of the waters.

Chemical signatures for the disposal water were determined from a series of measurements on samples of surface water in Lake Tutchewop collected by

HydroTechnology mainly during the period October 1993 to August 1994. The chemical signatures of groundwaters were obtained from measurements on porewaters (major-ion ratios) or wet sediment (D/H ratios) from drillcores.

Salinity

Surface Water

During the period October 1993 to August 1994 the salinity of Lake Tutchewop ranged from about 71,000 to 118,000 mg/L (neglecting two anomalous samples of < 35,000 mg/L). A graph of salinity against time for this period (Figure 27) has two parts: (1) the period between October 1993 and January/February 1994 when the salinity was almost constant at about 75,000 mg/L; and (2) the period after January/February 1994 when the salinity fluctuated in the 90,000 to 115,000 mg/L range. Presumably, the period of low, almost constant, salinity reflects high basin operating levels and low evaporation, and the period of high salinity reflects the obverse conditions.

Fluctuations of salinity in the disposal basin result from both operational variations and seasonal evaporation, and are superimposed on a progressive increase in salinity throughout its operational life. Although individual measurements have limited value, data supplied by HydroTechnology indicate a gradual increase in salinity from about 20,000 mg/L (1 sample) in 1973, through 40,000 mg/L (5) in 1984, to the 1994 salinity of about 75,000 mg/L. If the average basin operating levels have not increased significantly in this time, then the salinity increase alone will have created a gradual increase in the lateral and vertical heads in the disposal basin with time.

Groundwater

Groundwater salinities around and beneath Lake Tutchewop are presented as salinity versus depth graphs for individual sites (e.g. Figures 28, 29 & 30) and as iso-salinity contours plotted in cross-section for the eastern margin transect (Figure 31).

The latter (Figure 31) shows that the lowest salinity waters (e.g. 40,000 mg/L) underlie the colluvial area at the base of the lunette. Lakewards of this area, most groundwater salinities lie in the range 60,000 to 100,000 mg/L There is an area of slightly elevated salinity immediately lakewards of the area of incipient spring activity (as indicated by the hydraulic heads).

Salinity-depth profiles for individual sites on the eastern margin show narrow bands of relatively low-salinity (e.g. TEMT-1, Figure 28) or high-salinity (e.g. TEMT-9, Figure 29) water at the top of the profile. Site TEMT-1, which is in the colluvial zone of the lake margin, contains low salinity waters in the upper part of the vadose zone. This is

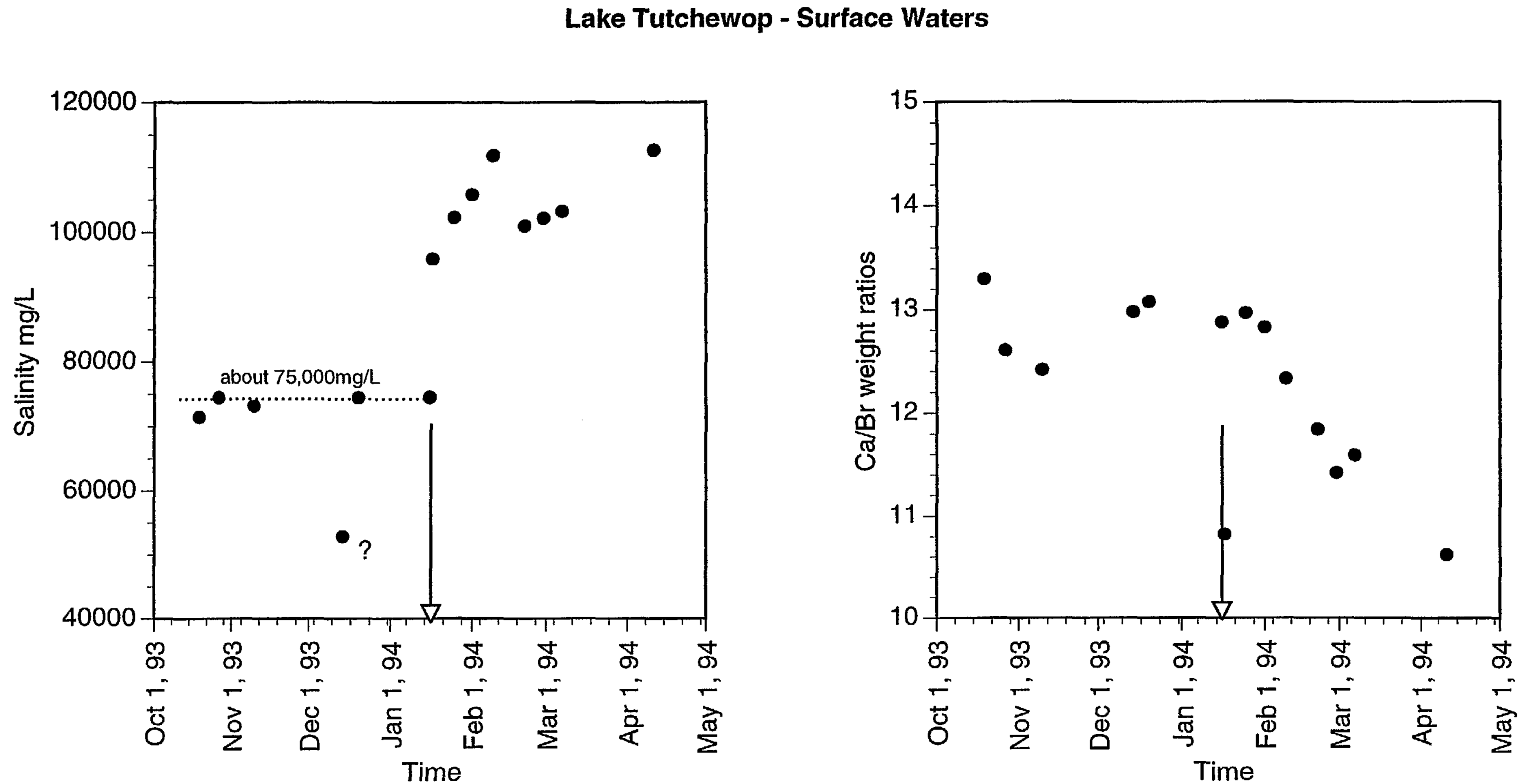


Figure 27. Salinity and Ca/Br ratios of Lake Tutchewop surface waters; October 1993 to May 1994.

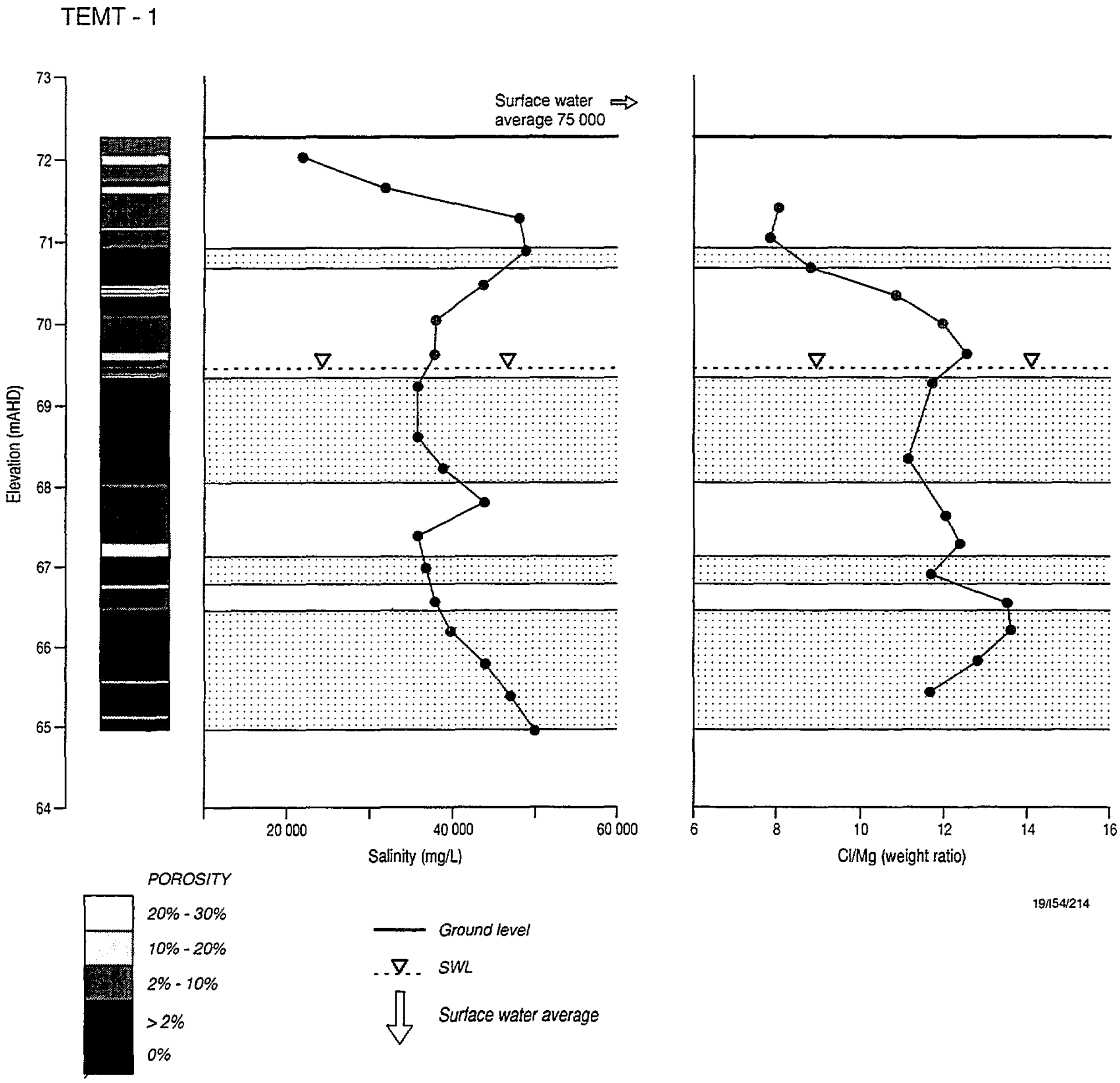


Figure 28. Relationships of sediment porosity to groundwater salinity and Cl/Mg ratios at a colluvial site on the Lake Tutchewop eastern margin.

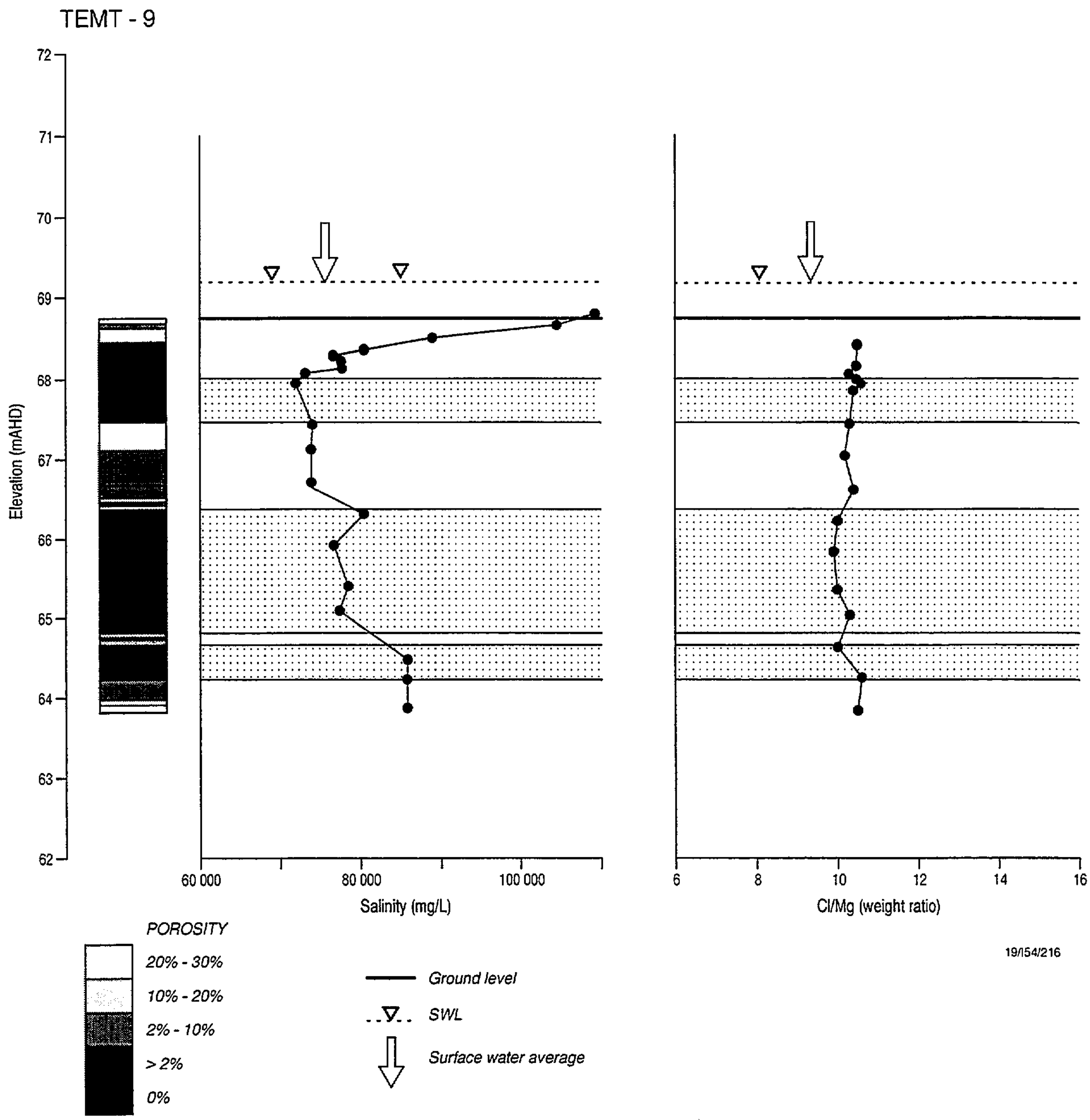


Figure 29. Relationships of sediment porosity to groundwater salinity and Cl/Mg ratios at a submerged site near the Lake Tutchewop eastern margin.

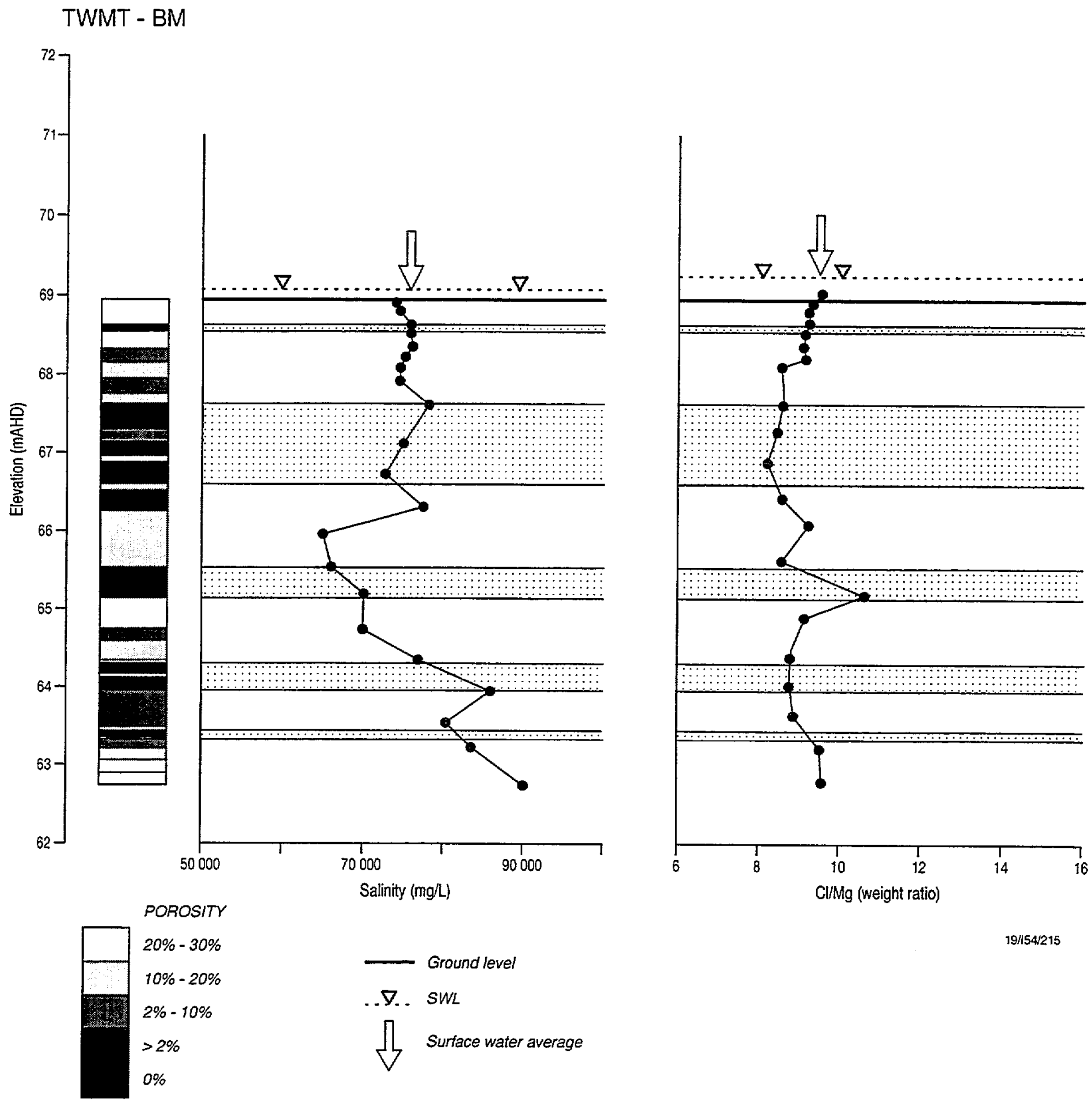


Figure 30. Relationships of sediment porosity to groundwater salinity and Cl/Mg ratios at a submerged site near the Lake Tutchewop western margin.

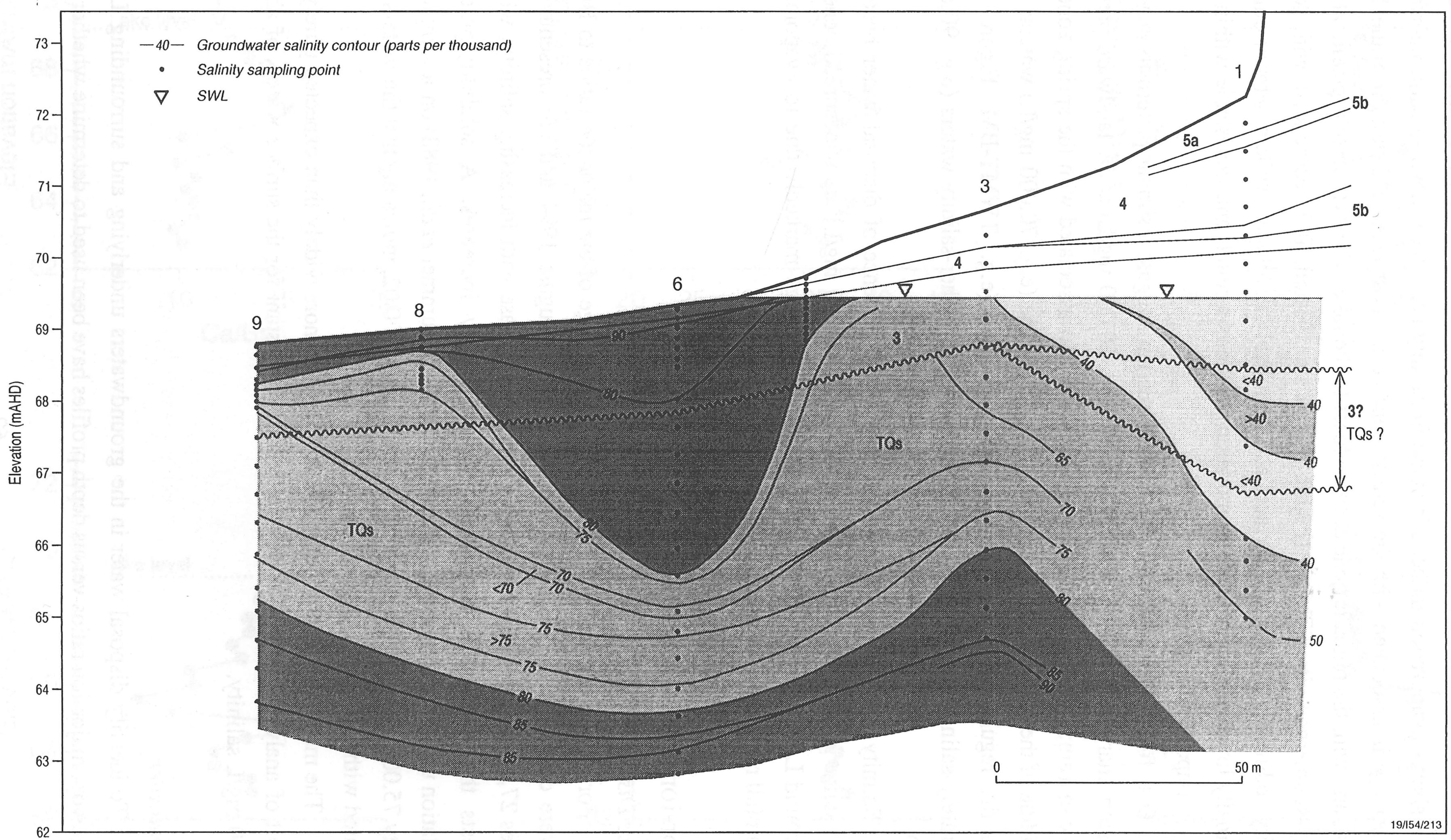


Figure 31. Iso-salinity contours, Lake Tutchewop eastern margin transect (TEMT).

consistent with a situation where recharge exceeds evaporation. Sites further lakewards show a sharp, evaporation-induced increase in salinity near the vadose/phreatic interface. This increase is associated with the vadose zone at the most landward sites from the lake margin, and with the phreatic zone at sites closer to the lake. The evaporation profile at the usually-submerged site TEMT-9 (Figure 29) is unexpected. It is associated with low-porosity sediments close to the surface, and it probably developed while emergent during abnormally low basin levels. This evaporation profile is a relict, and metastable within the relatively impermeable clays.

Data for individual sites on the western margin suggest a similar pattern to that for the eastern margin: that is, (1) lower salinities (e.g. 50,000 mg/L) at the landward part of the lake margin; (2) high salinities (e.g. 120,000 mg/L) associated with the spring zone in the middle of the lake margin overlying moderately-saline (e.g. 70,000 mg/L) waters; and (3) in the regularly flooded/usually submerged areas (e.g. TWMT-BM, Figure 30) moderately-saline waters (e.g. 65,000 mg/L) overlying higher-salinity waters (e.g. 90,000 mg/L).

Salinity cannot be used as an indicator of the presence of disposal water because natural saline groundwaters (in the range 60,000 to 90,000 mg/L) are widespread beneath and around Lake Tutchewop, and their salinity may change markedly due to evaporative and rainfall recharge overprints.

Major-Ion ratios to Br or Mg

Surface Disposal Water

For surface disposal water , the range and average of the major-ion ratios to Br or Mg were calculated for the period October 1993 to August 1994 and are presented in Figures 27, 32 & 33. Ratios involving Ca tend to decrease with increasing salinity, which suggests that gypsum is precipitating as the salinity increases. A solubility-product calculation using the computer program PHRQPITZ (Plummer *et al.*, 1988) on a sample of salinity 75,000 mg/L gave a gypsum saturation index of 0.02, indicating that the waters are saturated with respect to gypsum.

The major-ion ratios (Figures 32 & 33) range more widely than expected purely as a result of analytical error, but they are relatively constant for the surface waters of about 75,000 mg/L salinity.

Groundwater

To identify disposal water in the groundwaters underlying and surrounding Lake Tutchewop, major-ion ratios versus depth profiles have been used to determine whether the

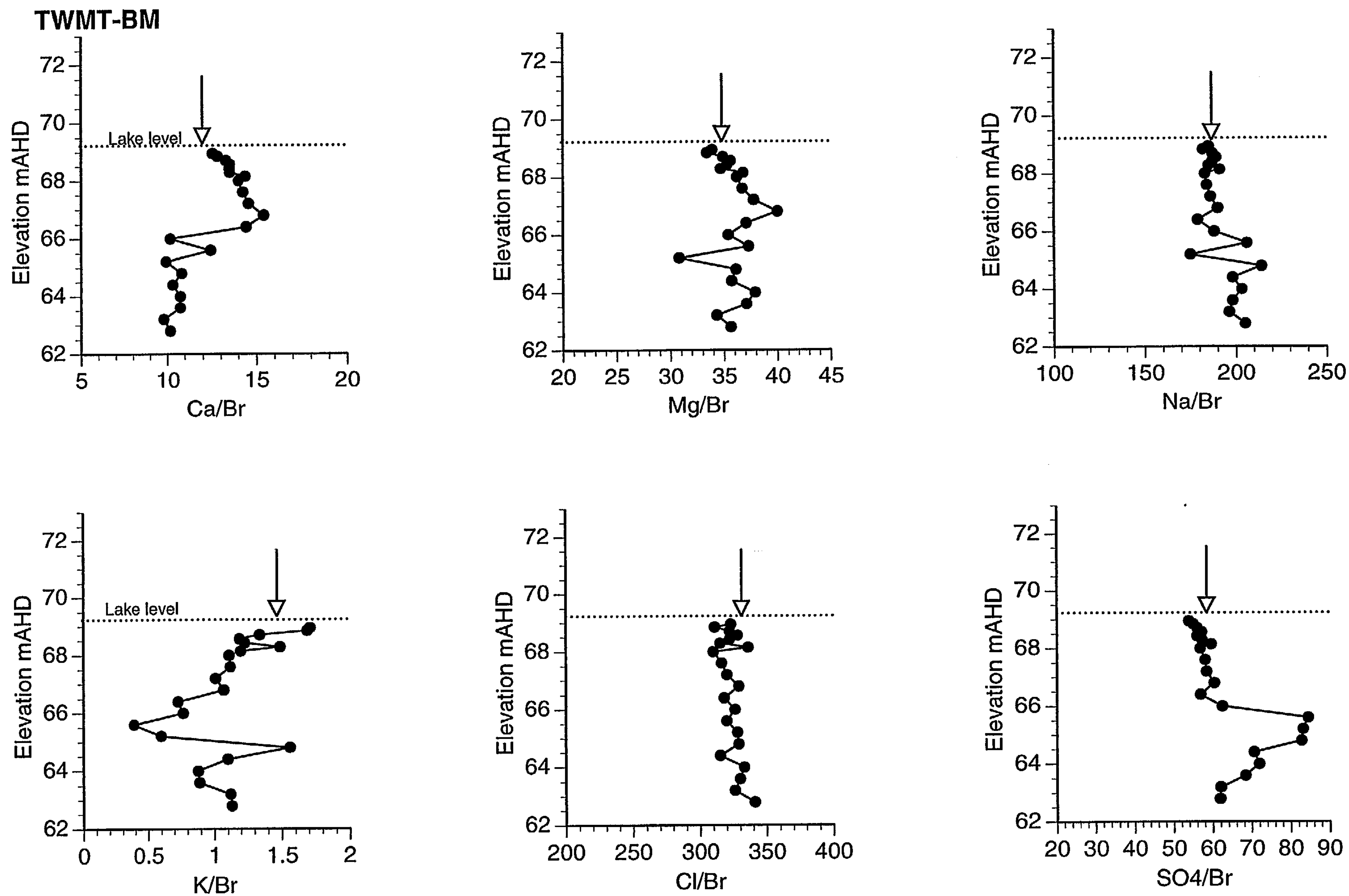


Figure 32. Lake Tutchewop western margin transect, site BM (TWMT-BM). Groundwater and surface water major-ion ratios to Br. (Shaded area is the surface water range and the arrow the average).

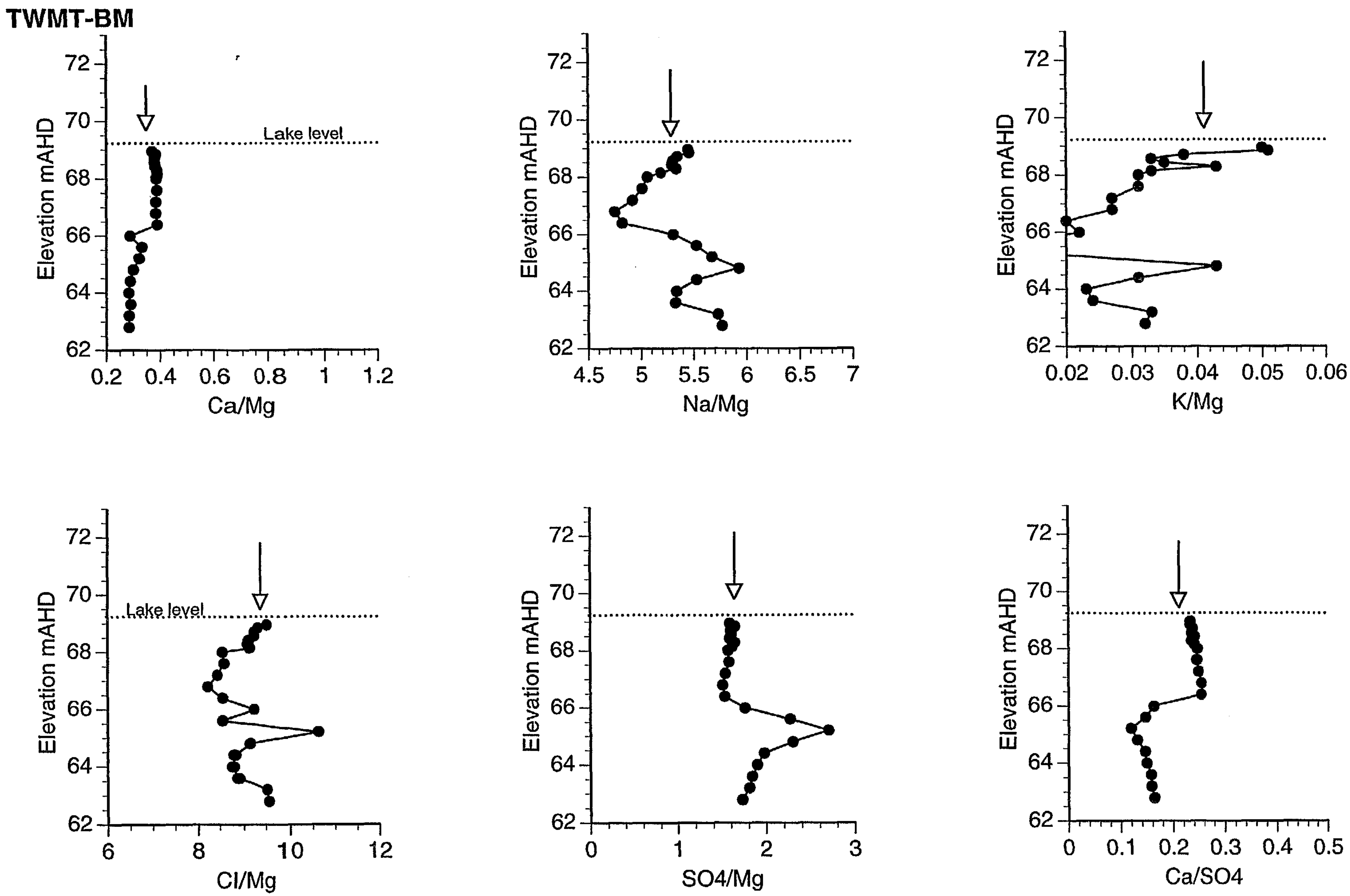


Figure 33. Lake Tutchewop western margin transect, site BM (TWMT-BM). Groundwater and surface water major-ion ratios to Mg. (Shaded area is the surface water range and the arrow the average).

groundwater composition approaches that of the surface disposal waters with decreasing depth. The clearest example of a profile where this condition is fulfilled is that for the submerged site TWMT-BM (Figures 32 & 33). Here the major-ion ratios to Br or Mg show: (1) definite trends towards the average surface-water values for most ratios; and (2) no definite trends away from the average surface-water values for the other ratios. The trends point closely towards the average values measured for the surface waters, and support the view that the average surface-water values are the most pertinent indicators of the presence of disposal water in the groundwater. The ratios shown in Figures 32 and 33 indicate that, as a first approximation, the proportion of disposal water in the natural groundwater system at this site decreases steadily with depth and is not detectable below an elevation of about 67.0 mAHD, which is about 2.2 m below the sediment surface.

The effectiveness of the major-ion ratios of the groundwaters as a semi-quantitative indicator of the presence of disposal water in the sediments varies from site to site depending on: (1) the magnitude of the difference between the major-ion ratios of the local groundwater and that of the disposal water; and (2) the extent of evaporation and precipitation/re-solution of gypsum and other evaporite minerals in marginal areas, particularly in the vadose zone. To minimise the effects of the latter processes, data from the vadose zone, and major-ion ratios involving Ca and/or SO_4, have not been used as disposal water indicators. The remaining data has been semi-quantitatively assessed for the presence of disposal water by determining whether the trend in each ion ratio with decreasing depth is: (a) towards the average surface disposal water ratio (Yes = 2); (b) away from the disposal water ratio (No = 0); or (c) ambiguous (Maybe = 1). A percentile score for the probable presence of disposal water at each site is presented in Table 3. Disposal water is positively identified at two locations on the western margin. At TWMT-BM, disposal water may be present at depths between 0.8 to 2.2m (68.0 and 67.4 mAHD) and is positively identified above 0.8 depth (68.4 mAHD). At TWMT-TU5, disposal water is identified in the top 0.2 m of sediments. Disposal water is unlikely to be present at the 5 other sites selected for investigation (Table 3).

Deuterium

D/H ratios are potentially a good indicator of the presence of disposal waters because evaporation from surface water can lead to much higher δD values than those which result from capillary-zone evaporation of groundwater.

Table 3. Probability that disposal water is present in groundwaters beneath and around Lake Tutchewop

Based on major-ion ratios to Br and Mg

	Depth[1]	Ratios/Mg			Ratios/Br			Total % Favourable Indicators	Disposal Water Present?
		Yes	Maybe	No	Yes	Maybe	No	Y=2;M=1;N=0	
TEMT-S1		2	0	4	1	1	4	30	No
TEMT	to 0.4m	2	1	3	3	0	3	45	No
S3	>0.4m	4	0	2	3	0	3		
TEMT-	to 0.4	1	1	4	3	1	2	40	No
S9	>0.4	3	3	0	2	0	4	55	Unlikely
TWMT-	to 0.4m	2	1	3	4	0	2	55	Unlikely
TU3	>0.4m	1	0	5	1	0	5	15	No
TWMT-TU1		1	0	5	1	0	5	15	No
TWMT-	to 0.2m	4	2	0	6	0	0	90	Yes
TU5		1	1	4	1	0	5	20	No
TWMT-	to 0.8m	5	1	0	4	2	0	90	Yes
BM	0.8 to 1.2m	4	2	0	3	2	1	75	Maybe
TNMT-	to 0.5m	4	2	0	2	1	3	65	Unlikely
TNM	> 0.5m	2	2	2	3	0	3	40	No
TNMT-	to 0.4m	3	0	3	1	2	3	40	No
4	>0.4m	2	0	4	0	0	6	15	No
TSMT-	to 0.4	3	1	2	1	1	4	40	No
TSM	> 0.4	1	0	5	1	1	4	20	No
TSMT-	to 0.4	2	3	1	4	1	1	65	Unlikely
10	> 0.4	1	0	5	3	1	2	30	No

[1] Depth below sediment surface (submerged sites); or depth below the water table (other sites).

Surface Disposal Water

δD values of surface waters in Lake Tutchewop are about 20‰ at salinities near 75,000 mg/L, and about 30‰ at salinities near 115,000 mg/L.

Groundwater

Groundwaters from 18 piezometers located close to or in the disposal basin, have δD values between -5 and -30‰, with all but two values being in the range -15 to -30‰. This distinct difference between the groundwaters and surface waters indicates that the δD values should be a much more sensitive indicator of disposal water than the major-ion ratios.

Detailed δD versus depth profiles for site TWMT-BM are compared to salinity versus depth and Mg/Br versus depth profiles in Figure 34. The δD data demarcates the zone above 67.0 mAHD, for which major-ion ratios indicate the presence of disposal water, as a zone of high but widely and erratically fluctuating δD values. Below this zone, δD decreases sharply with depth. Within the zone above 67.0 mAHD a plot of δD versus salinity is approximately linear (Figure 34) but a plot of δD versus Mg/Br shows two mixing lines and some intermediate samples. i.e., the greater resolution afforded by the combination of the δD and Mg/Br data indicate that the sediments above 67.0 mAHD contain mixtures of a natural groundwater (δD, +2; Mg/Br; 32) with disposal water (δD, +30; Mg/Br, 36) and/or another natural groundwater (δD,+10; Mg/Br, 38).

Discussion

The Lake Tutchewop groundwaters monitored in this investigation are associated with two main sedimentary units: (1) the thin lacustrine and thick aeolian deposits of the Yamba Formation; and (2) the clay-dominated sediments of the upper Shepparton Formation.

In these shallow, relatively impermeable sequences, the strong upward gradients from the underlying Parilla Sand have little effect except as a possible driving force for localised spring activity. Consequently, groundwater processes in the Yamba Fm./upper Shepparton sediments around Lake Tutchewop reflect a combination of: (1) the underlying regional, predominantly natural, groundwater regime in the Shepparton Formation; and (2) an overlying shallow groundwater hydrodynamic regime involving: (i) natural areas of high

TWMT-BM

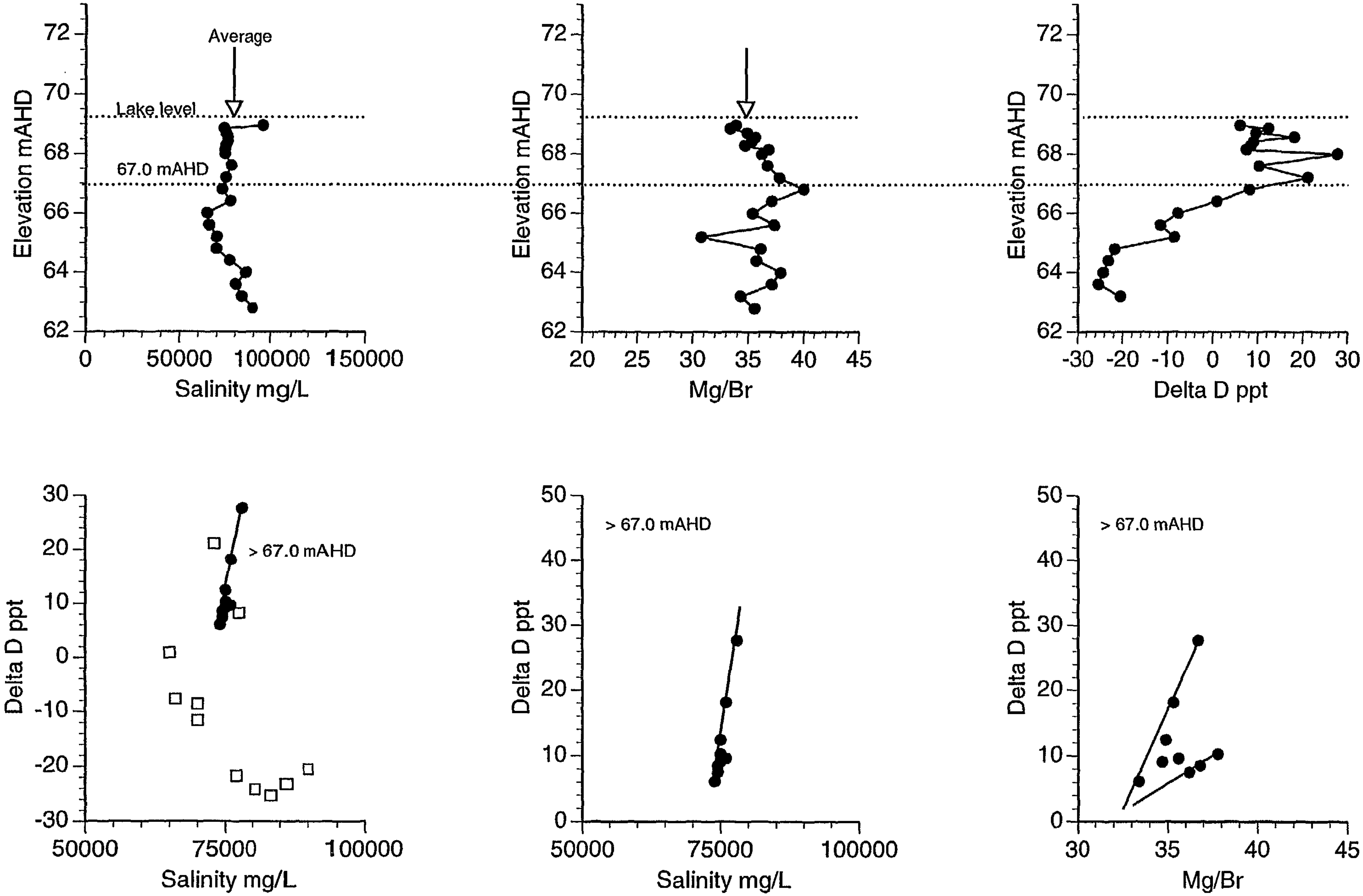


Figure 34. Lake Tutchewop western margin transect, site BM (TWMT-BM). Relationships of deuterium content of groundwater to depth, salinity and Mg/Br ratios.

recharge associated with the colluvial deposits at the base of the lunette; (ii) anthropogenically-induced artificial recharge associated with surrounding irrigation and associated engineered channels and floodplains; and (iii) possible recharge by the surface disposal waters. This investigation of Lake Tutchewop shows that there is clearly identifiable change in hydrodynamics with depth due, in part, to the generally low hydraulic conductivity of the sediments. The shallow groundwater systems are dominated by the natural and anthropogenic recharge processes, but there is minor spring activity which is probably induced by both regional and local factors. The deeper groundwaters show a greater influence of natural, longer-range processes.

Prior to its use as a disposal basin, the salinity of Lake Tutchewop probably varied in response to the relative inputs of surface water from the Avoca River (Taylor, Appendix II) and discharge of saline groundwaters from springs on the eastern and western margins. In general, the higher heads associated with the present-day anthropogenic conditions have probably inhibited groundwater spring discharge. However on the western margin, high surface-water levels in the Avoca River diversion floodplain and irrigation channel could increase the flow of the springs on the lake margin (Figure 35).

The shallow groundwater systems around the Lake Tutchewop disposal basin all show overall lateral hydraulic gradients from the hinterland to the disposal basin. The magnitude of the lateral gradients is strongly dependent on local conditions around the basin margins. The natural recharge systems associated with the lunette and its colluvium provide the most effective barrier to lateral movement of disposal water into the surrounding areas. Irrigation of floodplain areas to the northeast also helps support a basinwards gradient, as does the engineered floodplain/irrigation channels to the west. The most vulnerable area is to the southeast, where irrigation near the lake has been abandoned and, presumably, groundwater levels in the hinterland have decreased.

In the regularly inundated areas of the lake margins, interaction of the disposal basin waters with the surrounding groundwaters follows a cyclical pattern in the lateral heads as the disposal basin water levels rise and fall in response to fluctuations in input and evaporation. A feature of this pattern is the presence of a minimum in the lateral heads during parts of the cycle. Minima of this type have been observed in other disposal basins (e.g. Mourquong) and in natural salinas (e.g. a marine-continental sabkha at Shark Bay; J. Ferguson and L.A. Chambers, unpublished results). They appear be a normal feature of groundwater discharge areas in which the heads are determined mainly by infiltrating rainfall/runoff at the margins and/or fluctuating surface-water levels in the topographically lower areas. Presumably, the profiles observed at Lake Tutchewop are intermediate between the first two of three conditions (Figure 36): (1) those at very low basin operating

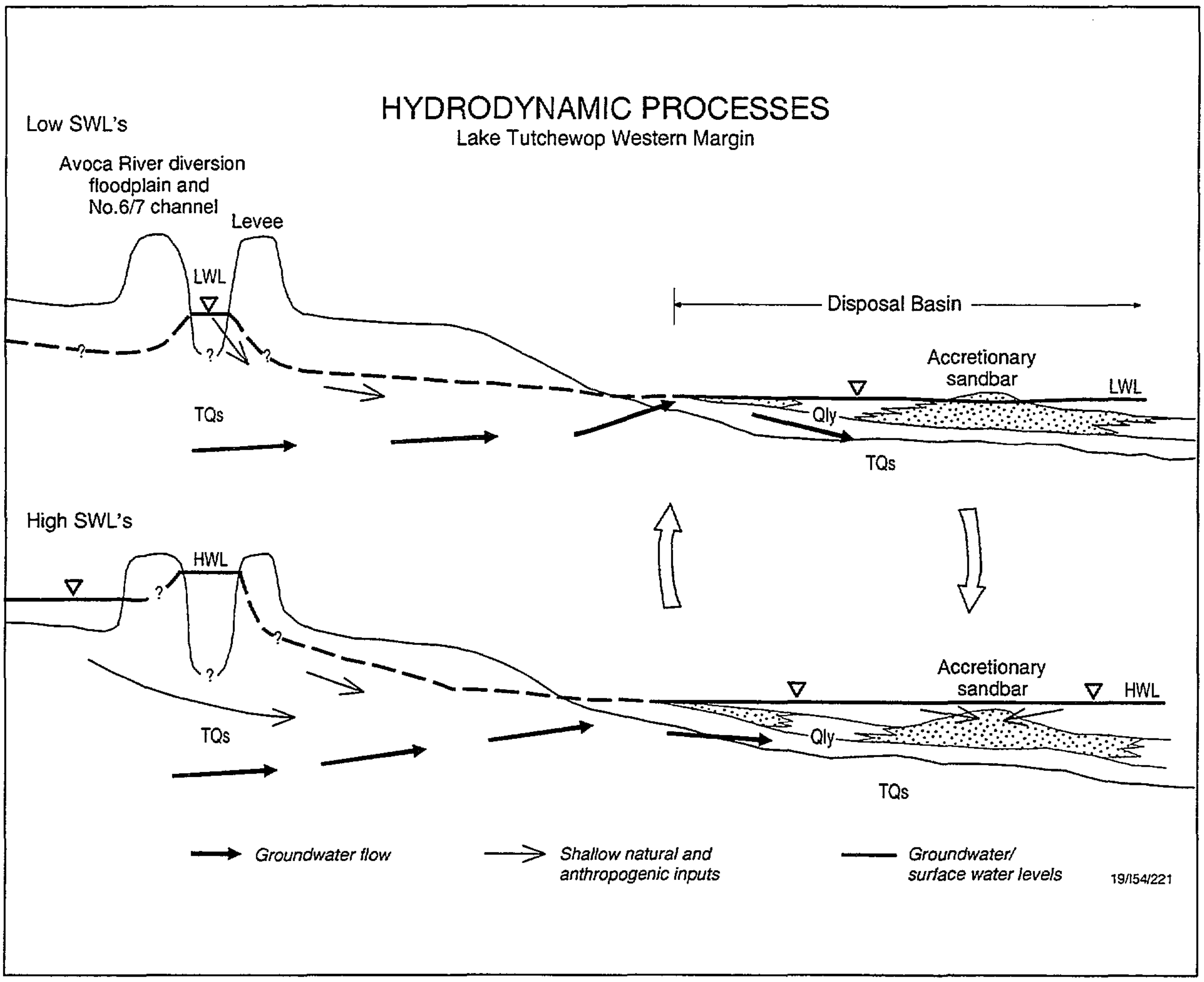


Figure 35. Hydrodynamic processes at the Lake Tutchewop western margin.

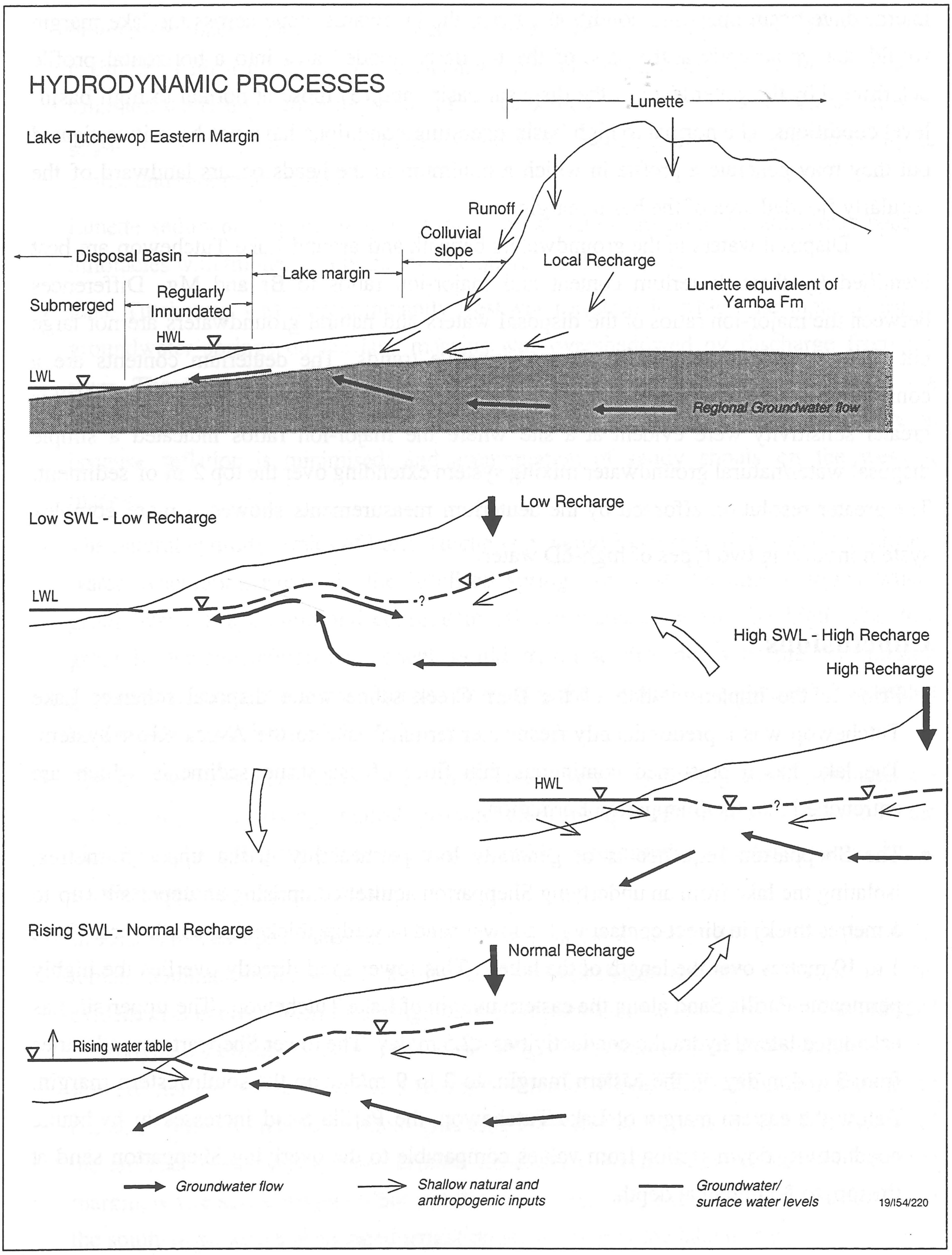


Figure 36. Hydrodynamic cycle in the regularly flooded marginal areas of the Lake Tutchewop disposal basin.

levels, when the lateral heads would show a distinct slope lakewards across the margins and more moderate slope from there towards the remaining inundated area; (2) those at intermediate basin operating conditions, when the lakewards slope across the lake margin would change abruptly at the edge of the regularly flooded area into a horizontal profile determined by the water level in the disposal basin; and (3) those at normal to high basin-level conditions. The normal to high basin-operating conditions have not been investigated but they may generate a profile in which a minimum in the heads occurs landward of the regularly flooded area of the basin margin.

Disposal waters in the groundwaters beneath and around Lake Tutchewop are best identified by their deuterium content and major-ion ratios to Br and Mg. Differences between the major-ion ratios of the disposal waters and natural groundwaters are not large but changes with depth usually show distinctive trends. The deuterium contents are a considerably more sensitive indicator of the presence of disposal water. The results of this greater sensitivity were evident at a site where the major-ion ratios indicated a simple disposal water/natural groundwater mixing system extending over the top 2 m of sediment. The greater resolution afforded by the deuterium measurements showed a more complex system involving two types of high-δD water.

Conclusions

- Prior to the implementation of the Barr Creek saline water disposal scheme, Lake Tutchewop was a predominantly freshwater terminal lake to the Avoca River system. The lake has a presumed continuous thin floor of lacustrine sediments which are entrenched into the Shepparton Formation.
- The Shepparton sequence is of generally low permeability in the upper 5 metres, isolating the lake from an underlying Shepparton aquifer comprising an upper silt (up to 5 metres thick) in direct contact with a lower sand (a wedge thickening southwards from 1 to 10 metres over the length of the lake). This lower sand directly overlies the highly permeable Parilla Sand along the eastern margin of Lake Tutchewop. The upper silt has calculated lateral hydraulic conductivities <2.5 m/day. The lower Shepparton sand varies from 3 to 4 m/day on the eastern margin, to 3 to 9 m/day on the southwestern margin. Below the eastern margin of Lake Tutchewop, the Parilla Sand increases in hydraulic conductivity down section from values comparable to the overlying Shepparton sand at the top, to 30 m/day at depth.

- The lacustrine sequence below the periphery of Lake Tutchewop is subdivided into two units. A lower less-permeable unit comprises 0.9 to 1.3 metres of subdued mottled grey bioturbated muds with minor carbonate and ubiquitous traces of gypsum. The upper unit is thinner with a more variably-permeable sequence comprising 0.3 to 0.7 metres of sand and sandy mud, commonly biota-rich, calcareous, of variable oxidation and low in gypsum. Porosity in these Yamba sediments is predominantly interparticular in the sands, and bioturbation-related in muds.
- Lunette sediments on the eastern margins of all lakes are predominantly clay-pelletal lithofacies with thinner highly-permeable quartz sand lithofacies.
- Lake Tutchewop was a predominantly freshwater system in which the input of saline groundwater springs on the lake margins was overshadowed by discharge from the river. The resultant lake has the characteristics of surface water-dominated lakes - a circular outline; a relatively high elevation of the lake floor; gently-sloping lake margins because deflation is minimised; and accumulation of sandy shoals on the western margin.
- The natural hydrodynamics of Lake Tutchewop would have been dominated by surface water evaporation except in the localised spring zones at the lake margins where groundwater evaporation and consequent salinity increases would be high. The low groundwater evaporation component would minimise drawdown of the surrounding groundwater head, and the resulting depression in the regional groundwater table created by the lake would be shallow.
- The low surface-water salinities in Lake Tutchewop may have gradually reduced the salinity of the underlying shallow groundwaters by upwards diffusion of salt. In the vicinity of the spring zones this process would be minimised by the higher salinities of the evaporated spring discharges.
- In Lake Tutchewop, under present-day conditions the natural hydrodynamic processes remain dominant in the lunette and its colluvial deposits on the eastern margin and are evident in attenuated form as springs on the western and eastern margins. The artificial hydrodynamic effects of the disposal basin/irrigation systems are most prominent on the western margin where the close proximity of the irrigation channel/Avoca floodway to the lake produces high but variable gradients towards the disposal basin. The effects of the artificial systems probably decrease from the western margin to the north-eastern margin, where active irrigation but not drainage works are involved, and still further to the south-west, where abandoned irrigation areas occur at the lake margin.

- The artificial systems around Lake Tutchewop help reduce the lateral distance to which the disposal waters would have to flow into the surrounding areas to produce hydrodynamic equilibrium but, as expected from the low lakewards hydraulic gradients which were probably associated with the natural system, theoretical distances of the order of hundreds of metres could be involved. The disposal waters probably create significant vertically-downwards gradients because the upwards gradients from the Parilla Sand aquifer are isolated by the clays of the Shepparton Formation. These former gradients are difficult to quantify.
- Groundwater heads around Lake Tutchewop are highly variable as a result of the topography, and seasonal and artificial fluctuations in recharge and evaporation. Consequently, the calculated limits to lateral flow of disposal water are only approximate. The highly-variable nature of the lake margins is reduced to four transects within which there is severely limited time-dependant data. This limits the study to a sophisticated first-order approximation of the system.
- The theoretical maximum limit of disposal water invasion to the east is about 150 m - within the lunette, and to the north-east in the floodplain area, about 400 m from the disposal basin. To the west, the limit is strongly dependent on the water levels in the irrigation channel/floodway systems and a current best-estimate is about 120m from the disposal basin. To the south, the limit in the floodplain hinterland is more than 350 m from the edge of the disposal basin.
- In the worst scenario, the maximum distance the disposal water could have moved during the period of operation of the disposal basin is on average, about 200 m (based on lateral flow rates). More realistic flow rates indicate invasion laterally between 2 m in clay to 20 m in silt. These estimates of disposal-water migration have an extremely broad range of up to 2 orders of magnitude; a result of poorly-defined permeability characteristics in an anisotropic host with fluctuating lake and groundwater heads.
- Hydrochemical indicators suggest that the actual movement of disposal water is far less than that indicated by first-order flow-rate calculations. Disposal water has only been identified, by major-ion ratios and deuterium signatures, to have invaded sandy shoals and vertically penetrated less than 2m into the sequence on the western margin. Lateral invasion beyond the existing lake is not recognized. It is a distinct possibility that such indicators may be inapplicable under the mixed evaporitic-recharge conditions of the lake margins.

- The low conformance between flow-rate calculations and hydrochemical estimates emphasises the limitations in identification and quantification of the disposal water - groundwater interaction.

THE DISPOSAL BASINS

LAKE WILLIAM

The investigation of Lake William is based on four transects set at right angles to the margins of the disposal basin (Figures 37 & 38).The northern margin transect (Figure 38a) extends from the usually-submerged area of the disposal basin through the regularly-flooded zone, across the colluvium and other lake marginal areas, and terminates at a HydroTechnology / Sinclair Knight Merz piezometer nest within a dryland farming area in the lunette. Much of the marginal and submerged areas intercepted by this transect have been disturbed by salt mining, which has removed a thin veneer of surface sediments from the lake, and variably disturbed the underlying lacustrine sequence. The eastern margin transect (Figure 38a) extends across the lake marginal areas at the base of the lunette. This area has also been disturbed by salt mining. The western transect (Figure 38b) extends landwards from the regularly flooded area to the boundary between the lake marginal areas and adjacent active irrigation areas on the floodplain. This irrigated area extends almost to the lake margin and irrigation drainage-water flows into the disposal basin. The southern transect (Figure 38b) crosses the lake margin near the southern fringe of the lunette. Dryland farming on the lunette and active irrigation to the west are possible influences in this area.

Geomorphology

Lake William has a rounded trapezoidal outline with an almost level floor of the lake at 66.6m AHD, and relatively steep marginal slopes up to the lake margin at approximately 70.1m AHD (Figure 14). The lake is entrenched into the surrounding plain and has a series of high rounded lunettes to the eastern side. These lunettes have uneroded and gentler westerly slopes than seen at either Lakes Tutchewop or Kelly, and have three distinct ridge features. The youngest is the lowest, adjacent to the present shoreline, and

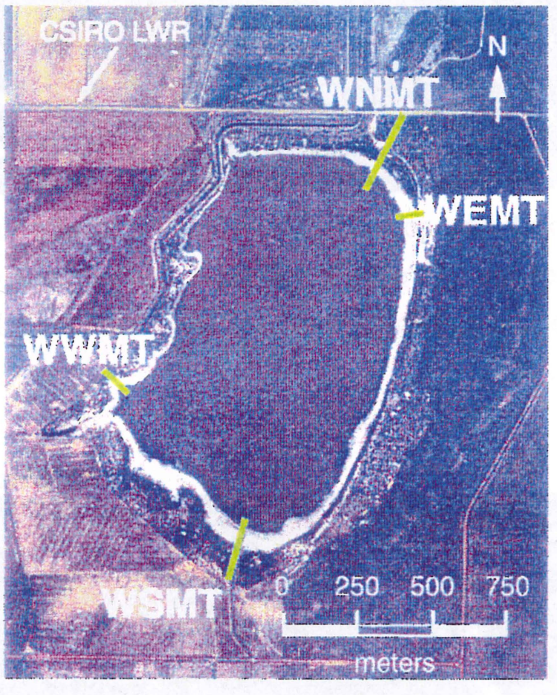
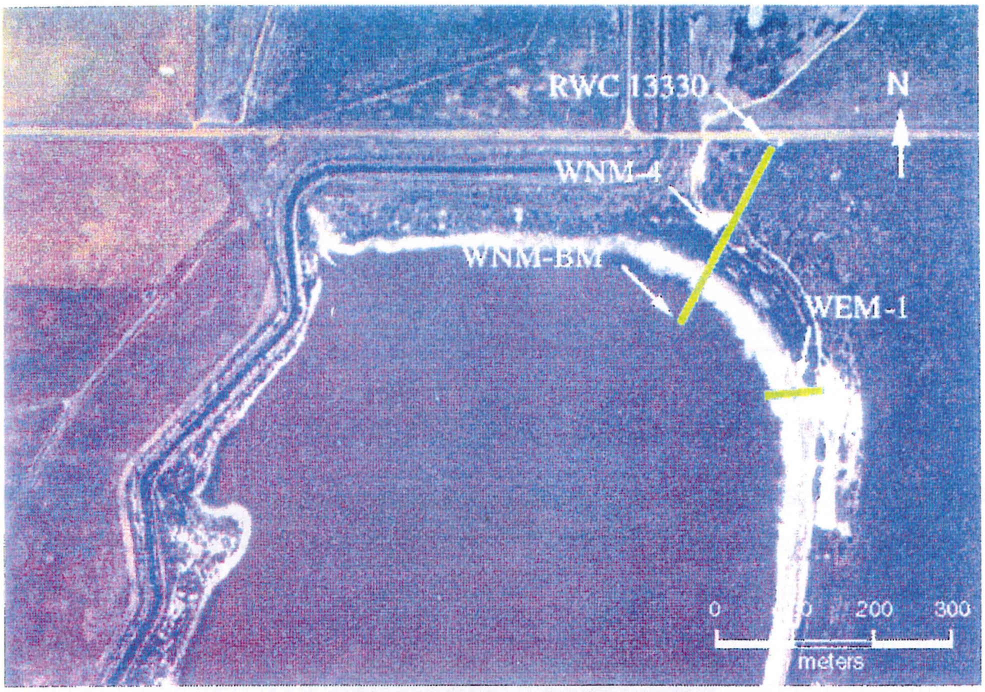


Figure 37. Locations of transects at Lake William.



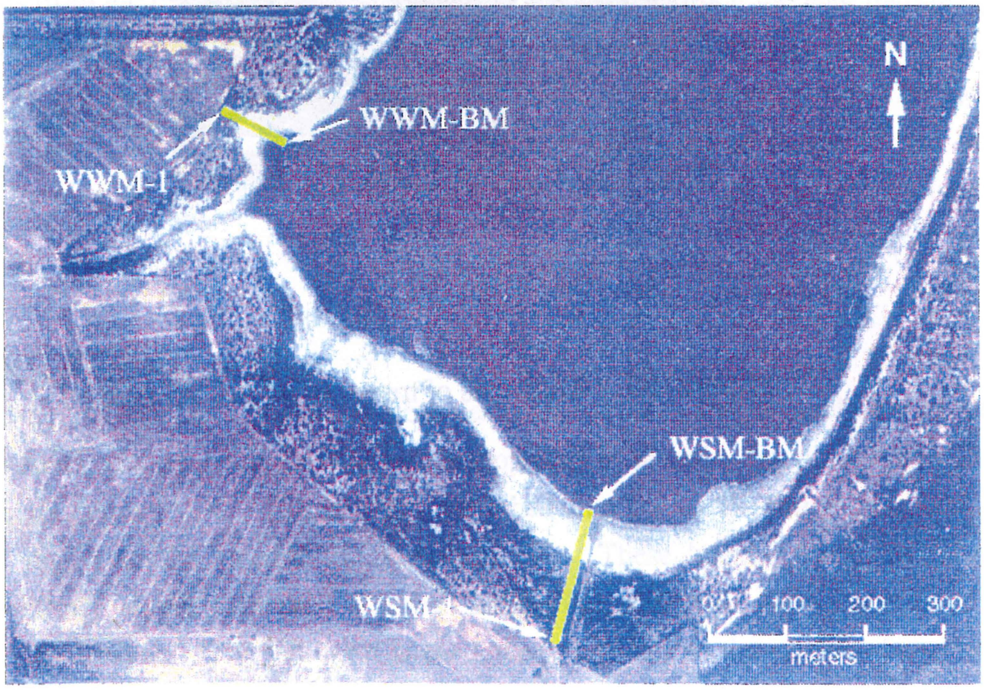


Figure 38. Locations of transects on (a) the northern (WNM) and eastern (WEM) margins, and (b) the western (WWM) and southern (WSM) margins of Lake William.

may be a modified beach deposit. The older ridges are higher and diverge northwards (Figure 1).

Stratigraphy

Three facies are recognized in the 2.2m of lacustrine Yamba Formation (Figure 10). The thin basal Unit 1 comprises seasonally-laminated lacustrine sediments with numerous millimetre-sized pyritic flakes which probably precipitated around either plant fragments or gypsum crystals.

The second lacustrine event (Unit 2) has distinctive evaporitic varve-laminites: cycles of thin basal clay, gradational up to and overlain by carbonate micrite, which grades up to porous sands of gypsum millet-seed crystals.

The uppermost event (Unit 3?) has a uniform sediment with scattered gypsum and halite? poikilotopic crystals, capped by a surface layer of granular euhedral salt cubes and hoppers. The homogenous nature of the unit could be an artefact of the disturbance by mining.

The upper surface of the Shepparton Formation is 3.5m higher (68.5 mAHD) in CSIRO LWR situated midway between Lake Tutchewop and Lake William, possibly indicating an eastward-sloping Shepparton surface (Figure 14) as a result of tectonic uplift on the eastern side of LakeTutchewop, or increased discharge and deflation in the Lake William area.

Porosity & Permeability

The porosity distribution in the underlying sequence is presented in Figure 39. In the Yamba Formation, porosity is variable, even within one unit at differing locations. The evaporitic laminites of Unit 2 and the homogenized sediments of Unit 3 have high interparticle porosity. The quartz sand lithofacies of the dune/lunettes has the highest interparticle porosity. Predicted k_h of these sands ranges from 3 m/day (medium sand) to 10- 40 m/day (coarse sand).

Within the Shepparton Formation the sequence is relatively tight for the upper 12 m. Between 52 to 54 mAHD, the silts have low permeabilities below the calculation threshold, but below 42 mAHD, very fine sands have k_h of 3 m/day.

Hydraulic Gradients

The following information is based on 1, 2, 3 or 4 sets of piezometer measurements made between August and November 1994. Basin operating water-levels during October-

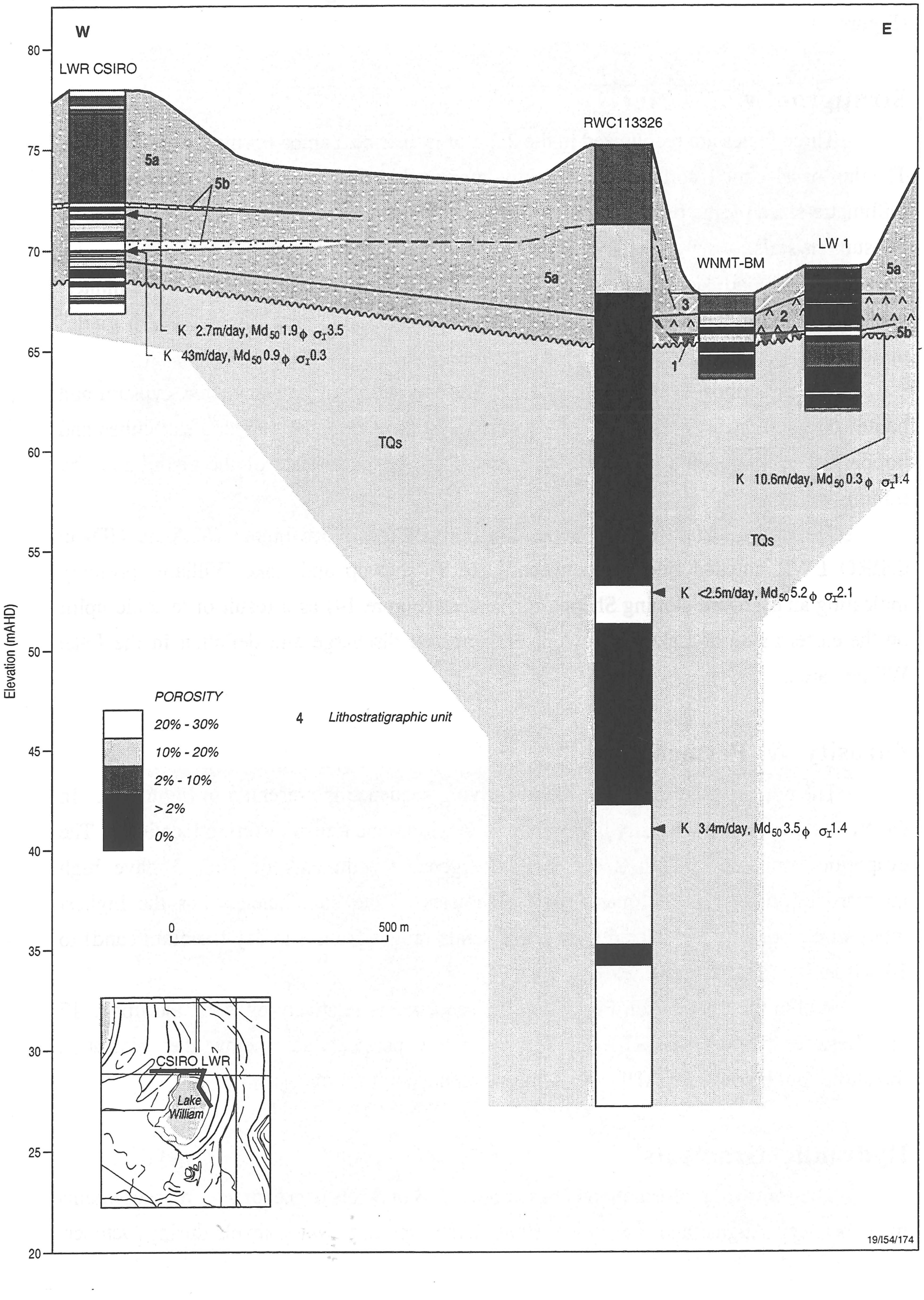


Figure 39 Porosity distribution in the Lake William area, composite transect LWR-WNMT -WEMT

November were in the range 67.9 to 68.0 mAHD, which is close to the mean water level of 68.79 mAHD at which the basin operated during the period July 1987 to April 1995 (Sinclair Knight Merz, pers. comm., 1996).

Vertical Gradients

Vertical hydraulic gradients were measured at a site on the lunette (WNMT, Figure 40); a site on the lake margin (WWMT-W1; Figure 38a); and a site in the usually submerged zone (WNMT-BM, Figure 40). The piezometer nest on the lunette extends into the underlying Parilla Sand and Renmark Group (Figure 40); the others are restricted to the Yamba and Shepparton Formations.

Beneath the lunette on the northern margin the gradient from the Renmark Group to the Parilla Sand was highly variable over the three measurements (-10 to 20 x 10^{-3} m/m; Table 4) and further measurements are needed to eliminate the possibility of measurement errors. There is a small upwards gradient from the piezometer in the Parilla Sand to the lowermost piezometer in the Shepparton Formation (e.g. 1 to 6 x 10^{-3} m/m; Table 4) but a much larger gradient from the lowermost Shepparton piezometer to the next highest (100 x 10^{-3} m/m; Table 4). This suggests that the lower Shepparton Formation and the underlying Parilla Sand aquifer do not have greatly differing hydraulic conductivities. The gradient between the two shallowest piezometers in the Shepparton Formation is much lower than that associated with the Parilla Sands but it is still significantly upwards (10 x 10^{-3} m/m; Table 4). i.e. the upward gradient from the Parilla Sand has not been completely attenuated by the Shepparton Formation clays.

The single measurement of the vertical gradient at the lake margin (WEM-1; Figure 38a) indicates an upwards gradient of a similar order of magnitude to that in the upper Shepparton Formation beneath the lunette. The two measurements at a usually-submerged site on the northern transect (WNMT-BM, Figure 40) are close to the detection limit and further measurements are needed to determine their reliability.

Lateral Gradients

Lateral gradients between Lake William and the adjacent marginal lake environments were measured using a three-piezometer array along the northern margin transect (Figures 38a, 40 & 41), two-piezometer arrays on the western (Figures 38b & 42) and southern margins (Figure 38b), and a single piezometer on the eastern margin (Figure 38a).

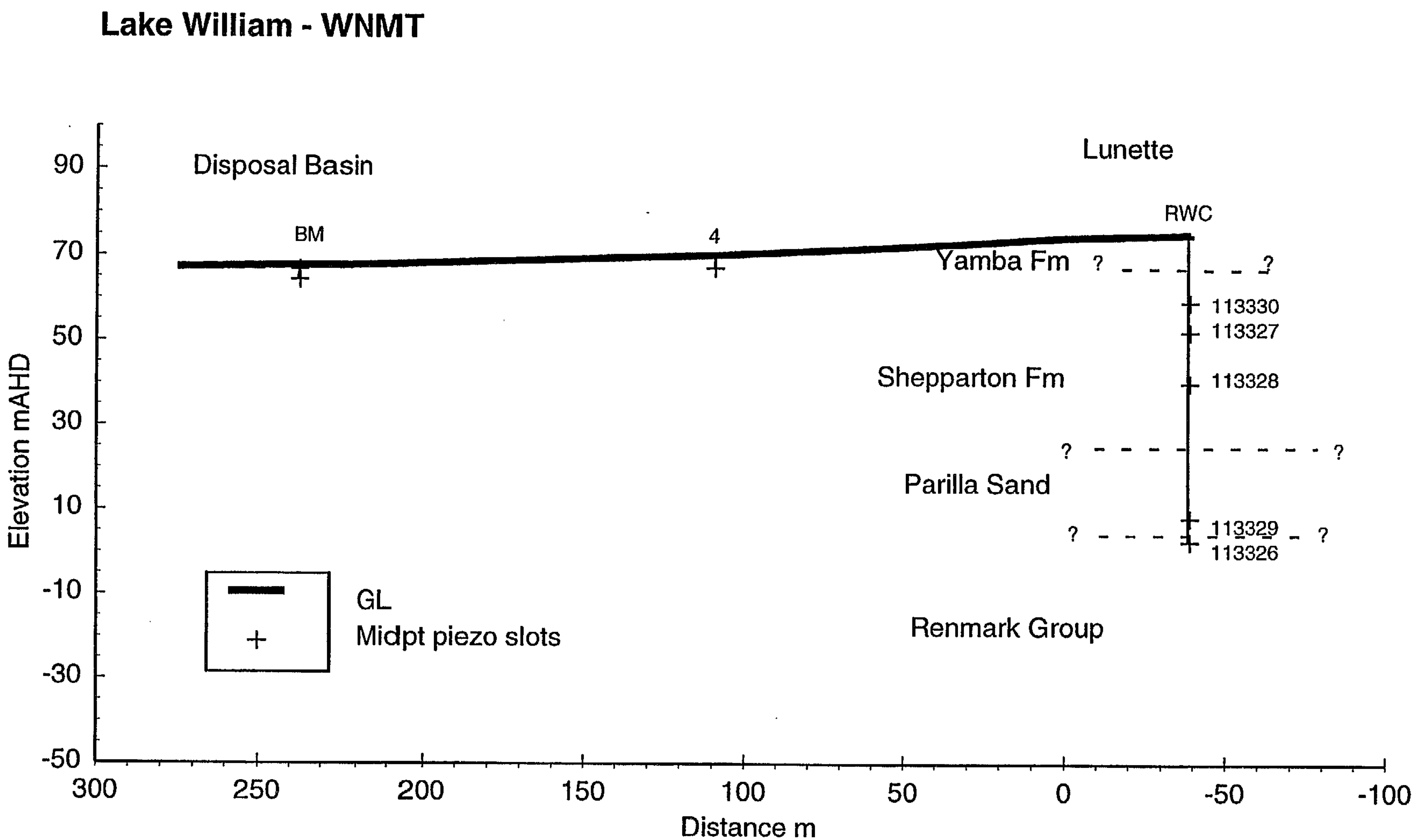


Figure 40. Lake William northern margin transect (WNM or WNMT); topography, drill-hole and piezometer sites.

Table 4. Vertical Hydraulic Gradients - Lake William

	April	August	October	Range	Average	Detection Limit
WNMT						
Lunette	+10	+10	+10	---	+10	+/- 2
Lunette	+100	+100	+100	---	+100	+/- 1
Parilla Sand	+6	+5	+1	+1 to +6	+4	+/- 1
Renmark Gp.	-10	+2	+20	-10 to +20	-3.5	+/- 4
WEMT						
WEMT(1)/115381	n.d	n.d	+10	---	+10	+/-4
WNMT						
Disposal Basin-BM	n.d.	+8	-10	---	-1	+/- 7

Piezometers are in Shepparton Fm. unless otherwise stated.
n.d. = not determined
Gradients are in (m/m)*10^3

┼ Midpt. piezometer slots (schematic)

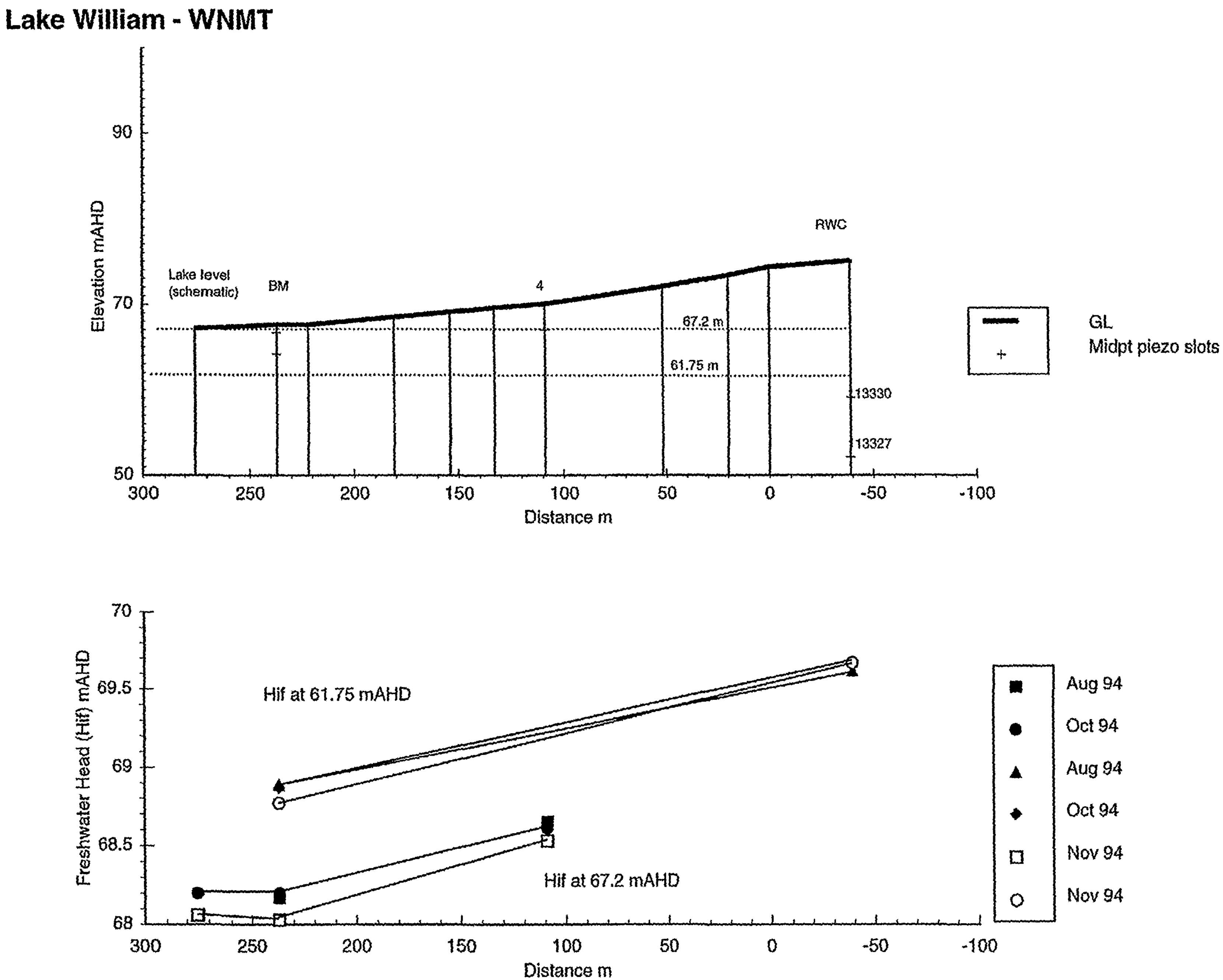


Figure 41. Lake William northern margin transect (WNM or WNMT); lateral (freshwater) heads at 67.2 and 61.75 mAHD.

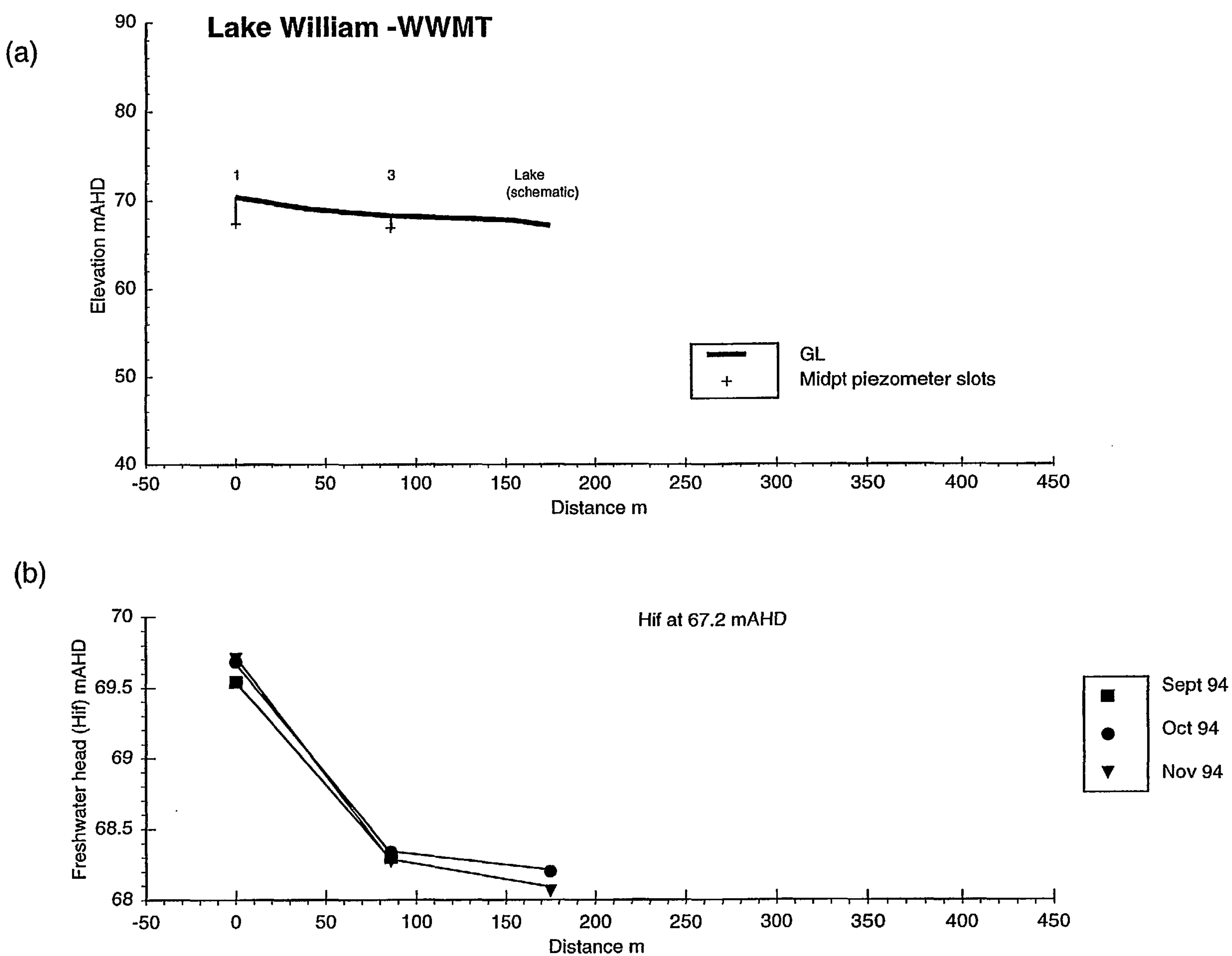


Figure 42. Lake William western margin transect (WWM or WWMT): (a) topography, drill-hole and piezometer sites; and (b) lateral (freshwater) heads at 67.2 mAHD.

Most lateral (freshwater) heads were calculated for a constant elevation of 67.2 mAHD and some for an elevation of 61.75 mAHD.

Northern Margin Transect (WNMT)

At the northern margin the lateral gradient at a constant elevation of 67.2 mAHD is lakewards from the colluvium to the usually-submerged areas (Figure 41). The lateral gradient at 61.75 is also lakewards from the lunette to the usually-submerged areas (Figure 41).

Western Margin Transect (WWMT)

At the western margin, the lateral gradient at 67.2 mAHD from near the landward boundary of the lake margin and the active irrigation area on the floodplain, to a site on the regularly-flooded part of the lake margin is lakewards and relatively very high (WWMT-1 to WWMT-3; Figure 42). The lateral gradient from the regularly-flooded to the usually-submerged area of the disposal basin is much lower (Figure 42). The lateral heads at the landward margin are remarkably constant over the measurement period considering the potential for fluctuations induced by usage changes in the adjacent irrigation area (c.f. the Lake Tutchewop western margin).

Southern Margin Transect (WSMT)

At the southern margin (Figure 38b) there is a relatively high lateral gradient at 67.2 mAHD towards the lake.

Eastern Margin Transect (WEMT)

At the eastern margin, the single piezometer at the landward boundary of the regularly-flooded area showed a gradient towards the disposal basin. The data from Lake Tutchewop suggest that heads and gradients in this area will change considerably in response to changes in the disposal basin water levels.

Potential Lateral Movement of Disposal Water

The lateral distances at 67.2 mAHD to which the disposal water could move (Table 5) were calculated for two disposal-basin operating levels: (1) an assumed freshwater-head operating-level of 68.5 mAHD; and (2) the actual average freshwater-head basin operating-level of 69.0 mAHD which prevailed in the period January 1988 to April 1995 (Sinclair Knight Merz, pers. comm., 1996). The freshwater heads in the surrounding groundwater systems used for the calculation were obtained by the averaging the available piezometer measurements (1, 2, or 3 measurements in the period August to November, 1994; Table 5) and interpolating as needed.

At a freshwater-head operating-level of 68.5 mAHD the disposal water should not move more than 10 m beyond the waters edge along any of the transects. i.e. the disposal water

Table 5. Possible Extent of Lateral Flow from the Lake William Disposal Basin

Location		Freshwater Head at 67.2 mAHD (mAHD) *Range* (Time period,1994))	*Average* (No. of readings)	*Maximum Extent of Lateral Flow (m)*	*Maximum Extent of Lateral Flow (m)*
Disposal Basin Operating level		(July 87 to April 95)	69.0	at 68.5 (assumed)	at 69.0 (actual)
WEMT	(1)/115381 no piezometer	68.38 to 68.46 (Oct-Nov)	68.42 (2)	------	------
WWMT	3	68.27 to 68.34 (Aug-Nov)	68.30 (3)		
	1	69.54 to 69.70 (Aug-Nov)	69.64(3)	0 (waters edge, lake margin)	10 (lake margin)
WNMT	BM	68.03 to 68.20 (Aug -Nov)	68.13 (3)		
	S4	68.53 to 68.65 (Aug-Nov)	68.60 (3)	10 (lake margin)	> 50
WSMT	2	(1 reading -Nov)	68.63 (1)		
(WSM)	1	(1 reading -Nov)	69.37(1)	<10 (waters edge, lake margin)	40

should be contained within the lake and its marginal environments (Table 5). At the actual freshwater-head operating-level of 69.0 mAHD the limit of movement to the west is about 10 m, which is within the lake marginal environments, and to the south it is 40 m, which is also within the lake marginal environments. To the north, the limit is > 50 m, but approximate values obtained from the piezometer nest on the lunette indicate that the limit is not beyond this site.

Hydrochemical Identification of Disposal Waters

Three types of chemical indicator were tested in order to identify the presence of disposal waters in the groundwaters underlying and surrounding Lake William. They are: (1) differences in salinity; (2) differences in ratios of the major ions to Br and to Mg; and (3) differences in the D/H ratios of the waters.

Salinity

Surface Disposal Water

During the period October 1993 to August 1994 the salinity of Lake William ranged from about 125,000 to 298,000 mg/L. A graph of salinity against time for this period plus one sample collected in April 1993 (Figure 43) has two parts: (1) the period between October 1993 and January/February 1994 during which the salinity gradually increased from about 255,000 to about 365,000 mg/L; and (2) the period after January/February 1994 when the salinity gradually decreased (neglecting three anomalous samples) to about 320,000 mg/L in August. The average over this period is about 300,000 mg/L.

There are extensive evaporite mineral deposits in Lake William during periods of low-basin operating-levels. Precipitation and re-solution of these evaporites buffers the salinity against the effects of seasonally-fluctuating evaporation and operating conditions.

Groundwater

Groundwater salinities around and beneath Lake William are presented as salinity versus depth graphs for individual sites (e.g. Figures 44, 45 & 46).

WNMT-S4, which is the furthest site from the lake for which a salinity profile has been determined shows salinities down to about 60,000 mg/L at shallow depths (Figure 44). At two sites nearer the lake (WWMT-S3 and WEMT-W1; Figure 44), the lowest salinities above 65.5 mAHD are about 100,000 to 110,000 mg/L. At a site within the lake (WNMT-BM, Figure 44), the lowest salinity is about 250,000 mg/L. At sites WEMT-W1 and WNMT-BM evaporation has sharply increased the salinity near the top of the phreatic zone.

Lake William Surface Water

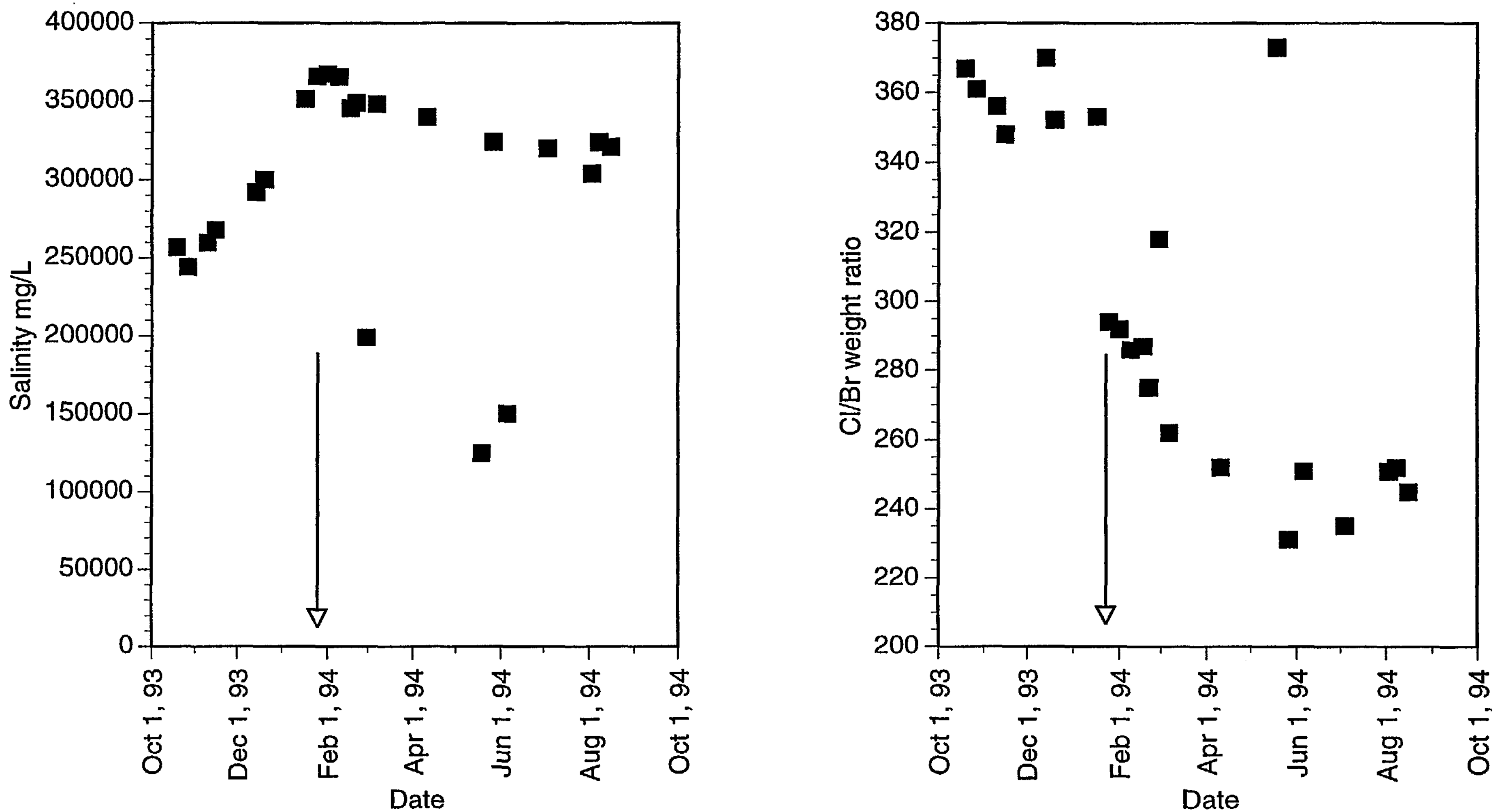
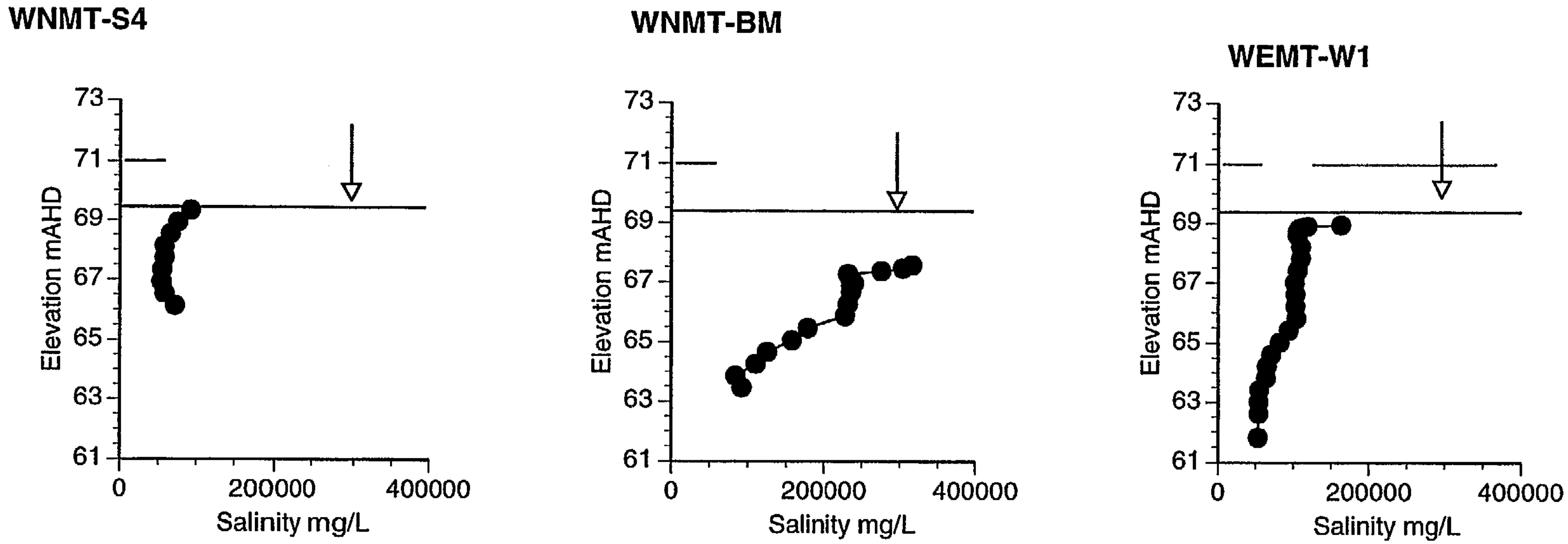


Figure 43. Salinity and Cl/Br ratios of Lake William surface waters; October 1993 to October 1994.



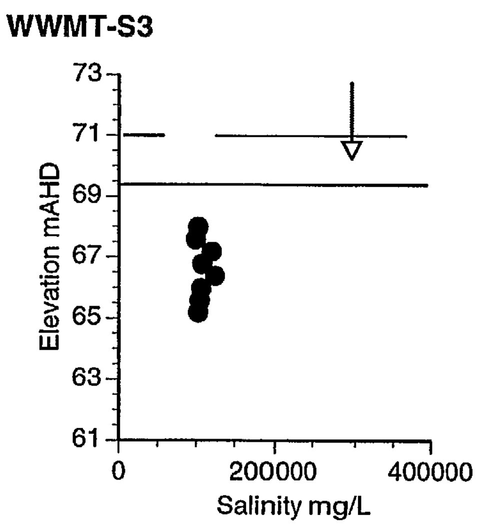


Figure 44. Salinity vs elevation profiles for Lake William groundwaters. Comparison of an usually submerged site (WNMT-BM) with marginal sites on the northern (WNMT-S4), eastern (WEMT-W1) and western (WWMT-S3) transects.

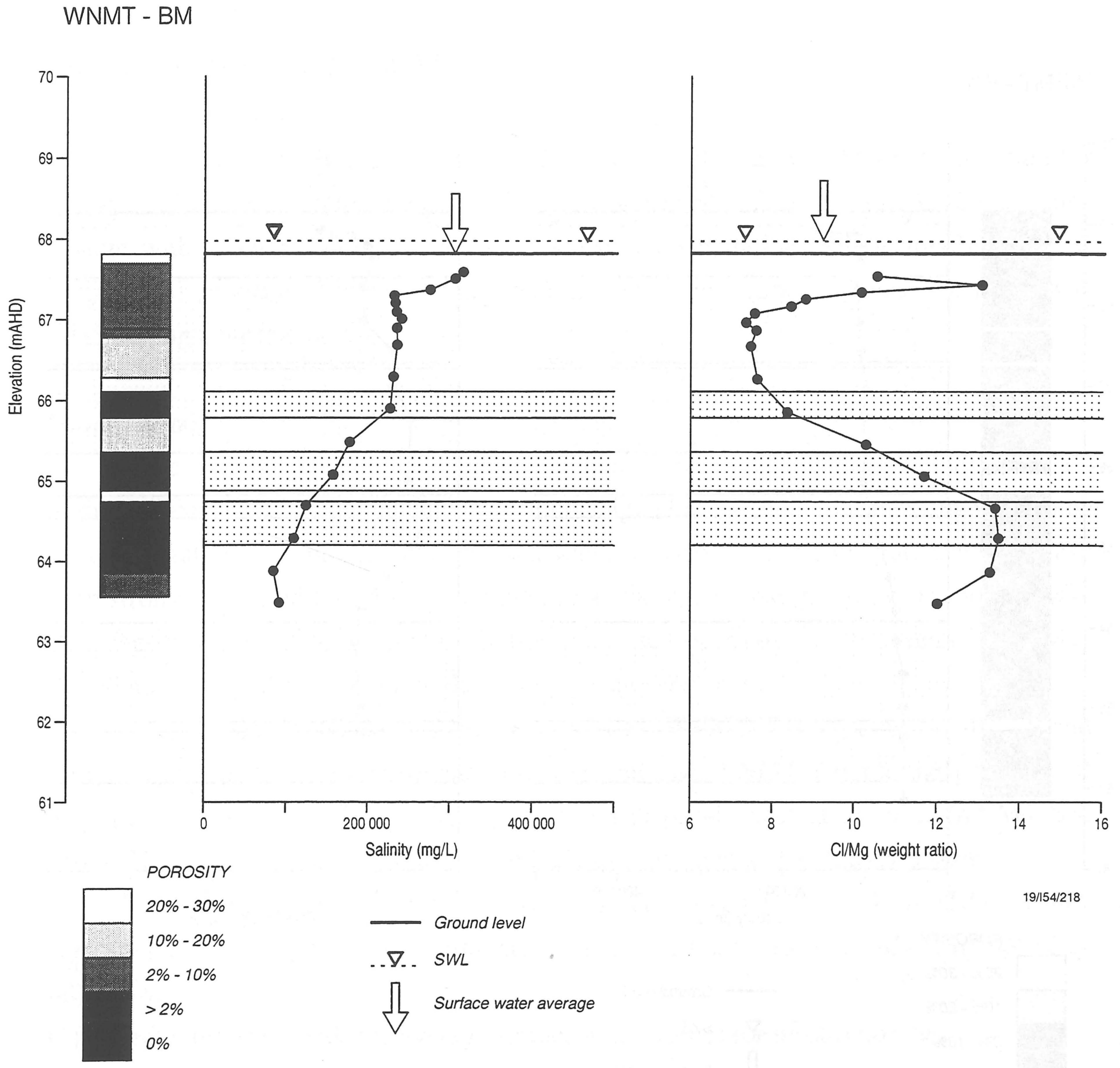


Figure 45. Relationships of sediment porosity to groundwater salinity and Cl/Mg ratios at a submerged site in Lake William.

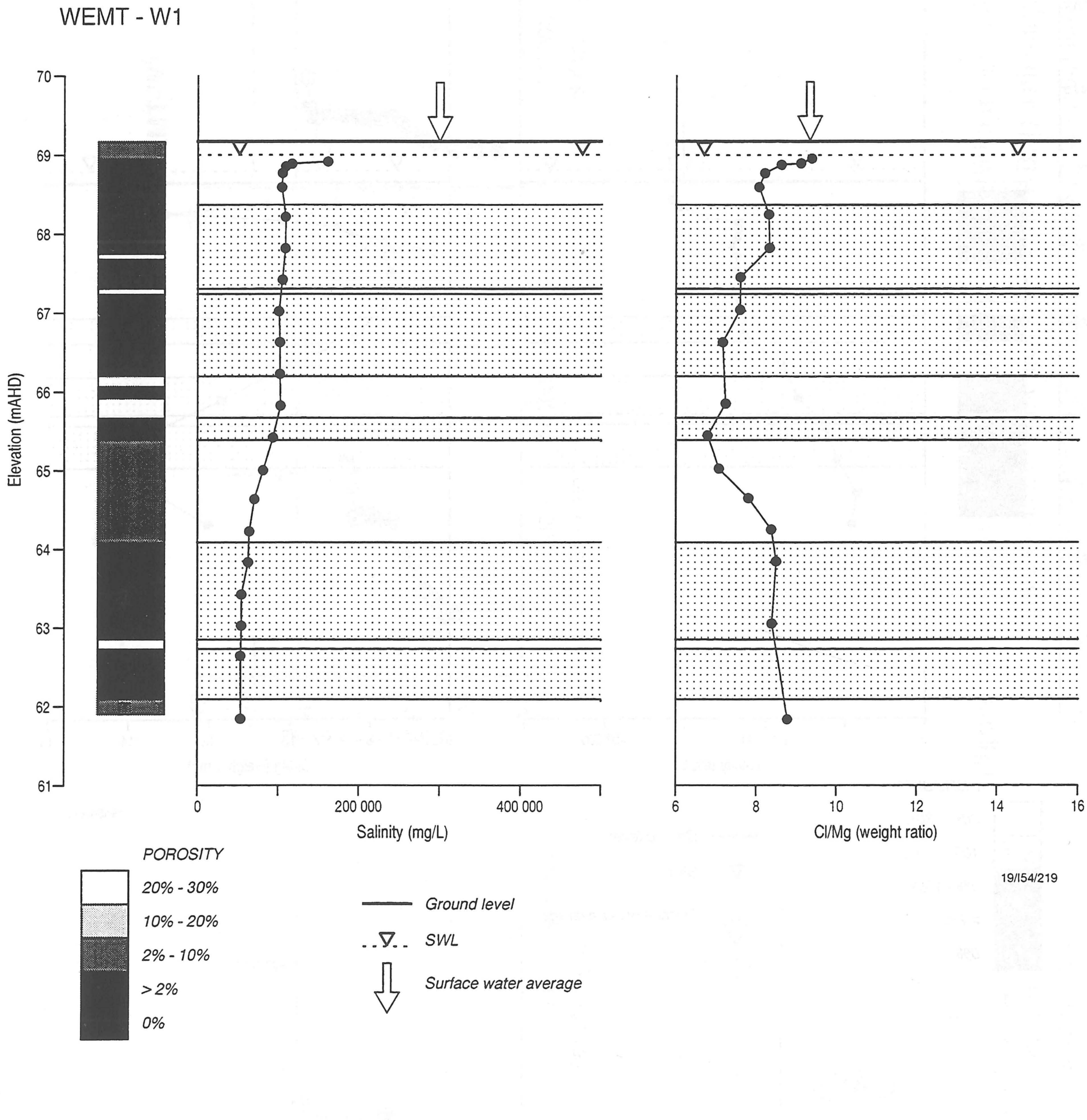


Figure 46. Relationships of sediment porosity to groundwater salinity and Cl/Mg ratios at a site in the regularly-flooded margin of Lake William.

Salinity is not a reliable indicator of the presence of disposal water. For example, the brines of salinity of about 100,000 mg/L which occur at sites WWMT-S3 and WEMT-W1 could be paleo-brines formed when Lake William was larger and less saline than during its most recent natural phase. This recent natural phase could have produced the 250,000 mg/L brines which are present immediately below the lake.

Major-Ion ratios to Br or Mg

Surface Disposal Water

The range and average of the ratios of major-ions to Br or Mg were calculated for the period October 1993 to August 1994 and are presented in Figures 47 & 48. Ca/Br ratios change with changing salinity, indicating gypsum precipitation. Ratios involving Cl/Br (Figure 43) decrease after the salinity peak in February, which suggests that halite was precipitating after that date.

Groundwater

Because the salinities of the Lake William surface waters and groundwaters are high, evaporation and consequent evaporite precipitation can cause large changes in some major-ion ratios. The presence of disposal water in surface or groundwaters which have been strongly affected by local evaporation (e.g. the uppermost groundwaters in WNMT-BM; Figure 44) or evaporation plus dilution (e.g. the uppermost groundwaters in WEMT-W1; Figure 44) will be difficult to detect using major-ion ratios.

Assessment of the data for sites WNMT-BM, WEMT-W1 (Figures 47, 48, 49 and 50), and two other lake margin sites (WWMT-S3 and WNMT-S4) for the presence of disposal water (Table 6) has positively identified disposal water at the sites WNMT-BM and WEMT-W1 and suggests that it is unlikely to be present at the other two sites.

For the submerged site WNMT-BM at elevations >67.0 mAHD (which corresponds to the top 0.5 m of sediment), the major-ion ratios to Br or Mg (Figures 47 & 48) show:

(1) definite trends towards the average surface water values for most ratios; and

(2) no definite trends away from the average surface water values for the other ratios (except Ca/SO_4 which is influenced by gypsum dissolution/precipitation).

The trends in the groundwater major-ion ratios point generally towards the average values measured for the surface waters, particularly if the top three points, which correspond to the zone of evaporation-induced salinity increase, are neglected. This trend supports the view that the average measured values for the surface waters are indicators of the presence of disposal water in the groundwater. The ratios shown in Figures 48 and 49 suggest that,

WNMT-BM

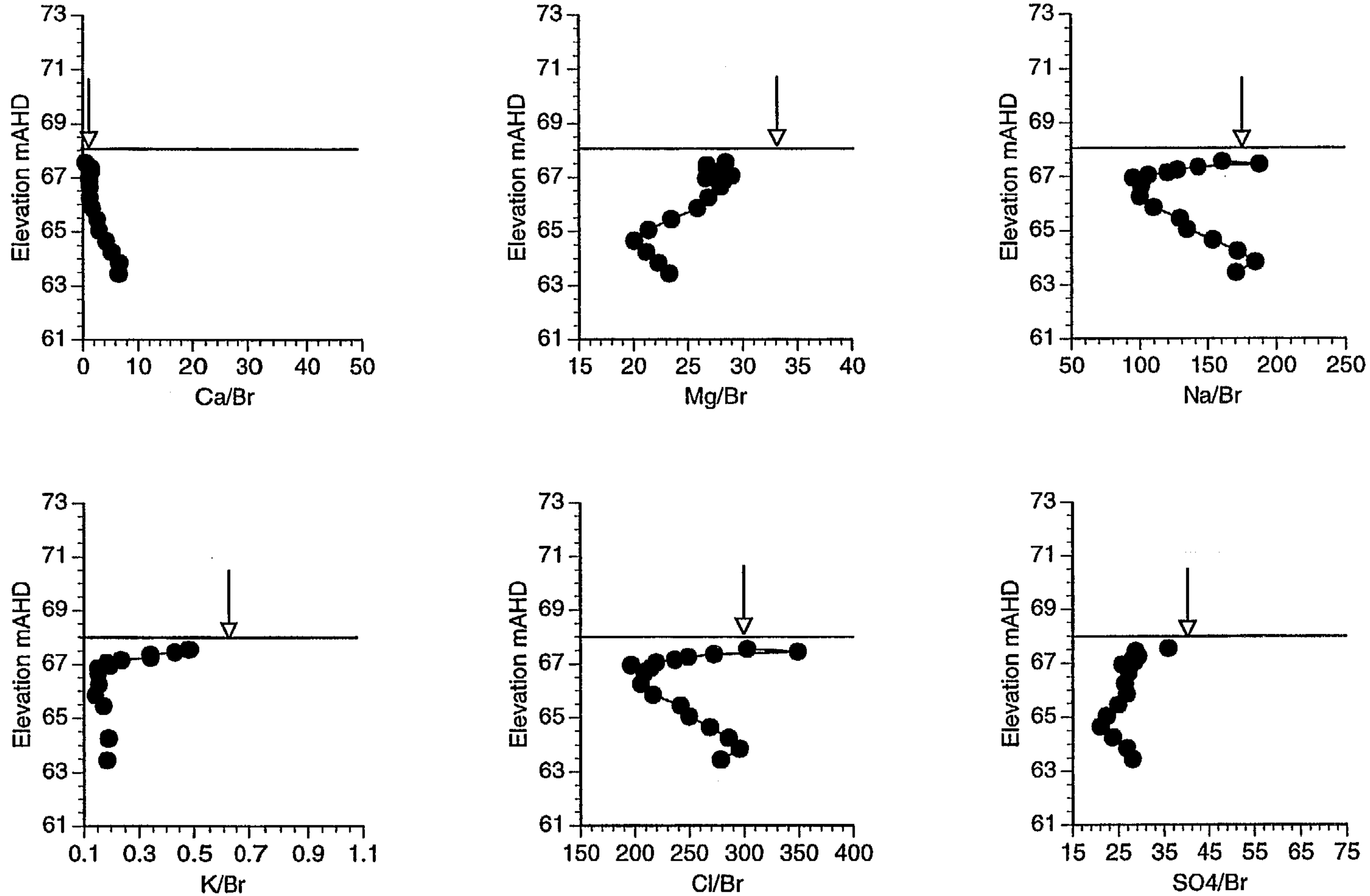


Figure 47. Lake William northern margin transect, usually submerged site BM (WNMT-BM). Groundwater and surface water major-ion ratios to Br. (Shaded area is the surface water range and the arrow the average)

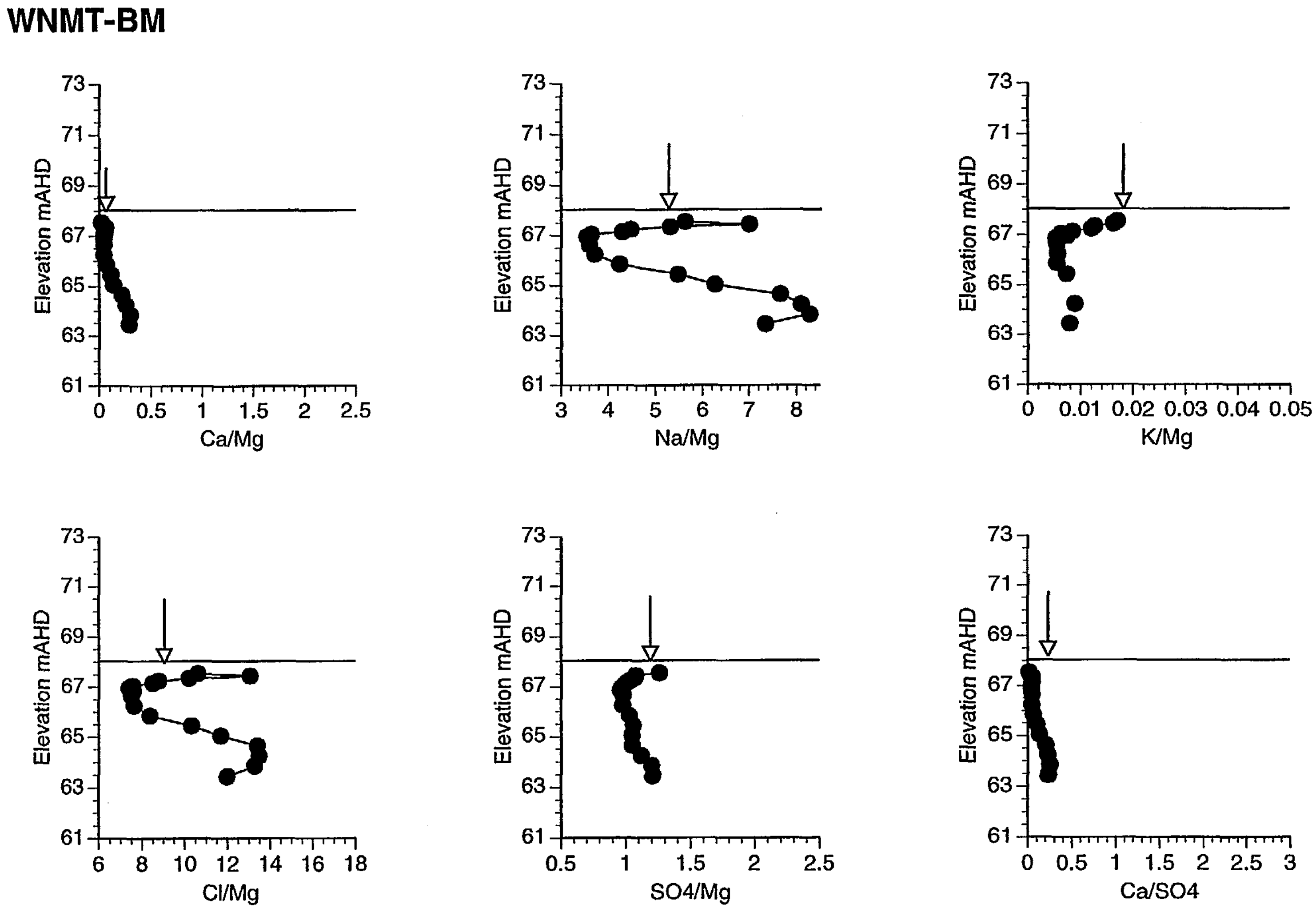


Figure 48. Lake William northern margin transect, usually submerged site BM (WNMT-BM). Groundwater and surface water major-ion ratios to Mg. (Shaded area is the surface water range and the arrow the average)

WEMT-W1

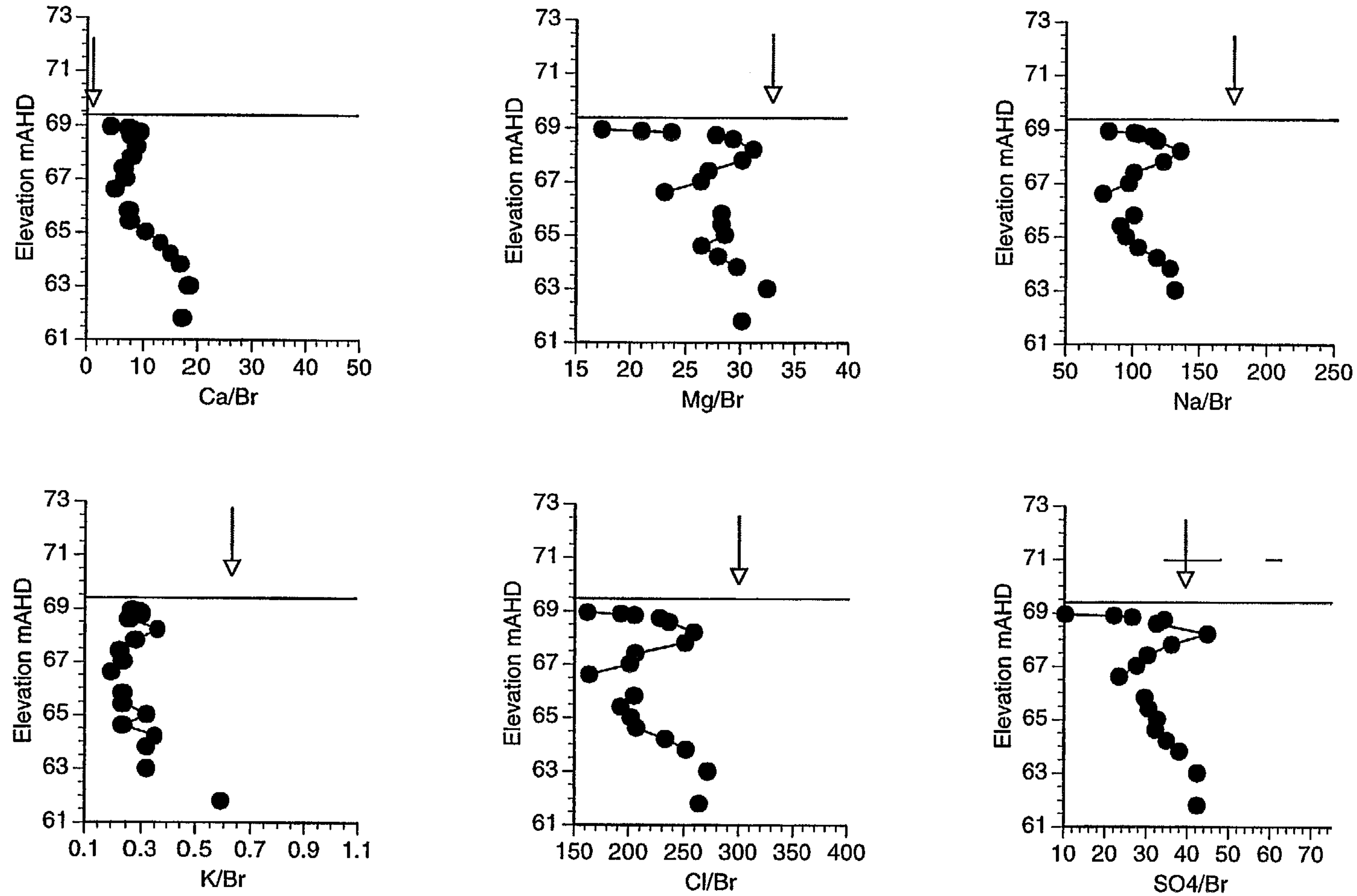


Figure 49. Lake William eastern margin transect, regularly flooded site W1 (WEMT-W1). Groundwater and surface water major-ion ratios to Br. (Shaded area is the surface water range and the arrow the average)

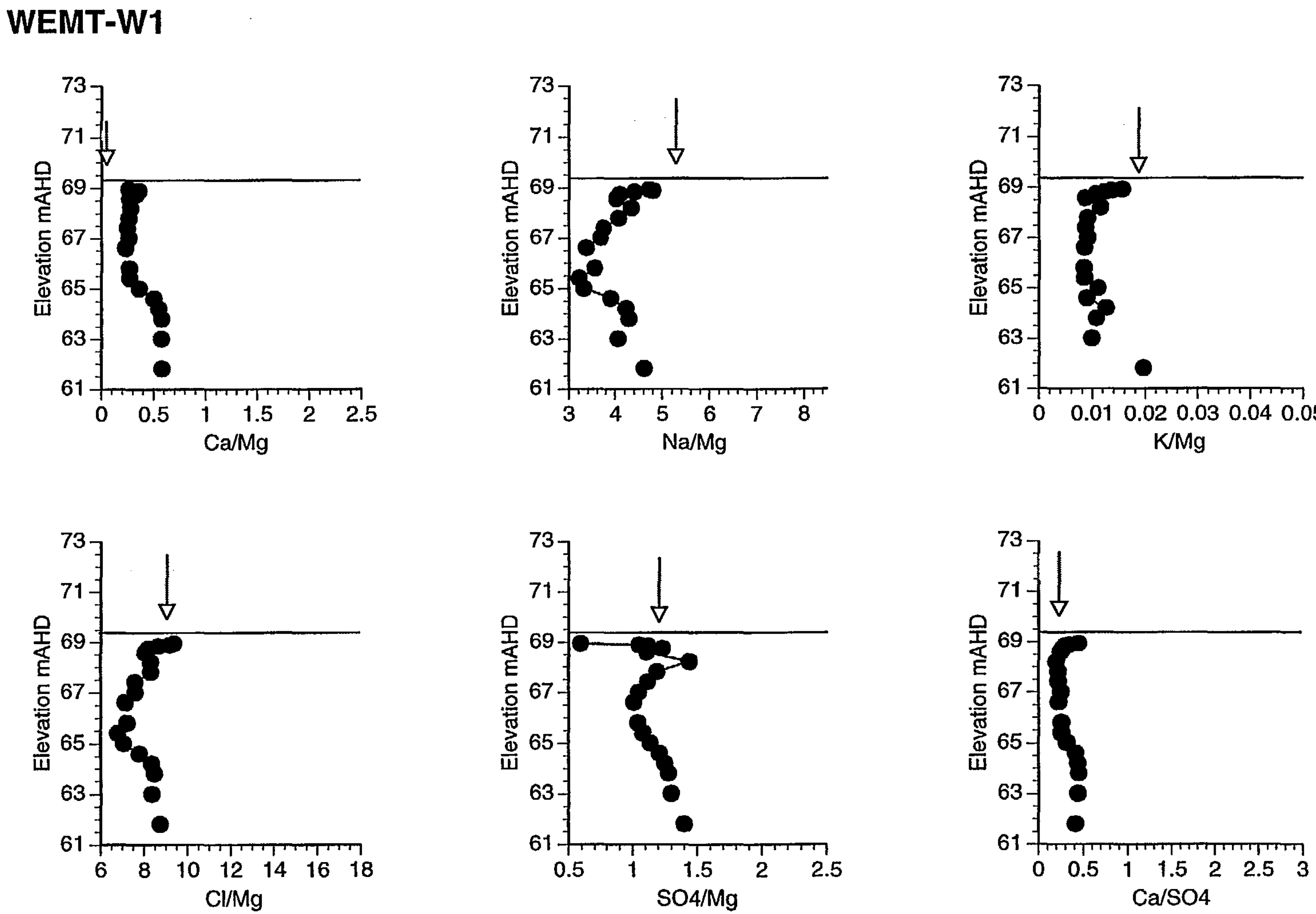


Figure 50. Lake William eastern margin transect, regularly flooded site W1 (WEMT-W1). Groundwater and surface water major-ion ratios to Mg.
(Shaded area is the surface water range and the arrow the average)

Table 6. Probability that disposal water is present in groundwaters beneath and around Lake William.

	Depth[1]	Ratios/Mg[2]			Ratios/Br[2]			Total % Favourable Indicators Y=2;M=1;N=0	Disposal Water Present?
		Yes	Maybe	No	Yes	Maybe	No		
WEMT-	to 0.4m	2	1	0	0	0	4	40	No
W1 (115381)	0.4 to 1.4m	2	1	0	4	0	0	90	Yes
WWMT-	to 0.4m	1	0	2	1	2	1	40	No
S3	>0.4m	2	0	1	0	0	4	30	No
WNMT-	to 0.4	0	0	3	2	0	2	30	No
S4	0.4 to 0.8m	2	0	1	1	2	2	60	Unlikely
WNMT-	to 0.6m	2	1	0	3	1	0	90	Yes
BM	>0.6m	0	0	3	1	2	1	30	No

[1] Depth below sediment surface (submerged sites); or depth below SWL.
[2] Excluding ratios involving Ca or SO_4

as a first approximation, the proportion of disposal water in the natural groundwater system decreases steadily with depth and is not detectable below about 67.0 mAHD

For the lake marginal site WEMT-W1 (Figures 49 and 50), ratios for groundwater between 67.0 and 68.5 mAHD generally trend towards the average measured values for the surface waters with increasing elevation. Groundwaters in the evaporation-affected shallow sediments above about 68.5 mAHD show strong deviations from the surface water values.

Deuterium

Surface Water

Two δD values of surface waters in Lake William have been obtained. In August 1994 the surface water had a δD value of -2.5 ‰ but this decreased to -5.1‰ in September 1994 . This gives a very preliminary estimate of the average value of δD as -4 ‰.

Groundwater

A detailed δD profile for the marginal site WEMT-W1 is in Figure 51, which also includes corresponding salinity and Cl/Br profiles. The δD data between 67.0 and 68.5 mAHD support the conclusion from the major ion data that disposal water is present in this depth interval. More detailed analysis using plots of δD versus Cl/Br or Mg/Br (Figure 52) supports the concept of a mixing zone between natural groundwaters and disposal water in the zone 67.0 to 67.5 mAHD and perhaps above this to 68.8 mAHD. Plots of δD versus Cl/Br or Mg/Br are linear over this interval and suggest a maximum of about 60% disposal water in the sediments.

The natural groundwaters at WEMT-W1 below 67.0 mAHD show a considerable change in salinity (about 50,000 to 100,000 mg/L) accompanied by only a small change in δD (<5‰). This suggests that evaporation is not the only reason for salinity increases in the natural groundwaters beneath the lake.

Discussion and Conclusions

- Porosity in the Yamba Formation is variable, even within one unit at differing locations. The evaporitic laminites of the middle unit and the homogenized sediments of the

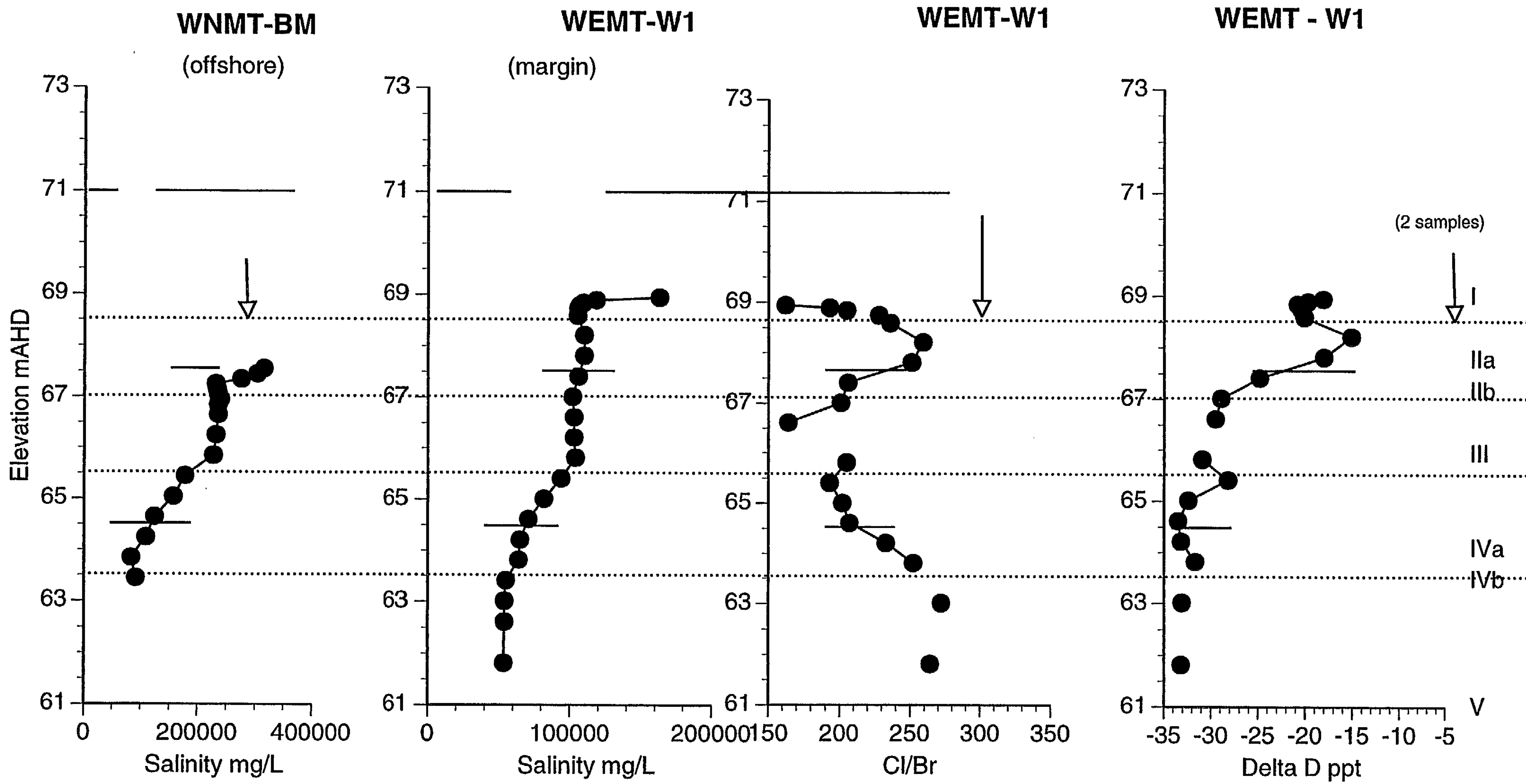


Figure 51. Lake William eastern margin transect, regularly flooded site W1 (WEMT-W1). Relationships of deuterium content of groundwater to elevation, salinity and Cl/Br ratios.

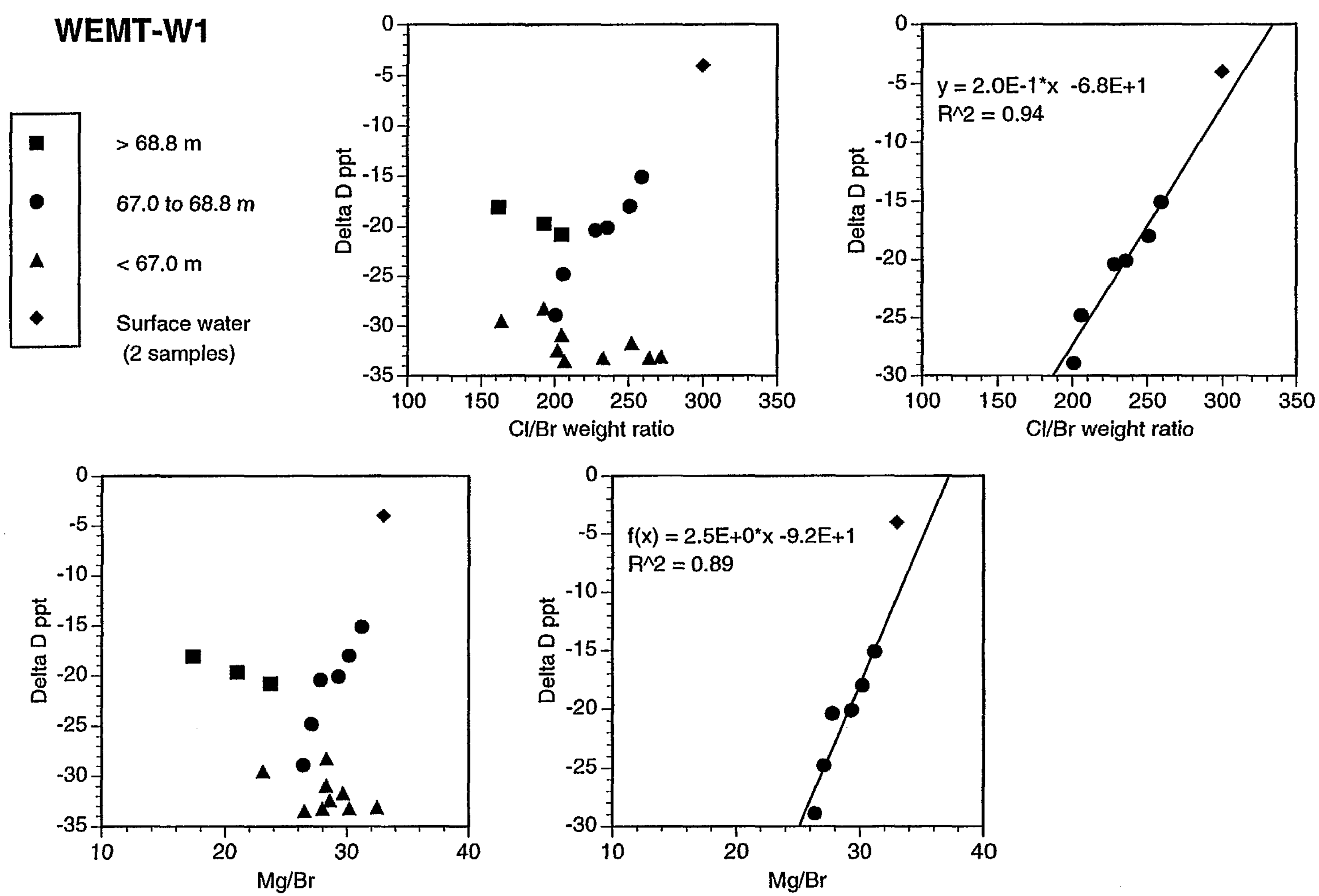


Figure 52. Lake William Lake William eastern margin transect, regularly flooded site W1 (WEMT-W1). Relationships of deuterium content of groundwater to Cl/Br and Mg/Br ratios.

uppermost unit have high interparticle porosity. The quartz sand lithofacies of the dune/lunettes has the highest interparticle porosity. Predicted k_h of these sands ranges from 3m/day (medium sand) to 10- 40 m/day (coarse sand). Within the Shepparton Formation the sequence is relatively tight for the upper 12 m.

- Vertical hydraulic gradients indicate that there is no major permeability barrier between the lower Shepparton Formation and the underlying Parilla Sand aquifer. There is a strong upwards gradient from these aquifers to the low permeability clays of the upper Shepparton Formation. Gradients in the upper Shepparton Formation are much lower but significantly upwards (10 x 10^{-3} m/m). This upward gradient indicates a much stronger groundwater influence at Lake William than at Lake Tutchewop, which is consistent with stratigraphic data indicating that the Shepparton surface slopes downwards from Lake Tutchewop to Lake William.
- Lateral hydraulic gradients between Lake William and the adjacent marginal lake environments are lakewards from the lunette and floodplain environments of the hinterland. The much higher gradient towards the lake from the irrigated floodplain areas to the west (17 x 10^{-3} m/m) compared to that from the lunette colluvium on the northeast margin (about 3 x 10^{-3} m/m) illustrates the significant confining effect of irrigation waters on the disposal water in the lake.
- The lateral distances to which the disposal water could move at average basin operating levels are within the landward boundary of the lake margins or, to the north, the colluvium - lunette boundary.
- Compared to Lake Tutchewop, the disposal waters can move only relatively small distances laterally. This limit is partly determined by the close proximity of the active irrigation areas on the western and, to a lesser extent, the southern margins. However, the lower elevation of Lake William and its steeper margins, both of which reflect a more groundwater and deflation-dominated history than that of Lake Tutchewop, are natural features which would favour higher natural groundwater gradients towards the lake.
- Salinity is, at best, a general guide to the presence of disposal waters in the groundwaters underlying and surrounding Lake William. The salinity in the disposal basin is influenced not only by seasonally-fluctuating evaporation and operating conditions, but by precipitation and re-solution of the extensive evaporite mineral deposits which are present during periods of low-basin operating levels. There is a brine of salinity 250,000 mg/L immediately beneath the lake which could be disposal water or a natural brine emplaced during the recent, highly-saline natural phase. At two lake

marginal sites, similar groundwater salinities of about 100,000 mg/L are encountered, which is indicative of a paleo-brine formed when Lake William was larger and less saline.

- Use of the ratios of major-ions to Br or Mg to determine the presence of disposal water in the phreatic-zone groundwaters surrounding and underlying Lake William is constrained to those not affected by the precipitation of gypsum or halite. Deuterium is also an indicator of disposal water but the current best estimate of the average surface water value makes it a far less sensitive indicator than at Lake Tutchewop. Presumably, the difference arises because Lake William sometimes evaporates to dryness and the high-D waters are lost.
- Disposal water, as indicated by major-ion ratios, is present in the top 0.5 m of sediment at a usually-submerged site. Major-ion ratios at a marginal site close to the regularly-flooded zone show strong deviations from the disposal water ratios in the narrow zone of evaporation-affected upper sediments. Both major-ion ratios and δD data support the conclusion that a maximum of 60% disposal water is present in the underlying 1.8 m of sediment.
- The presence of disposal water beneath the disposal basin and at a close marginal site, but not elsewhere, is common to both the Tutchewop and William disposal basins. In contrast to the situation at Lake Tutchewop, there is no obvious correlation at Lake William between high porosity and/or high sand content of the sediments and the presence of disposal water in the groundwater.

THE DISPOSAL BASINS

LAKES KELLY AND LITTLE

The investigation of Lakes Kelly and Little is based on four transects (Figure 53). Lake Kelly has three transects, approximately normal to the edge at the eastern (KEM), northern (KNM/KNEM), and southern (KSM) margins; and a drillhole (KWM) on the western margin (Figures 54a &b, & 55a). One transect (LLWM) lies on the western margin of Lake Little (Figure 55b). The eastern margin transect extends from the main basin across a low intra-basin lunette and a sub-basin and to the base of the main system of lunettes. The northern transect extends to the inlet channel for the disposal water in the floodplain or broad marginal environments to the north of the lake. The other transects extend from the regularly-flooded area of the disposal basin to the landward boundary of the lake margin environments.

Geomorphology

Lake Kelly and Lake Little are components of a discharge complex which lies nestled into and east of a north-south regional dune (Figure 1). Collectively the lakes form an approximately equant feature but the lakes are separated by the eastern lunette of Lake Little. Within both lake basins, there is at least an additional lunette feature that subdivides the general deflation depression into smaller interconnected basins. Salt harvesting on the western side of Lake Kelly has additionally modified the shoreline and bathymetry in that region.

The main and deepest basin of Lake Kelly has a floor at 67.4m AHD and is elongate north-south. The low-relief lunette within the general basin parallels the existing lake, and causes partial separation of smaller flats at 69m and 70m AHD to the east, adjacent to the main lunette to the east of Lake Kelly.

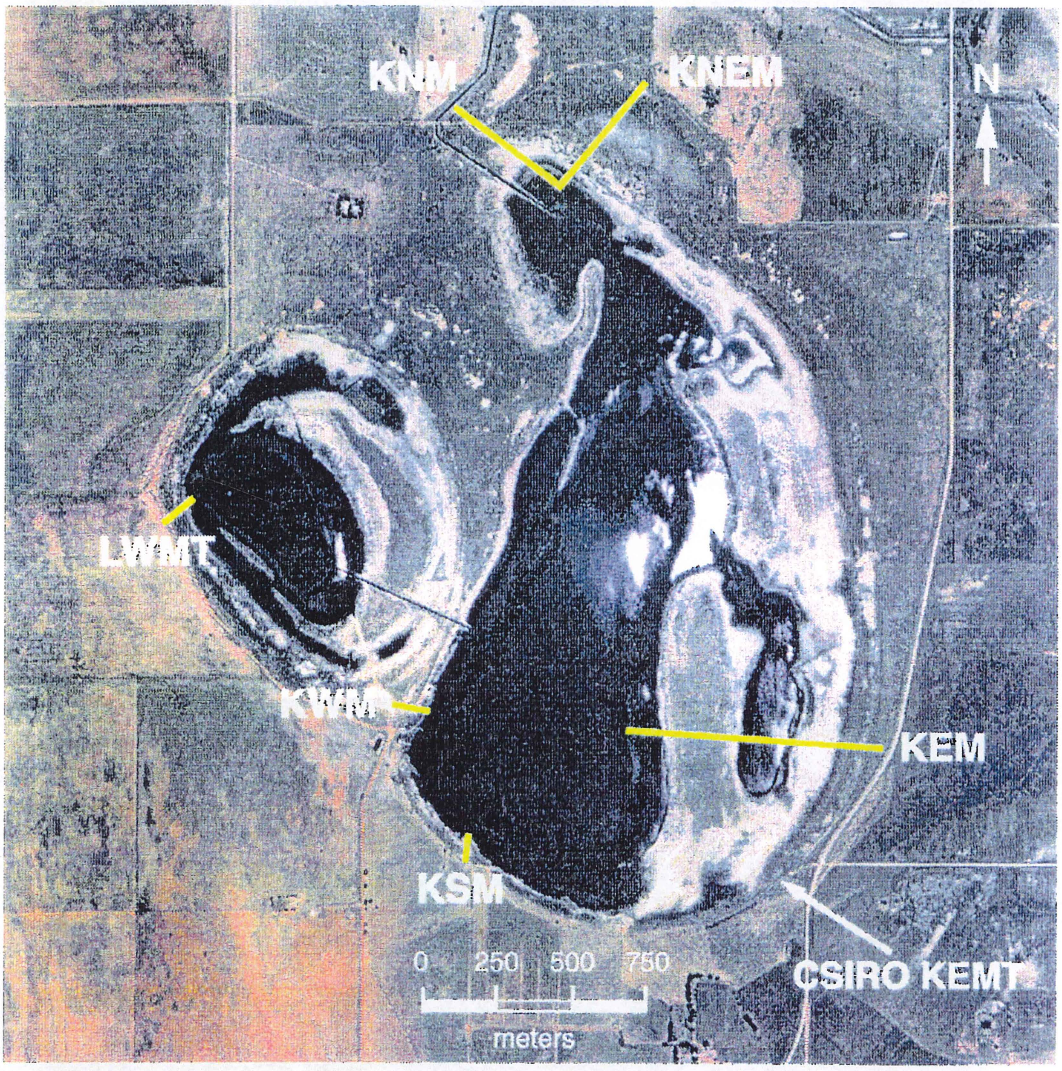


Figure 53. Locations of transects at Lakes Kelly and Little.

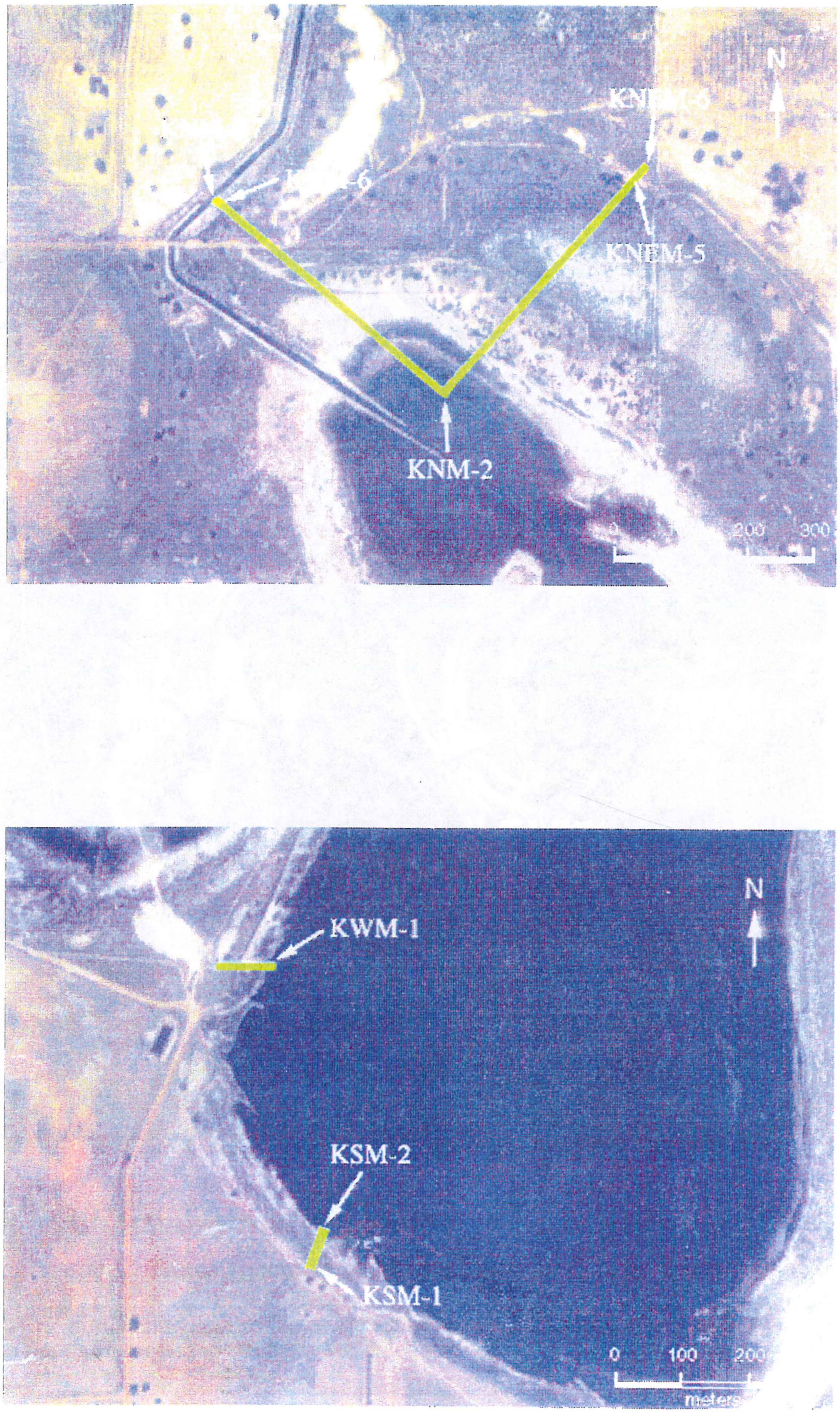
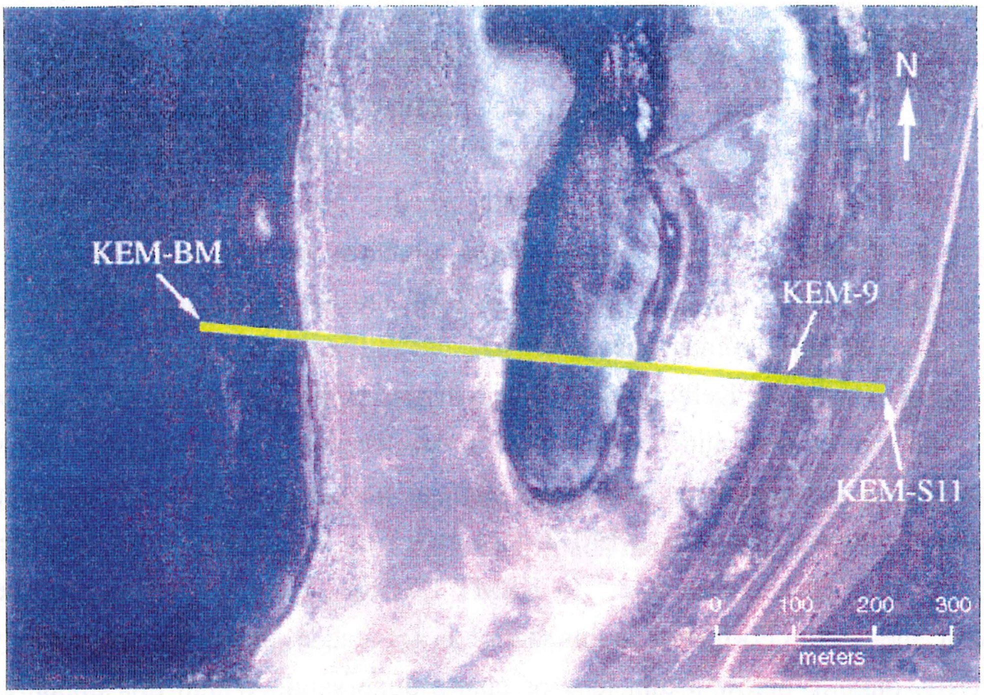


Figure 54. Locations of transects on (a) the northern (KNM) margin, and (b) the western (KWM) and southern (KSM) margins of Lake Kelly.



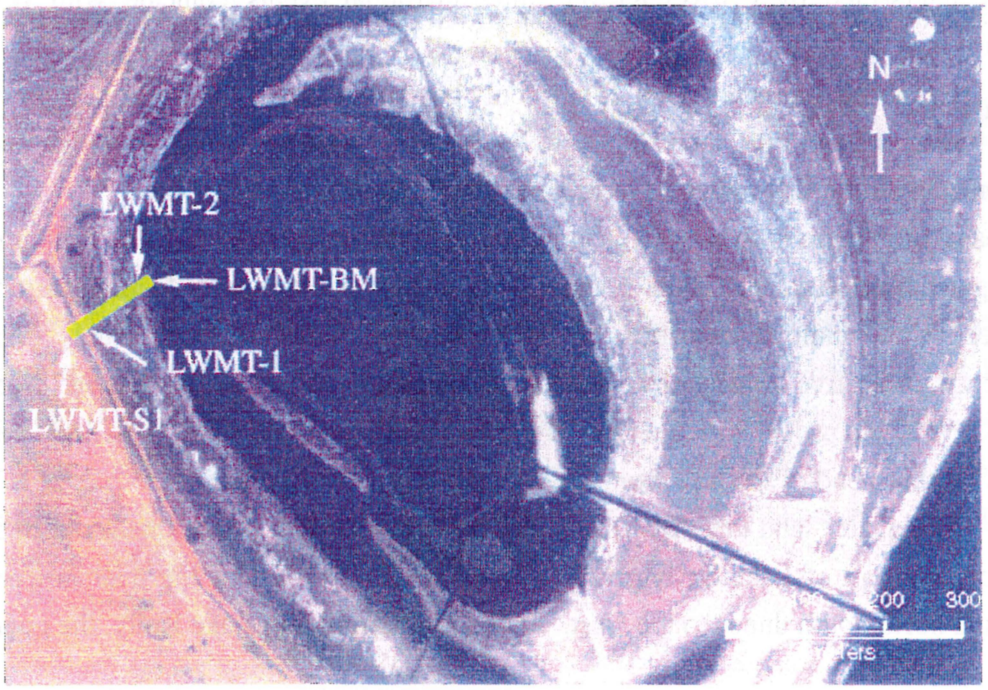


Figure 55. Locations of transects on (a) Lake Kelly eastern margin (KEM), and (b) Lake Little western margin (LLWMT).

Stratigraphy

The lacustrine sequence of Lake Kelly has the most complex geometry of depositional units of all the lakes (Figure 11). Within the lake basin, a north-south lunette covers and preserves the deepest and most distinctive evaporitic laminites of Yamba Formation. These laminites directly overlie a permeable sand stringer within the Shepparton Formation, a probable original spring site that initiated discharge and subsequent deflation of the lake basin. These laminites are comparable with the middle (Unit 2) laminated lithofacies in the Lake William sequence and may indicate that Lake Kelly commenced development subsequent to Lake William.

The present Lake Kelly floor has an asymmetrical profile and shallows east to west, with a planar central floor and steeper slopes on the margins. The basin floor and western marginal slopes correspond to an extrapolation of the upper surface of the Shepparton Formation between KEM 4 and KEM 2, and in K1 on the west side of the lake. This appears to be a deflation surface. In KEMT CSIRO on the eastern lunette, the upper surface of Shepparton Formation in this section is not readily identified, but probably lies at 71m AHD, directly below a thin lens of quartz dune sand. Within this upper 2.5m of Shepparton Formation intersected in this borehole, two overlapping pedogenic profiles and four erosional events are recognized. The erosional surface shallows gradually northward to about 68.5m AHD at KNM 2 and then rises on the margin to 72m AHD in KNEM 5.

It is uncertain how many deflation cycles are preserved in the lunettes of the complex. Within the lunette at KEM 4, three erosional events are apparent. In the main lunette intersected by CSIRO KEMT, three erosional events coincide with pedogenic overprints.

Evaporitic laminites (Unit 2) have only been observed in the lower section of KEM 4. In the other boreholes, there appear to be two lithofacies (Units 3 & 4) with a pedogenic overprint in Unit 3 that indicates lacustrine reworking of Shepparton clays.
The basal lithofacies is an evaporitic laminite, comparable to Unit 2 of Lake William.
Younger lithostratigraphic Units 3 and 4 have superficial similarity to Shepparton muds; mottled, with minimal oxidation of predominantly muds, but containing *Chara* and ostracods, indicative of lacustrine conditions. These units are more widespread from KEM 1 to KEM 2, and probably in the lake flats between KEM 4 and CSIRO KEMT, extending to the northern end of the lake from KEM 1 to KNM 2 (Figure 12).

The quartz sand lunettes (Unit 5b) flanking the eastern and northeastern margins of the northern part of Lake Kelly give some indication of timing of the main reworking of regional north-south dunes to the west. In this northern part of Lake Kelly, the quartz sand dunes are presently exposed adjacent to, and probably overlying, Unit 4 Yamba sediments. This implies very recent mobilisation of sands, initially into and across Lake Little, and then into and across Lake Kelly. It remains unresolved how these quartz sand lunette deposits relate to the pelletal clay lunettes further south and adjoining Lake Kelly.

Porosity & Permeability

At Lake Kelly, porosities are highly variable in both Shepparton and Yamba Formations (Figures 56 & 57). In the lunette deposits, there is a distinct difference between the eastern lunette which is generally porous (interparticle and fenestral porosity) and the lunette within the basin (KEM 4) where diagenetic gypsum cementation has significantly reduced original interparticle porosity. One of the basal fine quartz sands (Unit 5b) in the eastern lunette has a k_h of 5 m/day.

Within the lacustrine sequence, the basal mud-dominant Unit 3 is characteristically lower in porosity than the upper Unit 4 which has much more variable porosity that appears to diminish towards the lake margin.

The Shepparton Formation is generally tight with only thin sand horizons of high interparticle porosity. At the northern end of the lake, one very coarse silt interval has a k_h lower than the limit of resolution (<2.5m/day).

Hydraulic Gradients

The following information is based on 1 or 2 sets of piezometer measurements made between August and November 1994. During October-November, basin operating water levels were 70.26 and 70.55 mAHD. In November when most measurements were made, the operating level was 70.26 mAHD. This level is significantly lower than the mean water level of 70.56 mAHD during operation of the basin over the period July 1987 to April 1995 (Sinclair Knight Merz, pers. comm. 1996).

Vertical Gradients

Vertical hydraulic gradients were measured at a HydroTechnology piezometer nest at a site on the southwestern margin of the lake, between transect KSM and site KWM (Figure 54b). There is a strong upwards gradient from the deeper piezometer at -8.4 mAHD to the shallower piezometer at 56.9 mAHD (Table 7). Presumably this is a measurement of the difference in heads between the Parilla Sand and Shepparton Formation, or Renmark Group and Shepparton Formation.

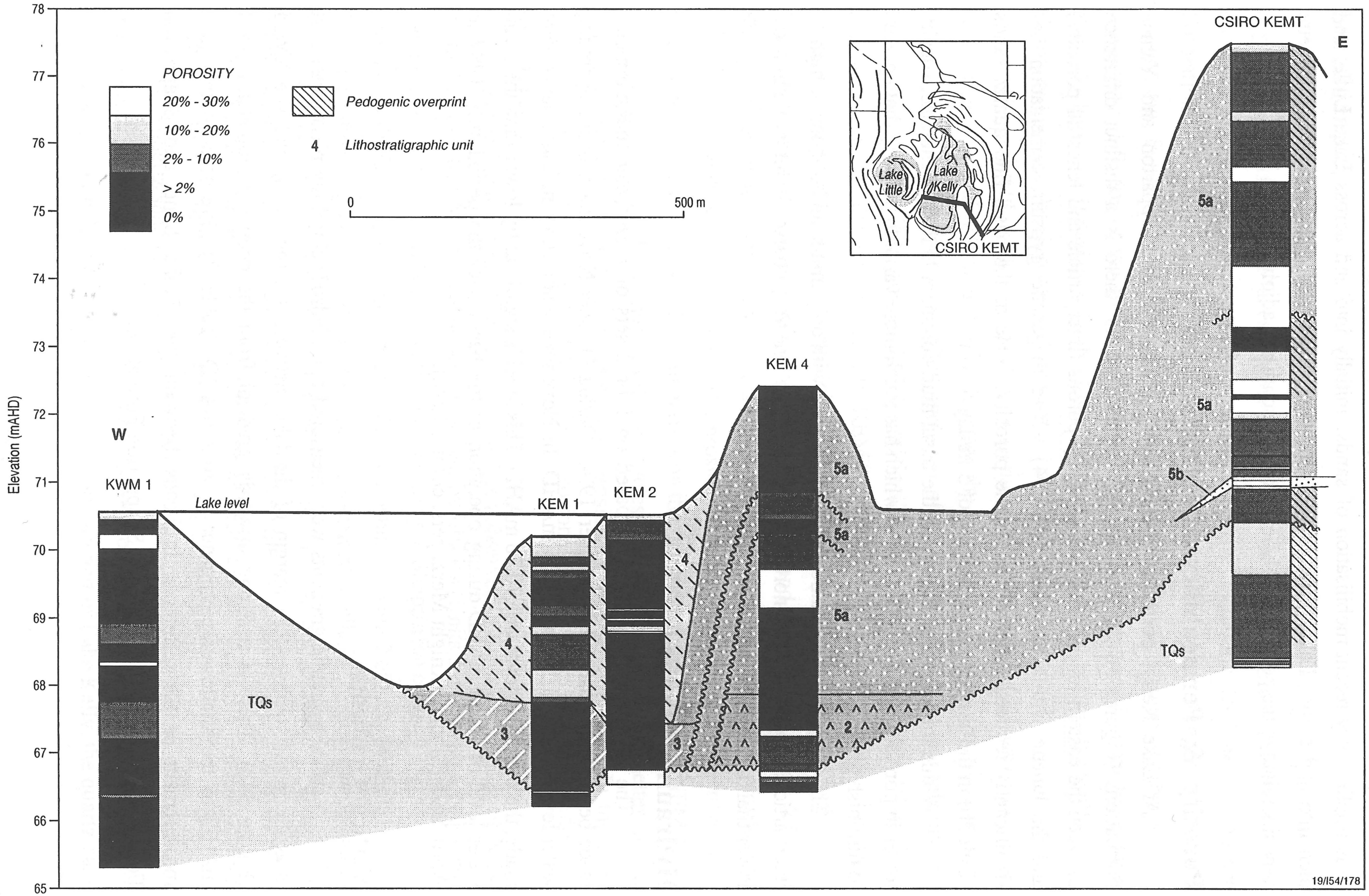


Figure 56. Porosity distribution in the Lake Kelly eastern transect (KEMT).

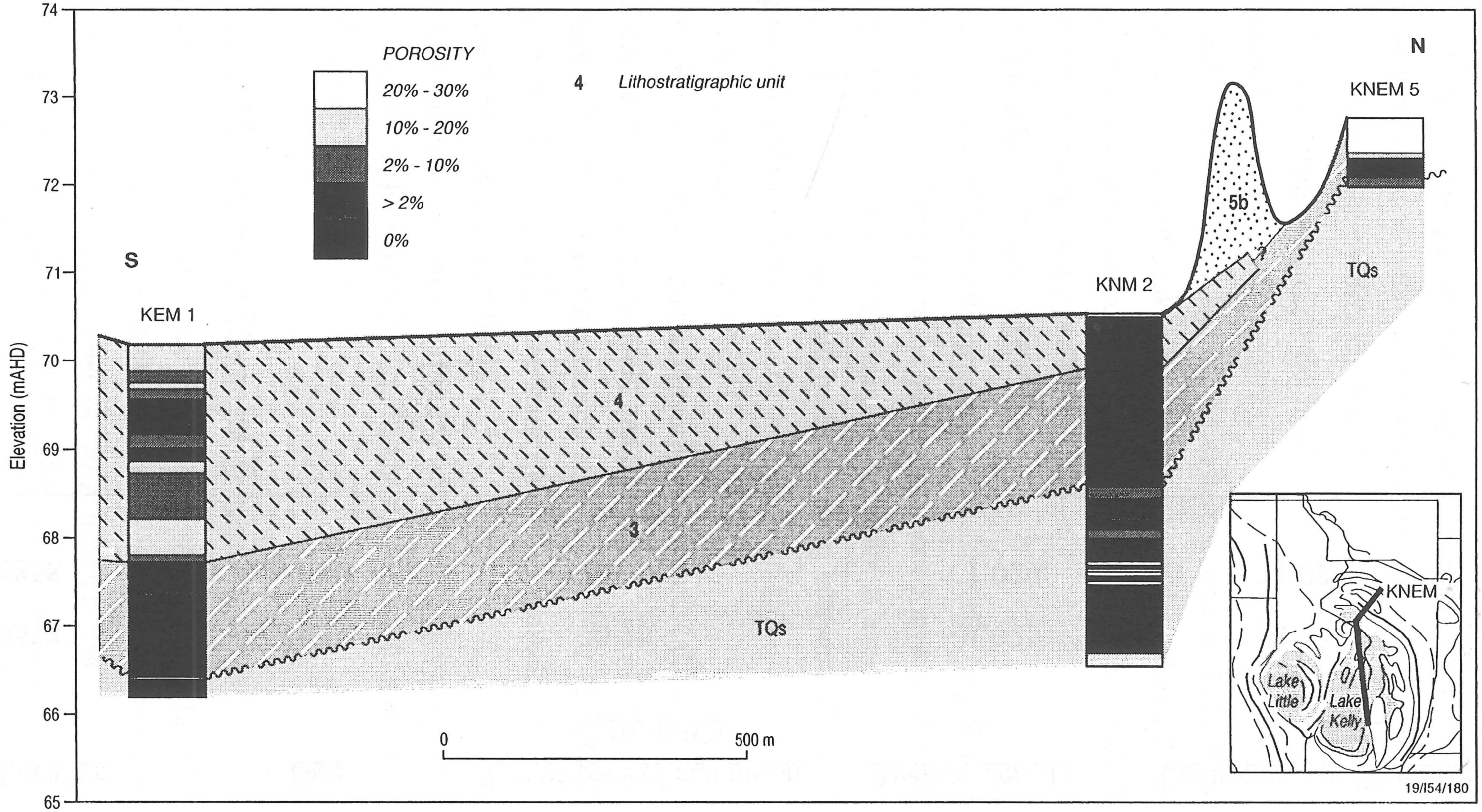


Figure 57. Porosity distribution in the Lake Kelly northern transect (KEM 1 - KNMT).

Table 7. Environmental Water Heads, Lake Kelly Western Margin Transect (KWM)

Location	Date	Top of zone of saturation Z_r (mAHD)	Average density ρ_a	Environmental Water Head H_{in} (ρ_f=1)
RWC 49573	17 Aug 1994	70.75	1.025	72.03
RWC 26858	17 Aug 1994	70.75	1.029	71.02

Lateral Gradients

Lateral hydraulic gradients between Lake Kelly and the adjacent marginal lake environments were measured using a four-piezometer array along the eastern margin transect KEM(T) (Figure 58), a five-piezometer array on the northern margin transect KNM (Figure 59) and a two- piezometer array on the southern margin (KSM). The Lake Little western margin transect contains a two-piezometer array.

Most lateral gradients were calculated for a constant elevation of 69.0 mAHD. Lateral heads cited are calculated freshwater heads.

Lake Kelly Eastern Margin Transect (KEM(T))

The lateral heads at 69.0 mAHD on the eastern margin of Lake Kelly (Figures 55a & 58). show the usual pattern of a lakewards gradient from the colluvium at the base of the main lunette to the usually-submerged areas, and a minimum in the heads in the regularly-flooded area of the lake margin (Figure 58).

Lake Kelly Northern Margin Transect (KNM)

The lateral heads on the northern transect at Lake Kelly (Figures 54a & 59) show the familiar pattern of a minimum in the regularly-flooded area of the lake margin. The lakewards gradient from near the inlet channel to this point is about 0.2×10^{-3} m/m, which is relatively low. The inlet channel could be intercepting lakewards-flowing groundwater, thus lowering the lateral heads in this area of the lake margin.

Lake Kelly Southern Margin Transect (KSM)

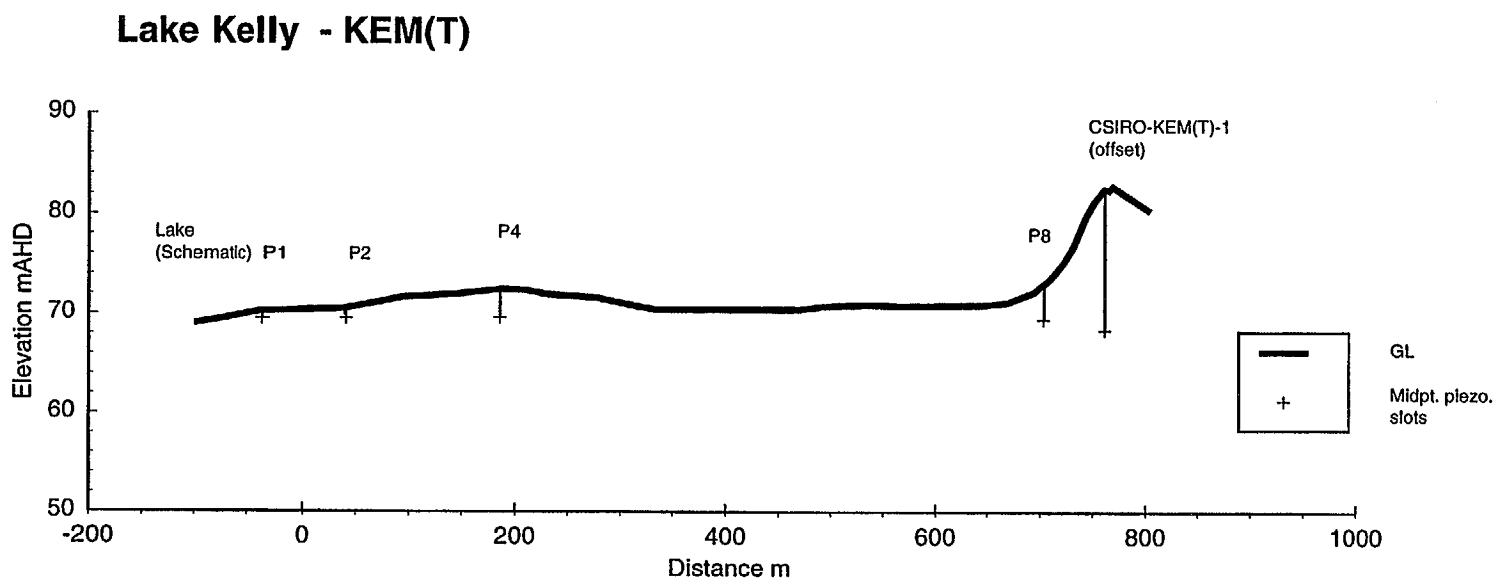
The Lake Kelly southern transect (Figure 54b) extends lakewards from a site at the landward boundary of the lake margin. Only one piezometer measurement is available. The head at this point midway across the exposed lake margin (70.42 mAHD) was slightly higher than that in the disposal basin at the same time (70.35 mAHD).

Lake Little Western Margin Transect (LLWMT)

The Lake Little western transect (Figure 55b) extends lakewards from a site at the landward boundary of the lake margin. The heads show the a minimum in the regularly-flooded area of the lake margin.

Potential Lateral Movement of Disposal Water

The lateral distances at a constant elevation of 69.0 mAHD to which the disposal water could move (Table 8) were calculated for two disposal-basin operating levels: (1) an assumed freshwater head operating level of 70.2 mAHD; and (2) the actual average freshwater head basin operating level of 70.7 mAHD which prevailed in the period January 1988 to April 1995 (Sinclair Knight Merz, pers. comm. 1996).



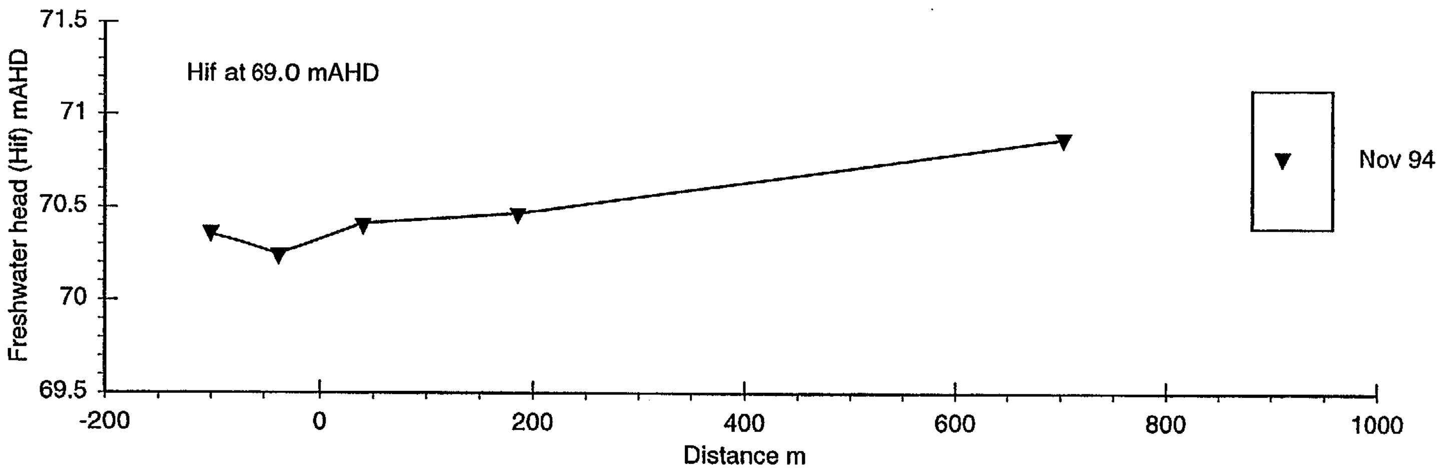


Figure 58. Lake Kelly eastern margin transect (KEM(T)): (a) topography, drill-hole and piezometer sites; and (b) lateral (freshwater) heads at 69.0 mAHD.

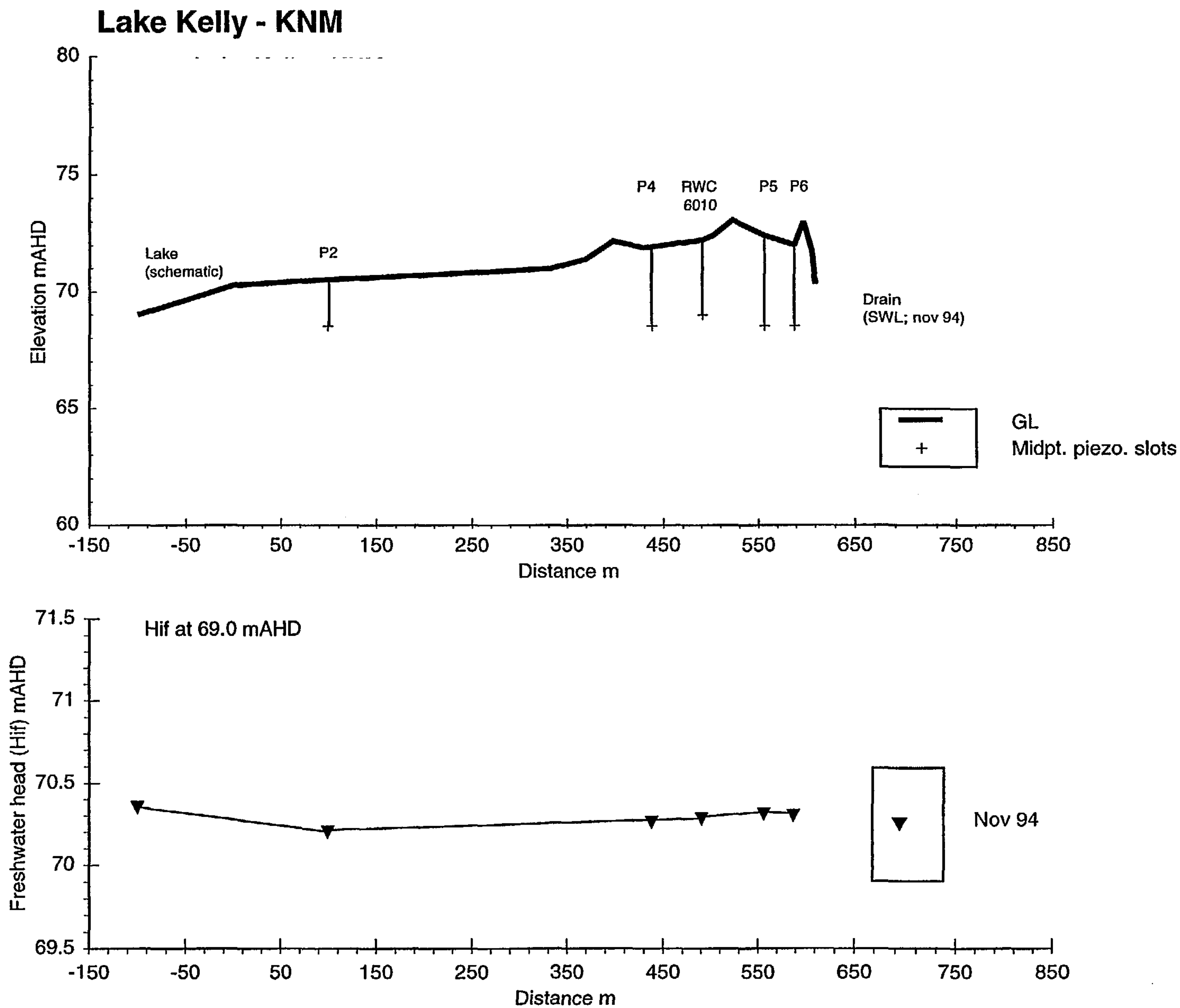


Figure 59. Lake Kelly northern margin transect (KNM): (a) topography, drill-hole and piezometer sites; and (b) lateral (freshwater) heads at 69.0 mAHD.

At a freshwater-head operating level of 70.2 mAHD the disposal water should not move more than 10 m beyond the waters edge. i.e. the water should be contained within the lake and its marginal environments (Table 8). At the actual freshwater head operating level of 70.7 mAHD the limit of movement to the east is lakewards of the colluvium at the base of the main lunette system, which is <700 m from the disposal basin. Elsewhere, the limit is beyond the landward ends of the transects (Table 8).

Hydrochemical Identification of Disposal Waters

As with Lake Tutchewop and William, the difference in salinity; and difference in ratios of the major ions to Br and major ions to Mg were tested as indicators of the presence of disposal water in the groundwater underlying and surrounding Lake Kelly. The D/H ratios of the waters were not determined.

The chemical indicators for the disposal water were determined from a series of measurements on samples of surface water in Lake Kelly collected by HydroTechnology mainly during the period January 1994 to September 1994. The chemical indicators for the groundwater were obtained from measurements on porewater from drill-cores.

Salinity

Surface Disposal Water

During the period January to September 1994 the salinity of Lake Kelly ranged from about 35,000 to 125,000 mg/L, with one anomalous sample of 304,000 mg/L. A graph of salinity against time for this period (Figure 60) has two parts: (1) the period between January and June 1994 during which the salinity gradually increased from about 98,000 to about 125,000 mg/L; and (2) the period after June 1994 when the salinity abruptly decreased to about 35,000 mg/L before gradually rising to 81,000 mg/L. The average over this period is about 100,000 mg/L. This is the clearest evaporation/dilution pattern of the three lakes. During 1988, six measurements averaged 55,500 mg/L and during 1994, 18 measurements averaged 103,000 mg/L (Sinclair Knight Merz, pers. comm., 1996).

Groundwater

The groundwater salinities around and beneath Lake Kelly are presented as salinity versus depth graphs for individual sites (e.g. Figures 61 & 62).

KEM-4 and KNEM-5, which are the sites furthest from the lake for which a salinity profile has been determined, have salinities down to about 55,000 mg/L and 45,000 mg/L, respectively, near the top of the phreatic zone (Figure 61). At the sites nearer the lake

Table 8. Possible Extent of Lateral Flow from the Lake Kelly/Little Disposal Basin

Location		Freshwater Head at 69.0 mAHD (mAHD) *Range* (Time period)	 *Average* (No. of readings)	*Possible Extent of Lateral Flow (m)*	*Possible Extent of Lateral Flow (m)*
Disposal Basin		(July 87 to April 95)	70.7(weekly)	at 70.2 (assumed)	at 70.7 (actual)
KEM	P4	(1 reading-Nov)	70.43 (1)		
	P8	(1 reading-Nov)	70.85 (1)	<10 (waters edge, lake margin)	<700 (lakewards of lunette colluvium)
LLWM	P2	(1 reading-Nov)	70.26(1)		
	P1	(1 reading-Nov)	70.51(1)	<10 (waters edge, lake margin)	>90
KWM	K1/115382	70.42 to 70.40 Aug-Nov)	70.56 (2)	<10 (waters edge, lake margin)	-----
no piezometer					
KNM	P2	(1 reading -Nov)	70.21(1)		
	P6	(1 reading -Nov)	70.31(1)	<10 (waters edge, lake margin)	>400
KSM	P2	(1 reading-June 95)	70.61 (1)		
	P1	(1 reading-June 95)	70.64 (1)	<10 (waters edge, lake margin)	>50

Lake Kelly

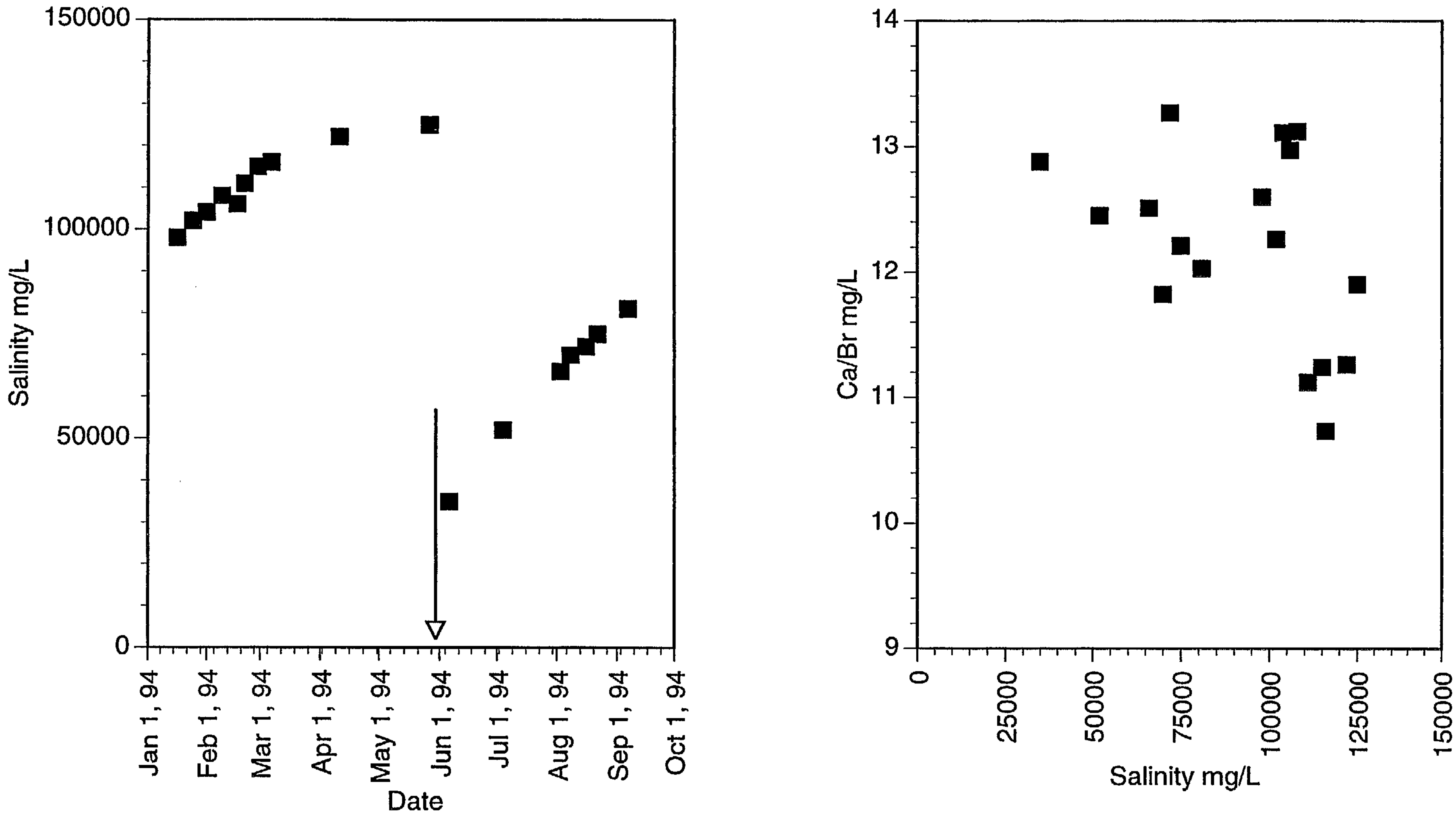


Figure 60. Salinity and Ca/Br ratios of Lake Kelly surface waters; January 1994 to October 1994.

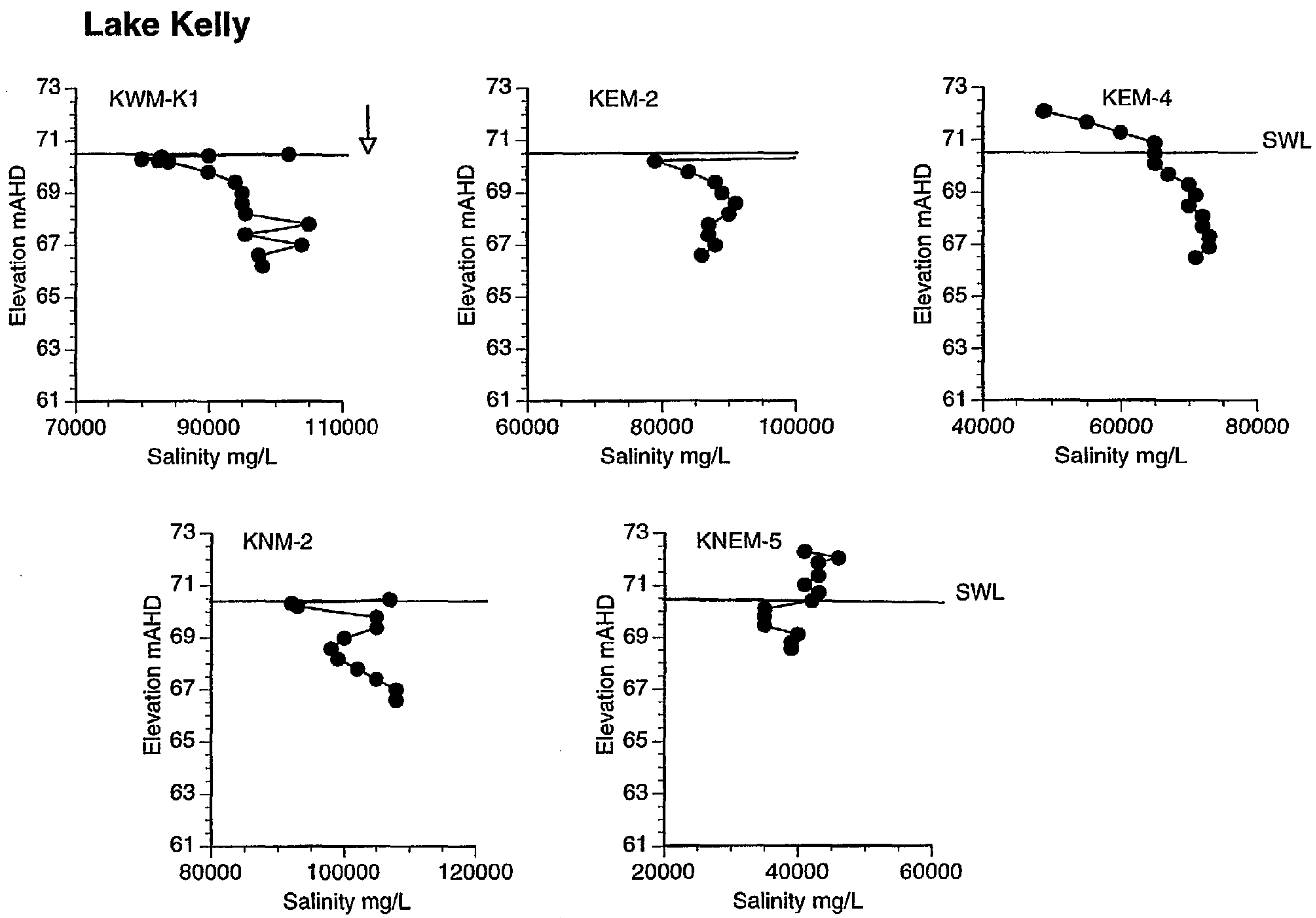


Figure 61. Salinity vs elevation profiles at various marginal sites around Lake Kelly. (Average salinity of the disposal waters in the period January to September 1994 is indicated by the arrow)

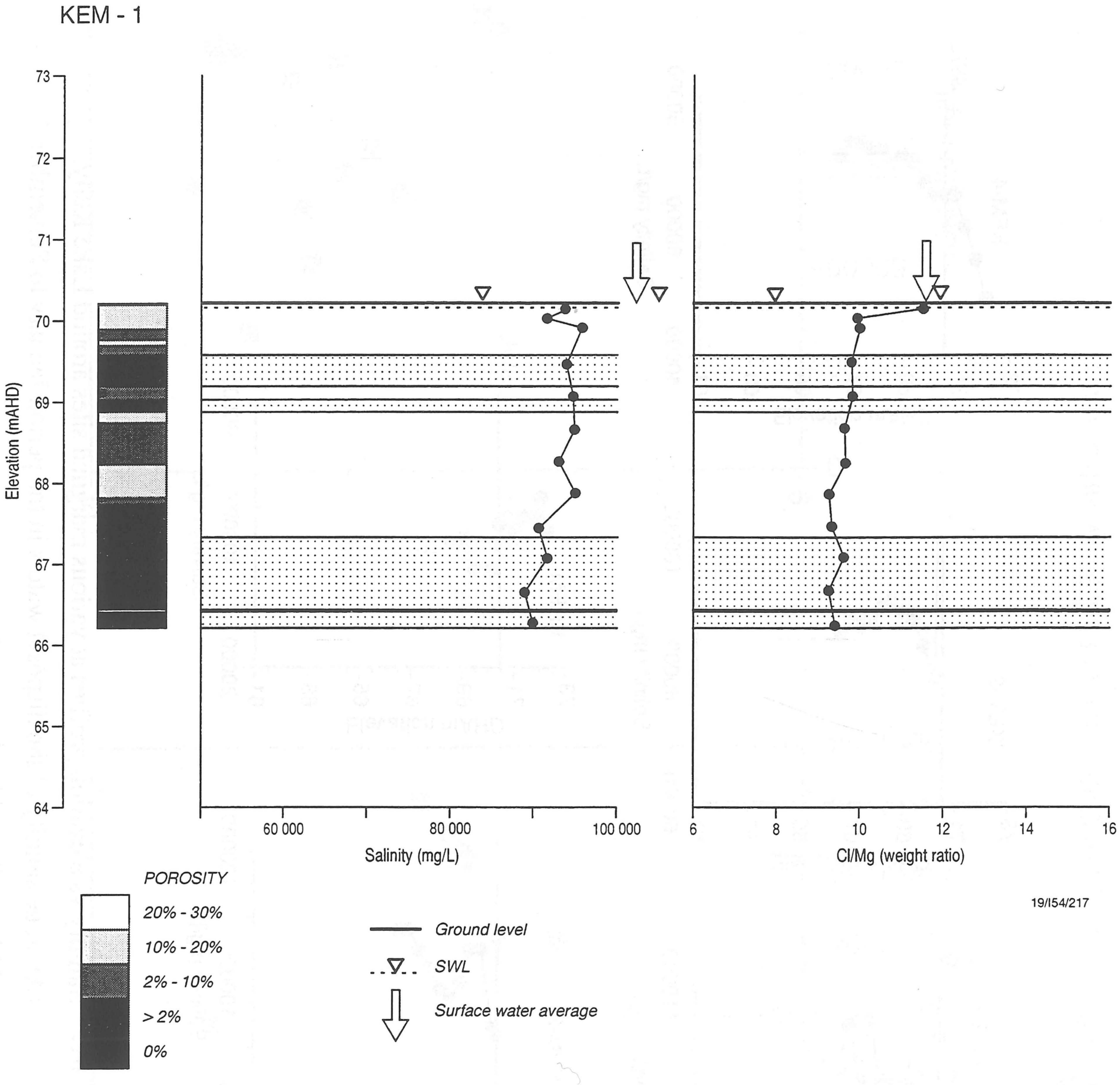


Figure 62. Relationships of sediment porosity to groundwater salinity and Cl/Mg ratios at a usually submerged site in Lake Kelly.

(KEM-2, KNM-2 and KWMT-K1; Figure 61), groundwater salinities are in the range 80,000 to 100,000 mg/L which is within the surface-water range and not greatly different from its average. At a site at the edge of the usually-submerged zone (KEM-1, Figure 62), the salinity does not change greatly with depth, and is about 90,000 to 95,000 mg/L.

As with Lake Tutchewop, salinity is not a reliable indicator of the presence of disposal water.

The maximum salinity encountered beneath the lake is 108,000 mg/L at KNM-2, which is close to that of the possible paleo-brine at Lake William.

Major-Ion ratios to Br or Mg

Surface Disposal Water

The range and average of the ratios of major-ions to Br or Mg were calculated for the period January to September 1994 and are presented in Figures 63 & 64. Ca/Br ratios change with changing salinity, indicating gypsum precipitation (Figure 58).

Groundwater

For the submerged site KEM-1 (Figure 58) at elevations >69.9 mAHD (i.e. the top 0.2 m of sediment), the major-ion ratios to Br or Mg (Figures 63 & 64) show: (1) definite trends towards the average surface-water values for most ratios; and (2) no definite trends away from the average surface-water values for the other ratios (except Ca/Mg). The ratios shown in Figures 63 and 64 indicate that, as a first approximation, the proportion of disposal water in the natural groundwater system decreases steadily with depth and is not detectable below an elevation of about 69.9 mAHD.

Assessment of the data for site KEM-1 and five other lake-margin sites for the presence of disposal water (Table 9) has positively identified disposal water only at KEM-1. Disposal water may be present in above 70.25 mAHD (i.e the top 0.25 m of sediment) at site KWMT-K1 but it is unlikely to be present at the other four sites (Table 9).

Discussion and Conclusions

- The lacustrine sequence of Lake Kelly has the most complex depositional unit geometry of all the lakes. Within the lake basin, a north-south lunette covers and preserves the deepest and most distinctive evaporitic laminites of the Yamba Formation. These laminites directly overlie a permeable sand stringer within the Shepparton Formation, a probable original spring site that initiated discharge and subsequent deflation of the lake basin. These laminites are comparable with the middle laminated lithofacies in the Lake

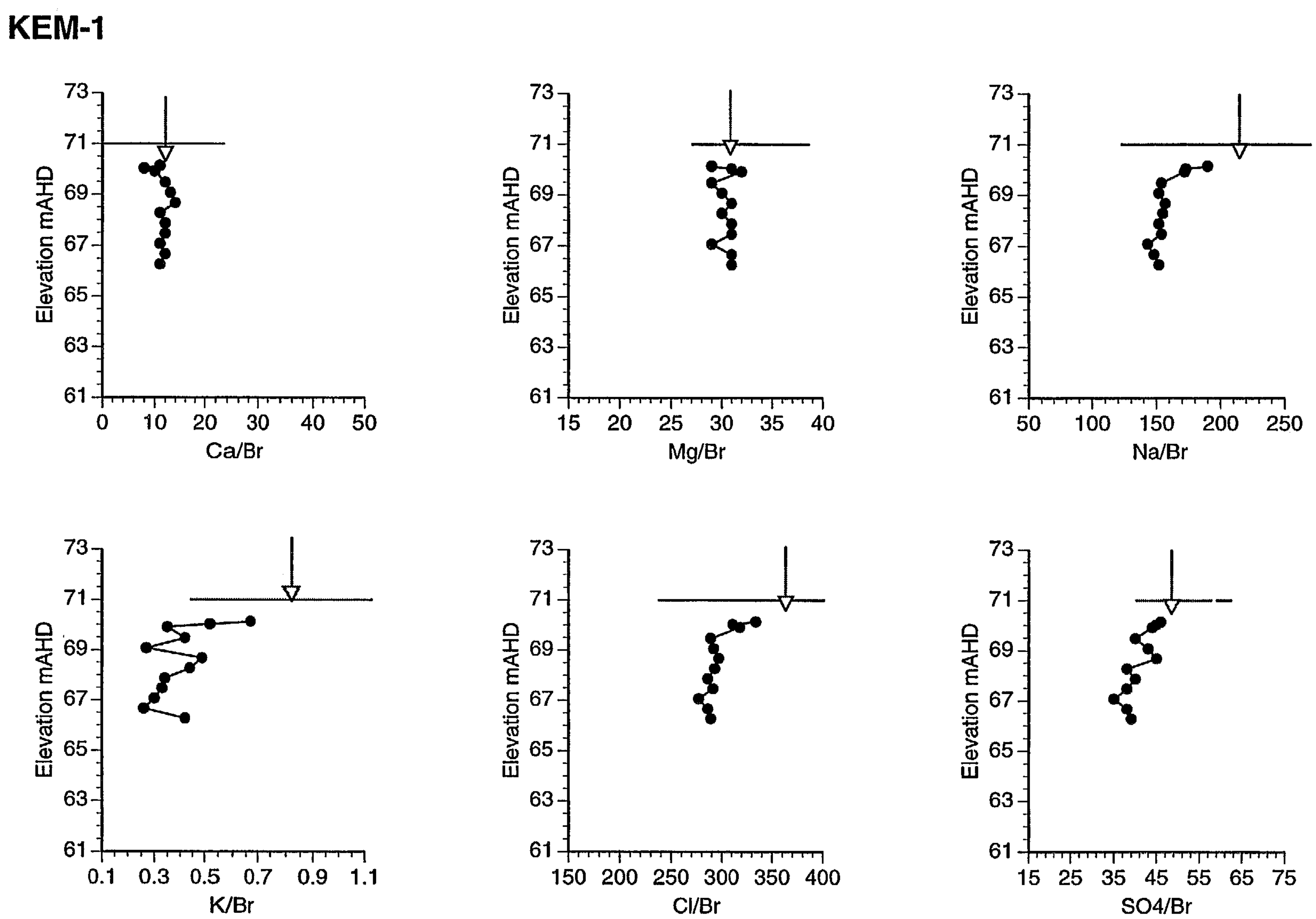


Figure 63. Lake Kelly eastern transect, usually submerged site KEM-1. Groundwater and surface water major-ion ratios to Br.
(Shaded area is the surface water range and the arrow the average)

KEM- 1

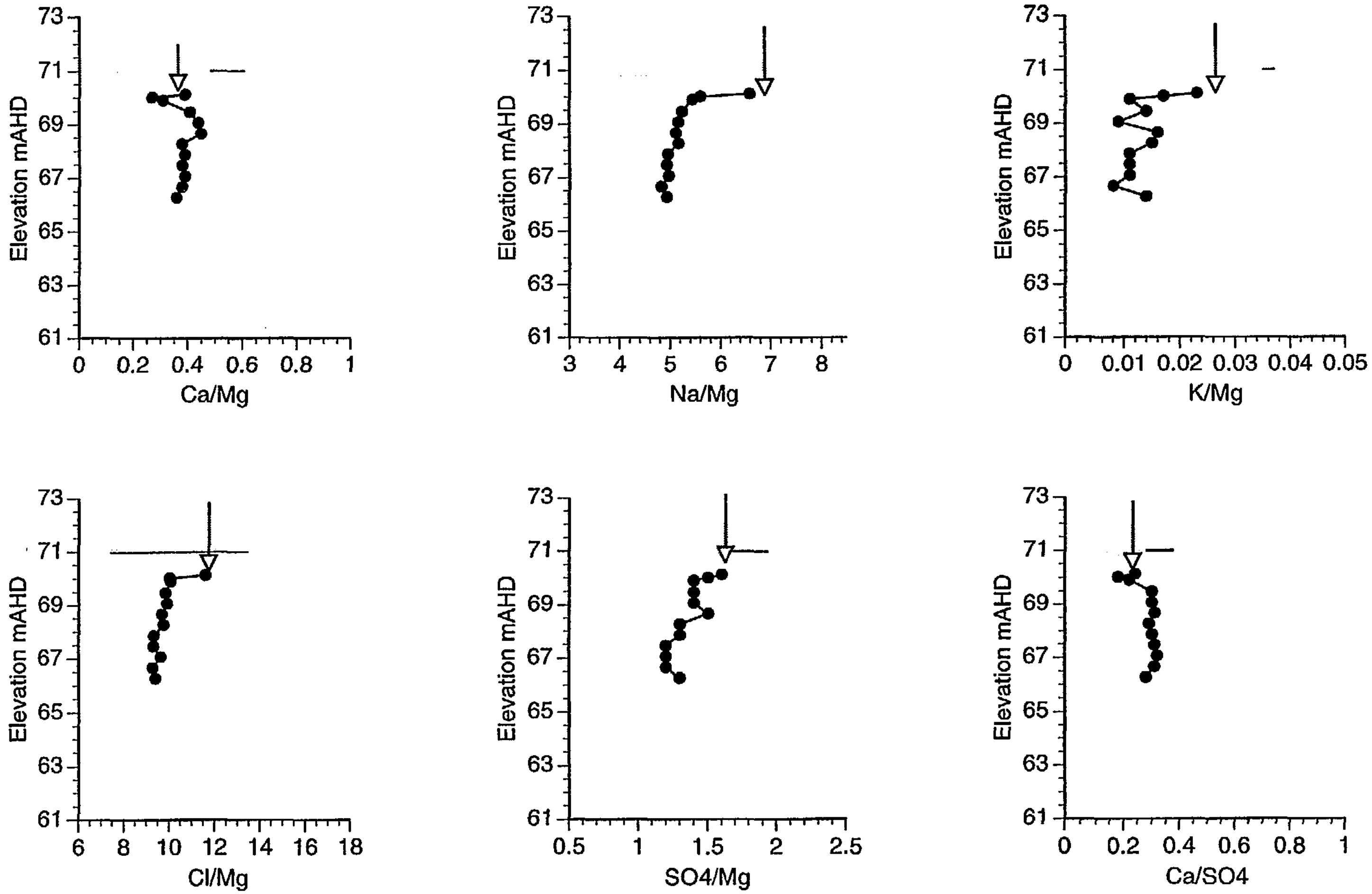


Figure 64. Lake Kelly eastern transect, usually submerged site KEM-1. Groundwater and surface water major-ion ratios to Mg.
(Shaded area is the surface water range and the arrow the average)

Table 9. Probability that disposal water is present in groundwaters beneath and around Lake Kelly.

	Depth[1]	Ratios/Mg			Ratios/Br			Total % Favourable Indicators Y=2;M=1;N=0	Disposal Water Present?
		Yes	Maybe	No	Yes	Maybe	No		
KNEM-5		0	0	3	0	1	3	10	No
KEM-4		1	1	1	0	2	2	40	No
KEM-2		1	2	0	1	2	1	60	Unlikely
KEM-1	to 0.2m	3	0	0	3	1	0	90	Yes
	>0.2m	0	2	1	2	1	0	50	No
KNM-2		1	1	1	2	1	1	60	Unlikely
KWMT-K1		2	0	1	3	1	0	80	Maybe

[1] Depth below sediment surface (submerged sites); or depth below SWL.

William sequence and may indicate that Lake Kelly commenced development subsequent to Lake William.

- The present floor of Lake Kelly appears to be a deflation surface incised into the Shepparton Formation. It is uncertain how many deflation cycles are preserved in the complex, but three erosional events are apparent within the basinal lunette, and three erosional events coincide with pedogenic overprints in the main lunette. The quartz sand lunettes flanking the eastern and northeastern margins of the northern part of Lake Kelly may give some indication of timing of the main reworking of regional north-south dunes to the west. There has been recent mobilisation of sand, initially into and across Lake Little, and then into and across Lake Kelly.
- Porosities are highly variable in both Shepparton and Yamba Formations. There is a distinct difference between the eastern lunette which is generally porous (interparticle and fenestral porosity) and the lunette within the basin, where diagenetic gypsum cementation has significantly reduced original interparticle porosity. One of the basal fine-grained quartz sands in the eastern lunette has a k_h of 5 m/day. Within the lacustrine sequence, the basal mud-dominant unit is characteristically lower in porosity than the upper unit . However in this upper unit, porosity is much more variable and appears to diminish towards the margins. The Shepparton Formation is generally tight with only thin horizons of sand with interparticle porosity. At the northern end of the lake, one very coarse silt interval has a k_h lower than the limit of resolution (< 2.5 m/day).
- Vertical hydraulic gradients at a site on the southwest fringe of the lunette are consistent with the Lakes Tutchewop/William data showing high gradients from the Parilla Sand aquifer to the overlying Shepparton Formation.
- Lateral (freshwater) heads (at 69.9 mAHD) along detailed transects at the eastern and northern margins of Lake Kelly show the distinctive minimum in the regularly-flooded area of the lake margin. This is evident under some conditions in Lakes Tutchewop and William.
- Pronounced overall lakewards gradients are evident for all transects except that at the northern margin. Along this transect the gradient from the edge of the disposal water drainage channel to the minimum in the regularly-flooded zone is very low and, under the measurement conditions, the head in the disposal basin was higher than that at the landward limit of the transect. This situation could be caused by the drainage channel which, if it is cut below the water table, may be intercepting any shallow groundwater flowing from the north towards the lake.

- For an assumed average freshwater-head operating-level of 70.2 mAHD lateral movement of the disposal water at an elevation of 69.9 mAHD should be limited to 10 m from the waters edge. For the actual average freshwater-head basin operating-level of 70.7 mAHD, which prevailed in the period January 1988 to April 1995, the limit of movement of disposal water to the east is lakewards of the colluvium at the base of the main lunette system. This is <700 m from the disposal basin. Elsewhere, the limit is beyond the landward ends of the transects.
- During the period January to September 1994, the salinity of surface water in Lake Kelly averaged about 100,000 mg/L. Near the lake, the maximum groundwater salinity encountered is 108,000 mg/L, which is close to that of the possible paleo-brine beneath Lake William and similar to the disposal water average. Consequently, salinity is not an indicator of the presence of disposal water in the groundwater.
- Disposal water in the groundwaters underlying and surrounding Lake Kelly was identified in highly porous upper 0.25m of sediments in a usually-submerged site on the eastern margin. It may be present at one marginal site and is unlikely to be present at four other sites. This general pattern of minor to moderate infiltration at some submerged sites and some close marginal sites, but not elsewhere in the lake margins and beyond, is consistent with the data from Lakes Tutchewop and William.

COMPARISON OF THE REGION WITH OTHER DISPOSAL BASINS

Lakes Tutchewop, William, and Kelly occupy deflation depressions within the Shepparton Formation. From the perspective of permeability, this host has a pronounced anisotropy caused by the random distribution of thin permeable sand and silt stringers throughout the clay/mud sequence. Additionally, the lakes have thin lacustrine deposits lining these depressions. All deposits have a predominance of impermeable muds over minor sand and silt.

The geometric configuration of the relationship of an impermeable host sequence, lined with predominantly impermeable lacustrine muds can be categorized with an existing lithostratigraphic classification (Radke *et al.*, in prep.) Because of their similarity, these lakes are ascribed to the same category, **uA p(C>S)**. This designation summarizes a uniform (**u**) anisotropic (**A**) host sequence, in this case the Shepparton Formation. The lacustrine deposits which line this host are planar (**p**) with clay/mud intervals predominant over sands (**C>S**) (Figure 65). Because of the amount of stratigraphic control available for Lakes Tutchewop, William and Kelly, the error probability of this designation is very low (10). With Lake Little, limited lithostratigraphic information creates a higher error probability (30).

uA p(C>S) is the second-largest category of disposal-basin types in the Murray System (Figure 66), comprising 16% of the disposal-basin population. Additionally, this category is one of the highest-ranked in its suitability for storage of saline water, based on the relative impermeability of both the host sequence and the basinal lining deposits (Radke *et al.*, in prep).

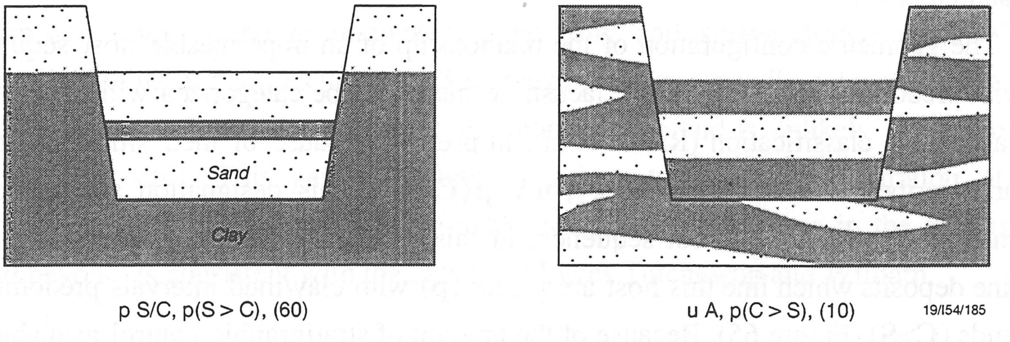


Figure 65. The most common types of disposal basin in the Murray Basin; Lakes Tutchewop, William, Little and Kelly are all type **uA,p(C>S)**

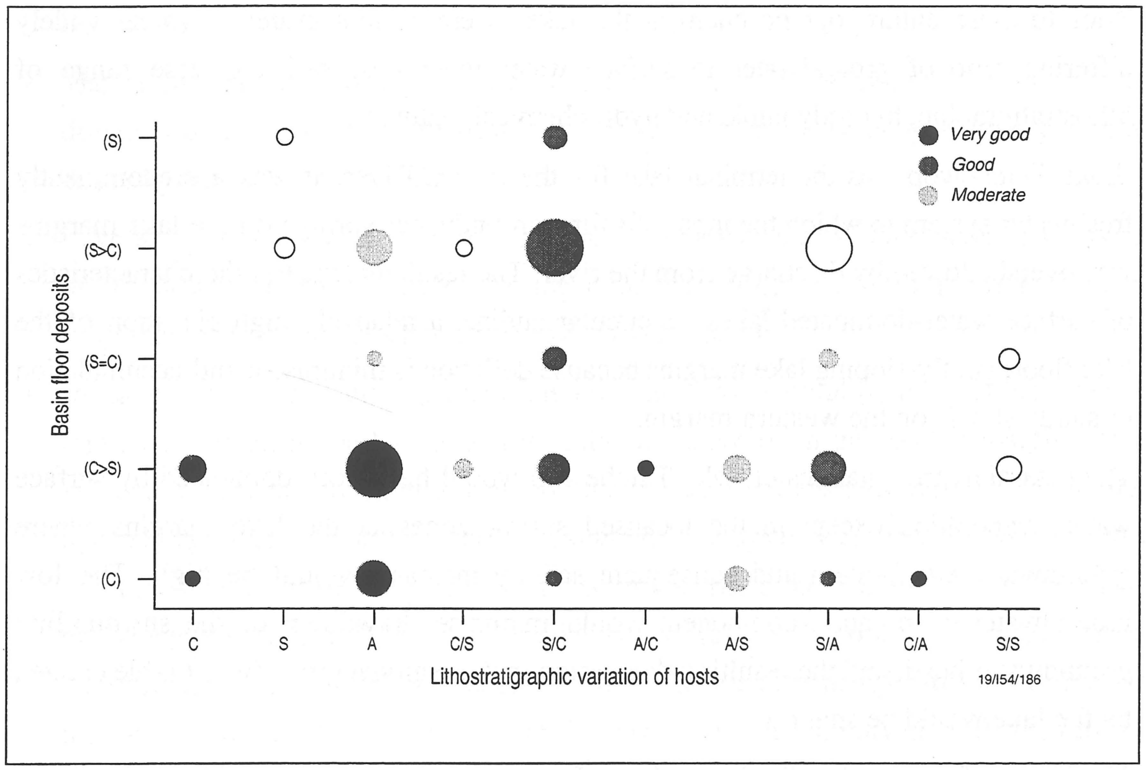


Figure 66. Potential for storage in disposal basins of the Murray Basin

CONCLUSIONS

- Lakes Tutchewop, Kelly and William are groundwater discharge areas whose natural characteristics have been extensively modified by a combination of their use as disposal basins, irrigation of the surrounding areas, and the installation of drains and channels associated with these activities.
- Prior to these anthropogenic changes the lakes were natural systems whose widely differing ratio of groundwater to surface water input produced a diverse range of lithostratigraphic, hydrodynamic and hydrochemical features.
- Lake Tutchewop was the terminal lake for the Avoca River. It was a predominantly freshwater system in which the input of saline groundwater springs on the lake margins was overshadowed by discharge from the river. The resultant lake has the characteristics of surface water-dominated lakes - a circular outline; a relatively high elevation of the lake floor; gently-sloping lake margins because deflation is minimised; and accumulation of sandy shoals on the western margin.
- The natural hydrodynamics of Lake Tutchewop would have been dominated by surface water evaporation except in the localised spring zones at the lake margins where groundwater evaporation and consequent salinity increases would be high. The low groundwater evaporation component would minimise drawdown of the surrounding groundwater head, and the resulting depression in the regional groundwater table created by the lake would be shallow.
- The low surface water salinities in Lake Tutchewop may have gradually reduced the salinity of the underlying shallow groundwaters by upwards diffusion of salt. In the vicinity of the spring zones this process would be minimised by the higher salinities of the evaporated spring discharges.
- Lake William provides the strongest contrast to Lake Tutchewop because the ratio of its groundwater to surface-water input would have been high. Surface water input could have been mainly overflow from a nearby lake through a small channel to the south-west. Groundwater input would have been facilitated by the relatively low elevation of the discharge area, which would have favoured higher artesian heads from the underlying Shepparton Formation.

- The saline groundwater-dominated hydrodynamic regime of Lake William would have favoured deflationary processes which would have further lowered the elevation of the lake floor, producing a topographic depression with relatively steep marginal slopes.
- The natural hydrodynamics of Lake William would have been dominated by groundwater evaporation from springs discharging into the lake and the consequent formation of highly saline surface brines. This groundwater evaporation would have had a significant drawdown effect on the surrounding groundwaters which, when combined with the effects of the relatively high topographic slope towards the lake, would have produced a depression of the regional groundwater heads much greater than that induced by Lake Tutchewop.
- The highly saline brines produced naturally in Lake William resulted in significant downwards movement of salt from the Lake into the underlying groundwater system, either by advection or diffusion.
- Lake Kelly was intermediate between Lakes Tutchewop and William in terms of its ratio of groundwater to surface water. During some periods of its evolution, Lake Kelly may have received floodwaters from the nearby river system.
- In Lake Tutchewop, under present-day conditions the natural hydrodynamic processes remain dominant in the lunette and its colluvial deposits on the eastern margin and are evident in attenuated form as springs on the western and eastern margins. The artificial hydrodynamic effects of the disposal basin/irrigation systems are most prominent on the western margin where the close proximity of the irrigation channel/Avoca floodway to the lake produces high but variable gradients towards the disposal basin. The effects of the artificial systems probably decrease from the western margin to the north-eastern margin, where active irrigation but not drainage works are involved, and still further to the south-western, where abandoned irrigation areas occur at the lake margin.
- The artificial systems around Lake Tutchewop help reduce the lateral distance to which the disposal waters would have to flow into the surrounding areas to produce hydrodynamic equilibrium but, as expected from the low lakewards hydraulic gradients which were probably associated with the natural system, theoretical distances of the order of hundreds of metres could be involved. The disposal waters probably create significant vertically-downwards gradients because the upwards gradients from the Parilla Sand aquifer are nullified by the clays of the Shepparton Formation, but they are difficult to quantify.

- Calculations based on lateral flow rates indicate that in the worst-case scenario, the maximum distance the disposal water could have moved during the period of operation of the disposal basin is about 200 m. More realistic flow rates indicate a range of between 2 and 20 m. Hydrochemical indicators suggest that the actual movement is comparable to or less than this latter estimate, and disposal water has moved only into sandy shoals on the western margin.

- In Lake William, under present-day conditions the natural groundwater regime is probably best preserved in the lunette-associated environments on the eastern margin, where vertical gradients are significantly upwards. Artificial systems dominate the hydrodynamics of the western and southern margins, where superimposition of the effects of active irrigation the natural groundwater heads produce high lakewards-sloping lateral groundwater heads.
- These high lakewards lateral gradients theoretically confine the disposal waters to within the lake marginal environments. The hydrochemical indicators suggest that actual movement is even less than this, with disposal water being positively identified only in shallow, usually submerged sediments within the basin and in the regularly-flooded marginal areas.

- Data for Lake Kelly are limited but the present-day hydrodynamics are probably intermediate between those of Lakes Tutchewop and William. The hydrodynamics to the north are affected by the channel carrying disposal water to the lake. In contrast to the situation created by the irrigation channel/Avoca floodway on the western margin of Lake Tutchewop, the drainage channel at Lake Kelly intercepts lakewards-moving groundwater and appears to reduce the lateral gradient towards the lake.

- The investigations of Lakes Tutchewop, William and Kelly have defined some of the wide variety of hydrodynamic situations produced at the margins of groundwater discharge complexes by as the existing natural hydrodynamics are modified by disposal waters and surrounding irrigation/drainage schemes.
- If containment of the disposal waters is the primary objective, then this may occur most effectively in groundwater-dominated sites such as Lake William. On the other hand, rises in the surrounding groundwater heads could be most significant at these sites as the strong drawdown effect of groundwater evaporation is reduced. Conversely, if

minimising the effects on the surrounding natural groundwater levels is of prime importance, then surface water-dominated discharge complexes may be the preferred site.

- No clear relationship between the sand/clay content of the sediments and the presence of infiltrated disposal water is evident. However, it appears that containment characteristics of the site as indicated by the actual movement of disposal waters are considerably by than those indicated by theoretical flow rate calculations and these are, in turn, considerably better than the theoretical limit at which hydrodynamic equilibrium is reached.

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APPENDIX I

METHODS

Drilling Techniques and Sediment Storage

The following procedures were designed to sample lacustrine clays and sandy clays in playas and salt lakes. The drilling equipment was readily dismantled and transported between sites with vehicle access to the lake shore, and then either hand carried or ferried by hovercraft. Lake surface conditions which ranged from dry, through muddy, to surface water less than 0.5 m deep have been successfully drilled. Existing techniques would have to be modified to cope with greater water depths.

The drilling method employed is a variation of the penetrometer technique in which steel tubes (5 cm diameter; 0.5 m long) are hammered into the sediments to 0.4 m depth using a drop hammer. The hammer is operated by a motorised hoist and mounted on an aluminium tripod derrick. The tripod accommodates lifting tools in 3m sections.

In lakes where surface conditions were wet or muddy a 20 cm diameter PVC tube was used to protect the drill-hole from influx of surface water. A steel tube was then hammered into the lake sediments, the uppermost wet, unconsolidated sediment removed, and the core tube extracted. A lightweight portable auger was then used to enlarge the core hole to 10 cm diameter The next steel tube attached to a drill rod was inserted and hammered down a further 0.4 m. This alternating hammering and augering procedure was repeated to the limits of the ability of the equipment to retrieve the cores, or until changes in the nature of the sediment made the technique inappropriate.

Holes up to 11 m and typically 6 m deep were cored by this method. The degree of success is a function of the clay content of the sediments. In the Murray Basin, the Blanchetown Clay and the Shepparton Formation were readily cored, and there was some success with the clayey sands which occur at the transition from the lacustrine clays to the top of the Parilla Sand. Water-saturated aeolian-derived sands, such as those which occur interspersed with lacustrine sediments can be cored if they are less than about 0.5m thick.

Cores were sealed and transported in stainless steel core tubes. Clay sediments were extruded either on site or in the laboratory using a specially designed hydraulic extruder. Cores containing sandy sediments could not be extruded and the tubes were cut lengthwise. The cores were extruded onto lengthwise-cut 8 cm PVC tubing and split. Each section was then sealed into an evacuated plastic sleeve to provide medium-term preservation against dehydration.

Porewater Extraction and Analyses

To minimise the possibility of contamination by ′float′, sediment samples for porewater analyses were obtained from the bottom 0.1m of each 0.5m tube. Salinity was determined by optical refractometry using a portion of small volume of porewater (typically ≤1 ml total) extracted from the sediments using a Manheim press or, occasionally for sandy sediments, by centrifugation.

Surface water samples were filtered through a disposable 0.45μ filter, and an aliquot (usually 10 ml) pipetted into a separate container for determination of alkalinity. A portion of the sample for determination of cations was preserved by addition of a small quantity of concentrated nitric acid.

Analyses of cations was by ICP and analysis of anions was by ion chromatography.

Installation of Piezometers

Piezometers used for water sampling and the determination of standing water levels in shallow holes were 8 cm - diameter PVC tubing, slotted over 1m in length. Where possible, the piezometers were cemented into place.

Piezometer Measurements

The standing water level and a two or three point salinity profile down the water column in the piezometer were measured and the salinity averaged if necessary. The density of the water in the piezometers was calculated from the salinity assuming a temperature of 20°C.

Calculation of Hydraulic Heads

Lateral and vertical hydraulic heads and gradients were determined separately using the concepts (Figure 67) developed by Lusczynski (1961) and Lusczynski and Swarenski (1966). This concept implies that lateral gradients can be determined from freshwater heads in piezometers screened to the same depth relative to a datum, and that vertical gradients can be obtained from environmental water heads measured along a vertical.

Application of the Lusczynski and Swarenski (1966) concepts to the hydrodynamics of groundwater discharge complexes has been described by Macumber (1991). The lateral heads are freshwater heads, calculated from the equation:

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

The vertical heads are environmental water heads, calculated from the equation:

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

H_{if} is the freshwater head at the point 'i' in groundwater of variable density

H_{ip} is the pointwater head at 'i'

Z_i is the elevation of 'i', with measurements being positive upwards

ρ_i is the density of water at point 'i'

ρ_f is the density of fresh water

ρ_a is the average density of water between elevations Z_r and 'i'

H_{in} is the environmental water head at 'i'

Z_r is the elevation of the reference point from which the average density of water to 'i' is determined, and above which the water is fresh

In the calculations of H_{in}, Z_r was taken as equal to the top of the zone of saturation. Because this measurement was not known at most locations, the SWL in the topmost piezometer was used instead. The value for the freshwater density was taken as 1.00 g/cm^3. Macumber (1991) showed that, for brines beneath Lake Tyrrell brines, a change of the freshwater density from 1.03 to 1.00 g/cm^3 made less than 4 cm difference to the value of H_{in}.

The lateral and vertical velocities were calculated from the equations:

$$v_x = - K_x [\delta H_{if}/\delta x]$$

$$v_z = - Kz[\delta H_{in}/\delta z]$$

For this investigation, the horizontal gradients were determined from piezometers set as close as possible to a constant elevation, and the vertical gradients from nests of piezometers at different depths at the same location. Under field conditions, installation of the piezometers to constant depth was not always feasible and the freshwater head at the designated depth was approximated by interpolation or extrapolation assuming a linear change in pressure with depth between piezometers. Care was taken to use interpolated data only from piezometers in the same aquifer (e.g. the Parilla Sand) or the same aquitard (e.g. the Shepparton Formation). These interpolated or extrapolated pressures were then converted to freshwater heads. For locations where only one piezometer had been installed, it was assumed that $P_{actual} = 0$ at a depth equal to the SWL in the piezometer, and the interpolations and extrapolations made on this basis.

Logging

Core preparation

Core was stored under dark coldroom conditions in air-evacuated sealed plastic tubes. Where possible core was extruded from the steel core tubes using a hydraulic press, into PVC half tubes and cut with a putty knife. If the sediment was predominantly sand, or the core old and the internal steel partly corroded, the core tube and sediment was cut with a power jigsaw and the core manually transferred to PVC half tubes. The homogenised cut surface was cleaned by a variety of methods dependant on the sediment type, stiffness, induration, or desiccation; cutting or scraping with a putty knife, or brushing with a soft bristle brush.

Documentation

Where possible core was photographed immediately in colour. Methodical observation of the sediment, observation of sedimentary structures, and measurement of clastic sediment particle size used a Wild M5 field stereomicroscope with calibrated graticule. Particle-size assessment usually involved disaggregation of a small fraction in a watch glass using distilled water and dilute HCl where necessary. The mineralogical composition was assessed visually at this stage. Where clay composition or an unidentified component required identification, X-ray diffraction samples were taken. Colour assessment was always made of wet surfaces, by comparison with colour tiles of the Rock Colour Chart, and recorded using the Munsell system.

Information was recorded on graphic log and notations as described by Radke (1992). Porosity type and qualitative abundance was assessed visually.

The scale of logging was generally at 1:2 Scotia fully cored holes.

In the deeper, 60 metre stratigraphic holes, coring was only undertaken in the uppermost 5 metres, and cuttings taken in each subsequent metre to the bottom of the hole. These holes were logged at 1:200 scale.

Logging Reduction

With the detailed logging at 1:2, it was necessary to reduce these logs for generalisations to be made on the lithostratigraphy. The condensing process was based on a 25 cm interval in which all information was reduced to one statement per category and recorded at 1:33. Lithologies in this reduction were recorded in histogram format, and the reliability of each increment qualified by a core-recovery assessment.

Core Sampling

Where minerals could not be identified, XRD samples were taken, either as a segment of core for clays and fine-grained carbonates, or individual particles hand-picked in the case of trace components.

Petrographic samples were taken of characteristic sediments, or unusual structures.

Particle Size Analysis

The procedure for sample preparation and analysis was as follows.

1. Dry total sample at low oven temperature for 2-3 days.
2. Cool samples in a desiccator and then split sample homogeneously to approximately 10-15 g.
3. Record the exact weights.
4. Wet sieve the sample through 2 mm (Gravel), 63 μ (Sand, with a centrifuge bottle to catch the mud fraction in suspension.
5. Wash the gravel and sand fractions into pre-weighed bowls, place in oven for drying and later weighing.
6. Centrifuge the mud fraction then siphon excess water, place mud in freezer and once frozen, put sample into freeze-drier until all excess water is removed.
7. Weigh dry gravel, sand, and mud fractions to obtain percentage composition.
8. Run approximately 2 grams of homogeneously split sand through the settler column, to obtain 0.2ϕ increment weights. Mean, standard deviation, skewness and kurtosis of sand is automatically computed.
9. Run mud fraction through the Sedigraph 5100 to obtain incremental and cumulative grain size percentages, and relative silt and clay abundances.
10. Enter gravel, sand and mud incremental weights with proportional percentages of each class toplot particle-size frequency curves and to compute median ϕ 50 and inclusive standard deviation.

Permeability Calculations

The granulometric data for the gravel, sand, and mud fractions of the 26 samples were combined and normalized. Particle-size frequency curves (Tables A5-A24, A47-A49, and A70-A73 of the data appendix, Ferguson *et al.*, 1995) were used to determine statistical parameters for the calculation of the measures - median (Md $_{50}$,) and inclusive graphic standard deviation (σ_I). A comparison of Md_{50} and σ_I for all samples is presented in Figure 3. These were used in the principal graphic algorithm of Masch & Denny (1966) (Figure **2**) to predict the hydraulic conductivity for the sands on the basis of experimental conditions with distilled water as the fluid at 17.5 °C. A summary of the estimated hydraulic conductivities is given in Figure 4.

APPENDIX II

A PRELIMINARY OSTRACOD-BASED PALAEOHYDROLOGICAL RECONSTRUCTION FOR THE KERANG LAKES AREA

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Summary:

Based on limited ostracod data, it can be generally stated that Lake Tutchewop was a relatively fresh lake (e.g. <10 gL^{-1}) during the top 1.35m of deposition. The ostracods found throughout the Tutchewop cores are consistent with its behaviour as a terminal lake for the Avoca River. A change in hydrology is evident at 18cm; a horizon that potentially coincides with European arrival, and a general rise in regional groundwater. Based on preliminary ^{210}Pb, hypersalinity (>35 gL^{-1}) was not evident in the lake until after the diversion of Barr Creek in 1968. At Lake Kelly the post-European elevation of the groundwater table, and the diversion of Barr Creek into the lake cannot be discerned because salt mining activities seem to have disrupted the upper part of the sequence. Assemblages found earlier in the record are presumed 30-40Ka (Quaternary Isotopic stage III) and suggest the sporadic influx, and subsequent evaporation of surface waters in the lake, possibly from a neighbouring lake or stream. In no part of the "surviving" record is hypersalinity evident. Ostracod abundance is too low in the Lake William record for anything constructive to be postulated regarding its environmental history.

Background:

The palaeohydrochemistry, and consequently palaeohydrology, of lacustrine systems can be estimated using a variety of biological remains preserved in the lakes' sediments. Ostracods, which are shelled aquatic microcrustaceans that superficially resemble tiny clams, are particularly suited to palaeohydrological investigations because they are both hydrochemically sensitive and are often found abundantly as micro-fossils (Delorme, 1969; Forester,1983; De Deckker, 1983). The ostracod shell, or carapace, is composed of low-Mg calcite and is readily preserved in well buffered lacustrine sediments where it is typically disarticulated into two valves.

Excluding human influences, variations in the physical and chemical limnology of lakes, and their biota, result from a complexity of interactions between climate, hydrology (surface and sub-surface), and topography. Consequently, a lakes response to a changing water budget (the ratio of precipitation/evaporation or similar), depends upon its hydrostratigraphical position within the drainage basin and the physico-chemical nature of the groundwater itself. Solute evolution (Eugster and Hardie, 1978) describes an evaporation-driven network of solute evolutionary pathways that connect critical compositional branchpoints. These branchpoints, or chemical divides (Drever, 1988), describe changes in solute composition that accompany mineral precipitation, and are controlled by the relative proportions of chemical constituents in solution. The first branchpoint occurs with the precipitation of calcite/high magnesian calcite. As evaporative concentration increases, the Mg/Ca increases, and the waters evolve towards the calcite branchpoint. At this critical junction, the water undergoes a radical transformation to Ca+Mg or HCO_3 enrichment depending on the initial Ca+Mg/HCO_3 ratio of the water. Generally speaking, following the calcite branchpoint, the Ca+Mg>HCO_3 system, which is now depleted in HCO_3, proceeds toward the gypsum branchpoint, and the HCO_3>Ca+Mg system, which is now depleted in Ca+Mg evolves toward the Mg-silicate branchpoint and/or the sulphate reduction branchpoint. This second chemical bifurcation can be elegantly predicted by the SO_4/Ca ratio of the water prior to the branchpoint (Herzeg and Lyons, 1991).

De Deckker (1983) demonstrated the importance of salinity to the distribution of Australian ostracod species and its palaeoenvironmental application and significance (De Deckker, 1982). Current research (Taylor, Ph.D in prep) aims to take this work one step further by providing a quantitative salinity transfer function to aid in the reconstruction of ostracod fossil assemblages, and to assess the importance of Ca+Mg/HCO_3 and SO_4/Ca ratios to extant ostracod communities. The following "qualitative" palaeohydrological assessments for the Riverine Plain, Victoria, represent some preliminary observations based on this work.

Before looking at the ostracod records from the Lake Tutchewop, Lake Kelly and Lake William disposal basins, it is instructive to look at some detailed ostracod records from other lakes in the Kerang Lakes Area (KLA) as a basis for comparison. The records presented here are from non-dated, short (< 40cm), cores and are thus of limited value for the interpretation of regional Quaternary palaeohydrogeology. They do, however, present clear evidence for recent dramatic changes in watertable elevation in the area, probably coinciding with European arrival.

Post-European Hydrogeological Change in the Kerang Lakes Area:

A series of short (*e.g.* <40 cm) cores were taken from Lakes Wandella (35°44.5S; 143°52.9E), Golf Course (35°28.9E; 143°36.7S), and Lookout (35°40.9E; 143°39.5S) in the KLA, using a gravity-coring method. The detailed ostracod stratigraphies from these cores are presented in Figure's 1, 2, and 3 respectively. The zonation of these diagrams is subjectively determined and corresponds to overt changes in the fossil assemblages. The zones are specific to a given lake.

Based on the ostracod records from these lakes a regional change in hydrology is observed at approximately 20 cm of deposition. At Lake Wandella (Figure 1), where the longest record exists (*e.g.* 40 cm), this change coincides with the replacement of a fresher water fauna consisting of predominantly *Candonocypris novaezelandiae* and *Ilypocypris australiensis* (Zone 2a), indicative of salinities of < 4 gL^{-1} and Ca+Mg/Alk ratios < 1, by *Mytilocypris praenuncia*, *Reticypris sp.*, and *Diacypris sp.* which imply salinities between 20-80 gL^{-1} and low SO_4/Ca ratios consistent with evolution towards the gypsum branchpoint (Zone 2b). A short, transitional, brackish phase (5-10 gL^{-1}; Zone 2a) pre-empts what is interpreted here as the rise of the Parilla Sand watertable following European land-clearance. In recent times, hydraulic heads in the Parilla Sands Aquifer beneath Lake Wandella have been up to 1.25 m above the lakes surface (Macumber, 1991). At Golf Course Lake (Figure 2) this rise in regional groundwater probably marks the sudden appearance of a halophilic ostracod fauna at 19 cm (Zone 2a). Prior to this (Zone 1), the lake was probably dry as judged by the 7cm+ sand unit at the base of the core, and the absence of biological material.

Another interesting feature of the Lake Wandella and Golf Course Lake records occurs at 10cm and 14cm respectively, with ostracod evidence suggesting a lowering of salinity ($<20gL^{-1}$) and the rise to prominence of the diatom *Campylodiscus clypeus*. At Golf Course Lake this change (Zone 2b) coincides with a change in community composition with the inclusion of *Mytilocypris praenuncia* and *Mytilocypris mytiloides*, while at Lake Wandella (Zone 2c), the "clypeus phase" (Yezdani, 1970) coincides with the elimination of the halophilic taxa *Reticypris* and *Diacypris*. This cosmopolitan species has a global salinity optimum of 4.4 gL^{-1} (S. Juggins, personal communication), and an Australian optimum of 4.2 gL^{-1} (Gell, 1995), and is found most frequently in waters with a high Na+K/Ca+Mg ratios. On the basis of this information, I propose that this taxon marks the movement of modern, Na-charged, recharge water (< 6 gL^{-1}), into the lakes following the implementation of large-scale flood irrigation in the KLA. Given that irrigation practices started in the region in the late 1880's (Corrick and Cowling, 1975) and that severe waterlogging and salinization were evident only nineteen years later (Macumber, 1991), the *ca.* 20cm transition probably represents a temporal unit of approximately 1910. This would be consistent with the preliminary ^{210}Pb date of 85 years (1911) (J. Olley, CSIRO, personal communication 1996) for an 10-12 cm unit in a core at Lake Tutchewop (see below). At Lake Wandella, *C. clypeus* is also found throughout the lower sequence of the post European record (Zone's 2a and 2b), albeit in lower general abundance. The initial burst of *C. cylpeus* at 20cm coinciding with the rise in regional groundwater however, potentially indicates that a lens of brackish water had developed below the lake during Holocene times. Similar brackish plumes have been identified beneath the Third, Middle and Reedy Lake sequence in the area (Bartley, 1992; Plumb *et al.*, 1996) as a legacy of lower regional water tables and downward hydraulic gradients.

At Lake Lookout (Figure 3), the interpretation is more complex because, at the present time, I do not know the degree to which this lake has been affected by irrigation, and the fossil record only extends to 23 cm. However, again at 20 cm (Zone 2a), ostracods make their debut in the record. In this situation however, the assemblage is representative of lower salinities probably in the range of 2 - 5 gL^{-1}, and, if groundwater does play a role in determining the composition of this community, it is probably through the elevation of salinity through the discharge of seasonal springs into the lake. Below this unit (Zone 1), the salinity of the lake was probably < 1 gL^{-1} as it is within this range that lakes are typically undersaturated with respect to calcium carbonate, and ostracods, had they lived in the lake, would not preserve as fossils in the sediment record. The change at 8cm (Zone 2b), again, might represent the mobilization of recharge waters into the lake as judged by the decline of the calciphilous taxa *C. novaezelandiae* and *Sarscypridopsis aculeata* (particularly the spiny morph), or simply the flow of irrigation waters into the lake itself. Figure 4, which shows the appearance of ostracods at 21 cm at Lake Cooper, Echuca (36°28.6S; 144°47.6E), illustrates that general rise in groundwater inferred from these diagrams was quite extensive on the Riverine Plain.

Lake Tutchewop:

Ostracods were present in low abundance in cores from TEMPT 1, TEMPT 6, and TEMPT 9 and from a short (*e.g* 15 cm) gravity core obtained from the southeastern portion of the lake (35°31.76S; 143°45.05E) near the Avoca outfall. The following interpretation involves an amalgamation of TEMPT 6, TEMPT 9 and the gravity core.

The earliest apparent occurrence of ostracods is at a sediment depth of 135 cm in TEMPT 6 (Figure 5). This assemblage is dominated by *Ilyocypris australiensis* and *Limnocythere porphoretica*, with minor components of *Limnocythere dorsosicula, Reticypris pinguis*, and *Diacypris spinosa*. With the exception of *R. pinguis* and *D. spinosa*, this assemblage is extant in Lake Hindmarsh (36°08.13S; 141°55.85E), a terminal lake of the Wimmera River in western Victoria. Based on a 179 sample data-set consisting primarily of lakes from western Victoria, these species are most common over an average salinity range of 1.3 to 1.9 gL^{-1}. The two Limnocytherid species have average Alk/Ca+Mg ratios of >1 whereas *Ilyocypris bradyi* has an average Alk/Ca+Mg ratio equivalent to 1. Based on this information this early unit in TEMPT 6 probably represents the discharge into, and subsequent evaporation of, Na-HCO_3 Avoca river waters in Lake Tutchewop. The presence of *D. spinosa* and *R. pinguis* indicates that salinity could have potentially varied to as high as 35 gL^{-1} or higher, though *D. spinosa* is most frequently encountered at approximately 10 gL^{-1} in high pH (>8.6) waters of moderate $NaHCO_3$ activity (as computed by NETPATH; Plummer *et al.*, 1991). Little is known about the *R. pinguis* as its modern occurrence has been limited to Lake George, NSW, over a salinity range of 4 to 35 gL^{-1} (De Deckker, 1981). The ostracod communities remain relatively unchanged until a sediment depth of approximately 18cm when *C. novaezelandiae* becomes a regular component of the Lake Tutchewop record (TEMPT 9; Figure 6). I believe that at this time regional groundwater levels rose (see above) in response to land-clearance, and higher levels of Ca were supplied to the lake. This species occurs most frequently at salinities of <3.5 gL^{-1} and at Alk/Ca+Mg ratios of <1. The sporadic occurrence of

Candonocypris novaezelandiae and charophyte oogonia throughout the TEMPT 9 record may indicate the periodic discharge of brackish springs into the lake in pre-European times.

Salinity remained low (*e.g.* <3 gL-*1*) until a sediment depth of 11 cm (Figure 7) when the *C. novaezelandiae-I. australiensis*-Limnocytherid dominated community (Zone 1) was abruptly replaced by an assemblage consisting predominantly of *Mytilocypris splendida* and *Diacypris* sp., suggesting a minimum salinity that probably exceeded 5 gL^{-1}. This 10-11cm unit (Zone 2; Figure 7) has been tentatively ^{210}Pb dated at 85 (-18+44) yrs BP (J. Olley, CSIRO, personal communication) and potentially marks the subterranean movement of irrigation-derived water into the lake (see regional synopsis above). Also evident in the ostracod stratigraphy of this short (*e.g.* 15cm), high resolution, core, is the rapid rise in lake salinity that accompanied the Torrumbarry Irrigation Scheme, and the diversion of saline water from Barr Creek into Lake Tutchewop via Lakes' William and Kelly. Between 6 and 8 cm, which has been tentatively ^{210}Pb dated at 40 (-6 +7) years BP (J. Olley, CSIRO, personal communication), the halophilic taxa *Australocypris*, *Reticypris*, and *Mytilocypris* first enter the lake (Unit 3a). I propose a salinity of 20-40 gL^{-1} for this transitional unit which maintains the occurrence of *M. splendida.* At 6cm, *Mytilocypris praenuncia* and *M. splendida* are effectively eliminated from the record. Salinities were probably averaged >50 gL^{-1} throughout this 0-6 cm unit (Zone 3b), which, based on observed and RWC salinity data of 40-108 mgL^{-1} , probably represents the 1980's and 1990's. The Australocyprid found in Lake Tutchewop was found to survive to 80 gL^{-1}. *Reticypris clava*, however, was found alive at 100 gL^{-1}.

Lake Kelly:

Ostracods first appear in the Lake Kelly Record (KEM 1; Figure 8) at about 2.5 m depth. This assemblage (Zones 2a and 2b), which is dominated by *Cyprinotus kimberliensis* and *Sarcypridopsis aculeata*, with an unknown species of *Reticypris*, was found living in Lake Albacutya in 1993, over a salinity range of 2-17.9 gL^{-1}. Prior to the implementation of the Wimmera Mallee Stock and Domestic System (WMSDS) in the late 1800's, Lake Albacutya was the terminal lake of the Wimmera River. Under the current hydrological regime however, about 50% of the mean annual flow of the river is diverted, and Lake Albacutya fills only sporadically. This assemblage may be indicative of a similar regime of periodic flow into Lake Kelly from a neighbouring lake or river system, during a period of enhanced fluvial activity, such as the Stage 3 sub-pluvial (30-50 Ka BP; Page *et* *al.*, 1991). The almost complete absence of Limnocythere, which generally lack drought-resistant eggs and are thus ineffective at the rapid colonization of temporary water bodies, suggests that Lake Kelly was a temporary waterbody during this episode. The same general interpretation of a temporary water body holds for unit 2b which differs from 2a mainly by the inclusion of *Bennelongia australis*, a frequent inhabitor of road-side pools (De Deckker, 1981b). This species may indicate that salinities did not reach as high as in Unit 2a as the highest recorded salinity of occurrence for this taxon is 4.4 gL^{-1}.

Ostracods are absent from the Lake Kelly record between the depths of 25 and 60 cm and consequently nothing can be said for palaeosalinity for this interval. At Zone 4 however, *Candonocypris novaezelandiae* appears in the record and may record the rise of regional groundwater on the Riverine Plain. However, gypsum and halite were regularly harvested at Lake Kelly, and I do not know to what extent this has altered the uppermost part of the record for this saline phase is completely missing from KEM 1.

Lake William:

Ostracods are found only sporadically in the Lake William core, and the dominant taxon was *Reticypris*, whose shells generally cannot be diagnosed to species level in fossil records. The co-occurrence of this genus with *Diacypris* and *Mytilocypris praenuncia* at 40 cm might suggest salinities of 30-50 gL^{-1} during this interval, increasing to possibly > 80 gL^{-1} for the remainder of the record.

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