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QUEENSLAND, AUSTRALIA

FINAL REPORT
SRDC PROJECT BS12S
DEVELOPMENT OF CRITERIA FOR DRAINING SHALLOW WATERTABLES IN THE ISIS IRRIGATION AREA

by

G Kingston

SD93002

Principal Investigator: Mr G Kingston
Senior Research Officer
Bundaberg Sugar Experiment Station
PO Box 651
BUNDABERG Q 4670

Phone (071) 59 3228

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SUMMARY

Seasonal persistence of shallow watertables was measured over the three year project in conditions which included a heavy wet season, major drought and progressive expansion of the irrigation area. The perennial persistence of the watertables and recognition of the shallow lateritic aquifer zone showed that the watertable at most sites should be classified as shallow rather than the normal interpretation of a perched watertable.

Watertables were classified into *non-seepage, seasonal seepage and permanent seepage* categories on the basis of seasonal variation in watertable depth.

Presence of a well developed nodular zone between 0.75 and 2.5 m depth in mid- or low-landscape positions, in areas with Tertiary Elliott Formation geology, was a good indicator of potential for waterlogging problems and potential requirement for improved drainage. New expressions of waterlogging hazards are appearing in mid-landscape positions rather than only in low-landscape positions. Low-landscape positions remain wet, but there was no significant elevation of watertables in this zone. An explanation for this phenomenon included allowance for differences in hydraulic conductivity and gradient.

The conceptual model for drainage design in Tertiary lateritic landscapes included the recognition that sub-surface drainage pipe should be located in the nodular zone, between 1.5 and 1.8 m depth, rather than in or on top of the clayey B-horizon. Design drain spacings were based on typical hydraulic conductivity data.

It was shown that regional groundwater was leaking upwards into the nodular zone aquifer. Specific hazard areas for such discharge were identified. It is unlikely that sub-surface drainage installations could be economically designed to cope with this discharge in addition to rainfall and irrigation percolation.

In Tertiary landscapes, the discharging water is of high quality and should be regarded as a resource rather than a liability.

A strategy was proposed for conjunctive use of this groundwater with reticulated surface water to enable draw down of the groundwater surface to an appropriate level. Details of the strategy will be the subject of further research by the Queensland Department of Primary Industries (Water Resources) and BSES.

It is extremely unlikely that economic subsurface drainage systems can be installed in Cretaceous landscapes because of lower hydraulic conductivities associated with heavy sodic clay B-horizons. Approval for installation of drainage schemes in such landscapes by a gazetted Drainage Board would be unlikely, because the highly saline nature of most drainage waters would prejudice existing stream water quality. Management options may therefore be constrained to efficient use of irrigation water on intake areas, and only restricted clearing of lower landscape locations.

Detailed chemical analyses for regional and shallow groundwater data on three occasions throughout the project provided the first comprehensive study of groundwater quality in the area. It was shown that high quality regional and shallow groundwaters from Tertiary landscapes could be objectively discriminated from poorer quality water from Cretaceous and Jurassic landscapes. These data will be useful as baseline data for observation of any changes in water quality associated with downstream effects of the irrigation scheme.

Levels of soluble phosphorus in the shallow groundwaters were very low, while on average 97% of samples contained less than the recommended level of nitrate in drinking water for humans.

1. INTRODUCTION

Expansion of the area planted to sugarcane in Queensland since 1974 increasingly has relied on areas in which adverse soil properties represent significant limitations to yield. These properties include depth and texture of soil, natural fertility, salinity, sodicity, and susceptibility to soil erosion and waterlogging. Input of capital and management expertise is necessary to overcome or manage these limitations.

1.1 Background to the project

Bureau of Sugar Experiment Stations (BSES) staff reported an increasing incidence of soil salinity in caneland in the Bundaberg, Isis and Maryborough Districts since the mid-1970s (Kingston, 1982). Regional surveys revealed that salt stored in the surface eight metres of earth represented a salinity hazard to 54% of 31 400 ha of landscapes in the Bingera District and to 37% of 40 800 ha in the Isis District (Kingston, 1987). There is a close relationship between expression of salinity and disturbance of the hydrologic balance (Peck, 1978).

Need for criteria to plan and implement integrated drainage schemes to control waterlogging in canelands of southern Queensland was recognised by Kingston (1982). In 1986, the Water Resources Commission (WRC) requested the Queensland Department of Primary Industries (QDPI) and BSES to assess suitability of soils in the Isis area for irrigation to facilitate design of irrigation reticulation to areas which would ensure viability of the irrigation scheme. The QDPI study found 2 000 to 3 000 ha of the 10 000 ha surveyed to be subject to salinity or drainage hazards (Forster and Macnish, 1987). The BSES survey showed that 1 100 ha were affected by salinity; this area included 200 ha of severe salinity hazard (Kingston, 1993). Similarity of geology, landform and soils developed from Cretaceous and Tertiary sediments throughout the region suggests that data acquired in the Isis area will be relevant to significant sectors of the Bundaberg to Maryborough region.

The Forster and Macnish (1987) work yielded only presence or absence of drainage limitations, based on observation of hydromorphic features in the profile. No data were available for depth to the seasonal watertable. This parameter is shown for soil survey reports published by the USDA, and is based on the indicative properties used by Forster and Macnish (1987), along with observation of the watertable during the survey and from short-term studies (Soil Survey Staff, 1983).

There is considerable discussion in the literature on reliability of seasonal watertable depths inferred from soil morphology. Simonson and Boersma (1972), Guthrie and Hajek (1979) and Vepraskas (1980) have studied the above relationship, but Hyde and Ford (1989) concluded that less variable relationships between morphology and watertable position were obtained as length of the study period increased, namely three to four years compared to seven to 10 years.

Daniels *et al.* (1987) concluded that absolute waterlevel, or duration of saturation above a certain depth, could not be predicted from morphological features alone. They suggested that description of watertable depth for a landscape unit would be more accurate than morphological classification of soils in the unit.

Depth at which a saline watertable presents a salinity hazard to crop production depends on the salinity of the water, frequency and amount of irrigation, soil physical characteristics, crop characteristics and weather (Peck, 1978). The critical depth for many soils lies in the range 1 to 2 m, although it can approach 7 m (Talsma, 1963; Rhoades, 1974).

There were no quantitative data for duration or elevation of shallow watertables in landforms of the Bundaberg to Maryborough region.

1.2 Effect of a shallow watertable on sugarcane

Sugarcane is a highly aerobic plant (Nickell, 1977) in which growth restrictions from waterlogging are attributable to decreased oxygen supply and accumulation of carbon dioxide (Vand't Woudt and Hagan, 1957; Williamson and Kriz, 1970; Carter, 1980). This condition restricts nutrient uptake.

The root system of sugarcane is most active in the surface 0.6 m of soil (Shen and Tung 1964; Baran *et al.*, 1974; Kingston, 1975). Gosnell (1971) showed that there was no effect on cane yield when a watertable was maintained 0.75, 1.0 or 1.25 m below groundlevel in a lysimeter study. However, elevating the watertable to 0.25 and 0.5 m caused yield reductions of 63% and 35 %, respectively, in relation to the 0.75 m treatment.

Rudd and Chardon (1977) found that cane yield was depressed by 0.46 tonnes /ha /day for each day the watertable was shallower than 0.5 m and represented a yield loss of 48% compared to sites where the watertable depth averaged 0.9 m during peak growth months. This response is of the same order of magnitude as the 35% loss reported by Gosnell (1971) and the 40% reduction for the peak growth stage by Gayle *et al.* (1987).

1.3 Shallow watertables in irrigation areas

Watertables within irrigation areas can rise in the short-term as a result of additional deep drainage from irrigation (Kelley, 1964; Hanson, 1984; Jensen, 1985; Schwartz *et al.*, 1987). Perched shallow watertables often demonstrate a strong dependence on seasonal conditions, whereas enduring shallow watertables in irrigation areas often result from interaction with deeper aquifers. Elevation of shallow watertables in irrigation areas in the Campaspe Valley of the Riverine Plain in Northern Victoria, Australia, was associated with increased recharge and pressure in an underlying deep lead aquifer (Ife and Trewhella, 1985). The hydraulic connection between shallow and deep aquifers in that region was demonstrated and exploited by Mehanni (1987), who pumped the deep aquifer to lower the level of shallow watertables. Similarly Ghassemi *et al.* (1988) showed that recharge of deeper Parilla Sand aquifers, in the Mildura area of Victoria, was responsible for discharge of shallow saline groundwater into the Murray River, and that aquifer pumping relieved piezometric head sufficiently to manage discharge into the river. Henschke (1983) concluded that saline seeps in the wheat-belt of Western Australia were all associated with hydraulic gradients which indicated potential for discharge of water from deep, semi-confined aquifers.

1.4 Rationale for the project

This project was proposed to the Sugar Research Council because qualitative data suggested a significant problem with waterlogging and salinity in hydromorphic sedimentary soils in the Bundaberg to Maryborough region. Also there were no quantitative data to indicate elevation of watertables in areas of hazard, nor were there any criteria to determine an approach to management of shallow watertables in the region.

2. OBJECTIVES

- Quantify the seasonal persistence of perched watertables in various soil types in relation to previously recognised soil morphological features associated with prolonged wetness.

- Determine the areas within which drainage schemes are required.

- Develop drainage design criteria/models for recognisable soil type x environmental situations to overcome the need for site specific investigations when farm and community drainage works are indicated.

- Acquire baseline water quality data for use in assessment of environmental impact of drainage works.

3. METHODS

3.1 The study area

Figure 1 shows that the Isis District is centred on the town of Childers, 53 km south of Bundaberg. The 15 217 ha of assigned caneland in the district are located within the catchments of the Elliott and Gregory Rivers and Stockyard Creek.

The study period from March 1988 to June 1991 spanned the period during which irrigation water was reticulated to most of the district.

3.2 Installation of bores

Watertable monitoring bores were installed at 194 locations, shown on Figure 2, between March and December 1988. Sites were chosen within each of the 15 sub-catchments in the District to ensure coverage of the major soil types from unpublished maps which supported Forster and Macnish (1987). Hydrologic data from high- to low-landscape positions were interpreted for 29 bores in 11 transects within seven of the sub-catchments.

Shallow watertable monitoring bores were drilled with a 100 mm open-flight power auger to depths at which a C-horizon or a heavy clay aquitard was encountered within the surface 5 m of earth. The frequency distribution of shallow bore depths is shown in Table 1.

Table 1

Percentage of 194 shallow watertable bores drilled to five depth categories in the Isis District

Depth range (m)	Per cent of bores
< 1.99	14.5
2.00 - 2.99	34.2
3.00 - 3.99	27.5
4.00 - 4.99	19.7
> 5.00	4.1

Each hole was cased with slotted 50 mm PVC tube and then back filled with 3 to 6 mm filter gravel to the base of the A_2-horizon and then to the surface with A-horizon soil.

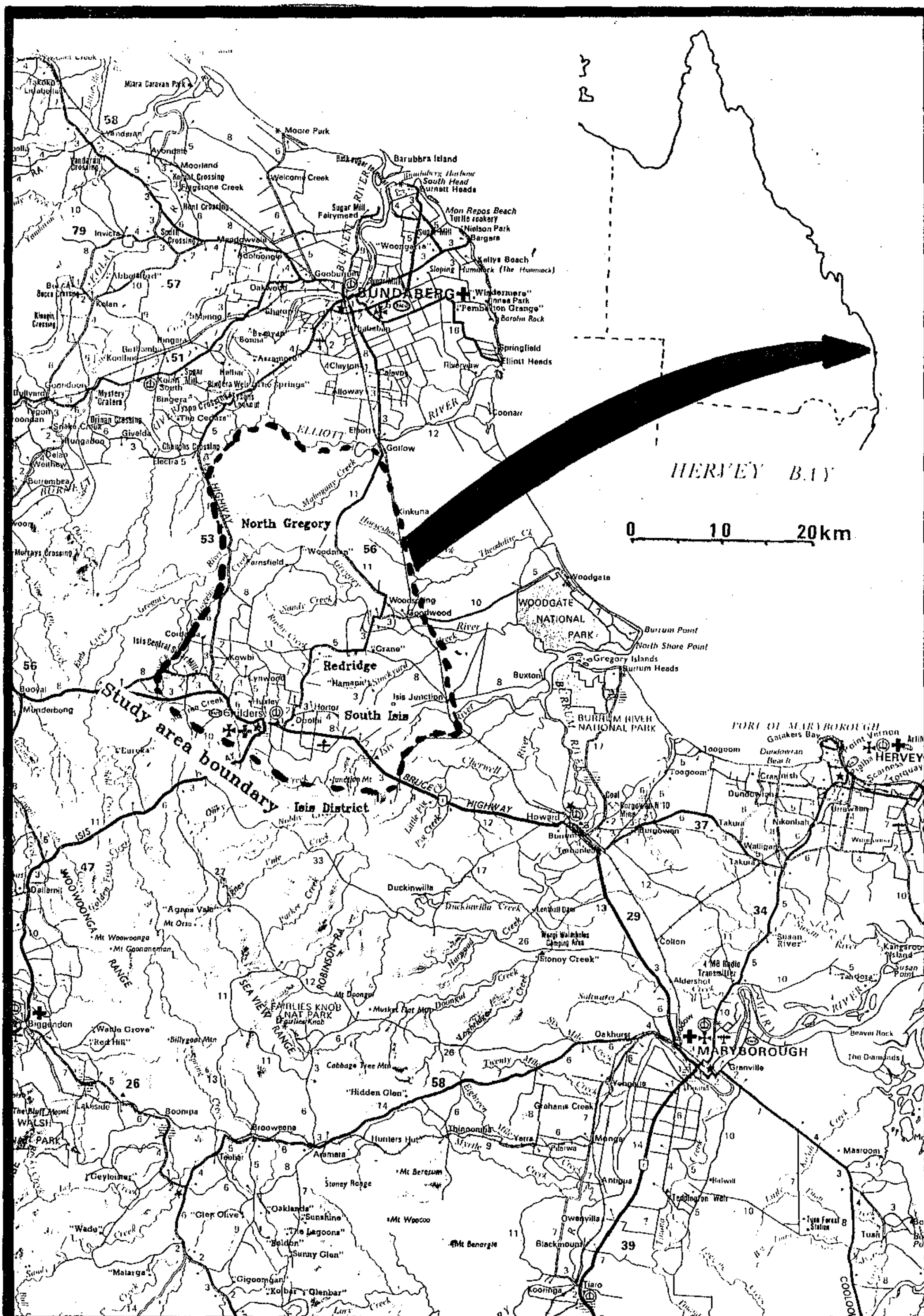


Figure 1 Location map for the Isis District and the study area.

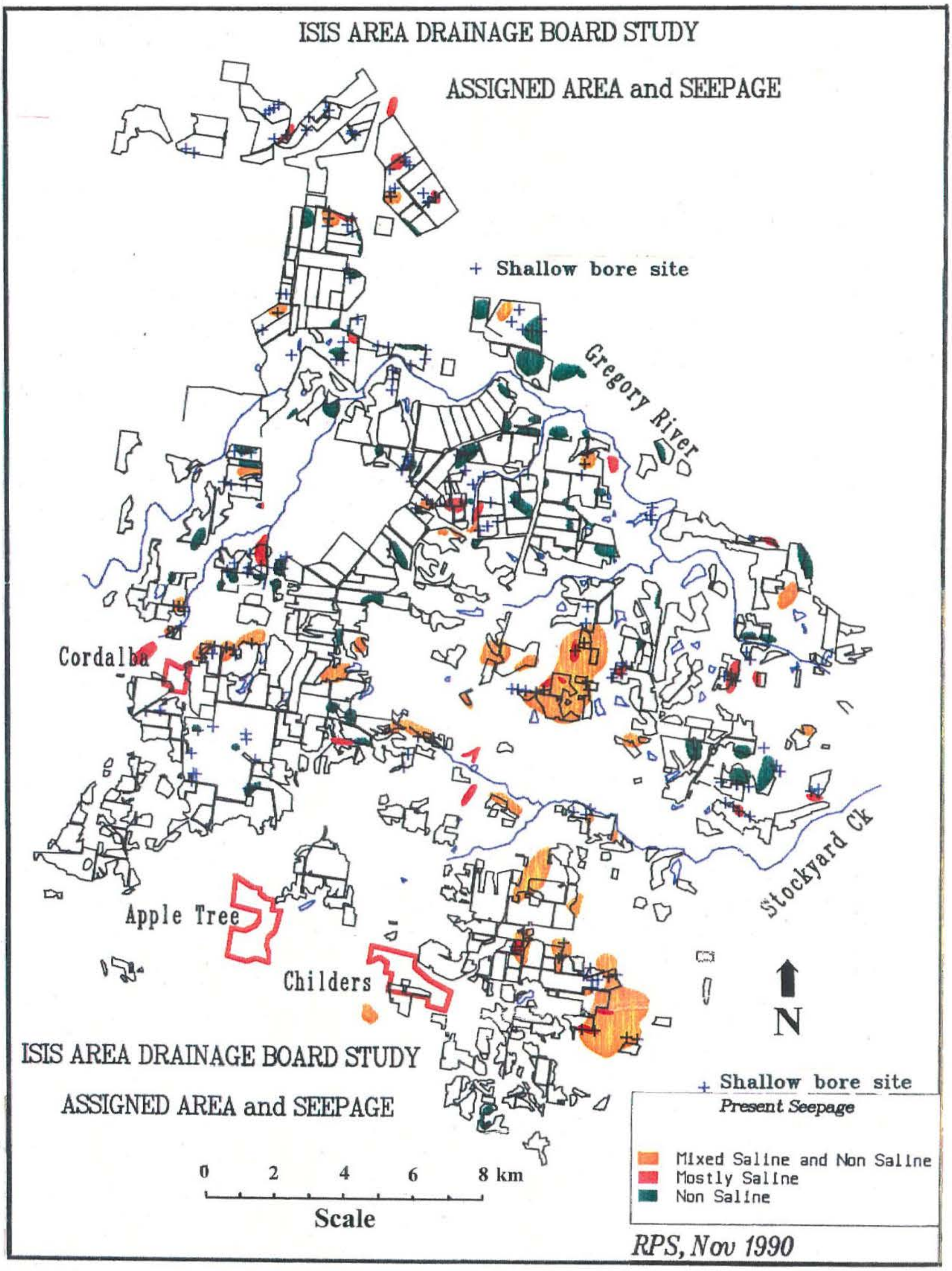


Figure 2 Locations for 194 shallow bores installed in the Isis District to study the hydrology of groundwater in the lateritic zone of the soil profile, and location of known saline and non-saline seepage areas. (Mapping by W P Thompson from information supplied by G Kingston and C D Jones.)

3.3 Data acquisition

A drilling log was maintained for each hole, and representative samples of the various horizons were taken for air drying and determination of the percentage by weight of the > 2 mm fraction, called gravel. The < 2 mm fraction was analysed for electrical conductivity ($EC_{(1:5)}$) and pH of 1:5 soil/water extracts.

Height of the soil surface and a datum for each tube above the Australian Height Datum (AHD) were established by WRC surveyors to allow determination of flow directions of water and reduction of levels. These data were required to determine potential for interaction between shallow watertables and regional groundwater. Depth to the watertable was measured at monthly intervals, except after major rainfall events where measurements were often obtained at 7 to 14 day intervals.

Hydraulic conductivity of the water bearing zone was measured by the slug test (Bouwer and Rice, 1976) at 36 bore sites in eight landscape transects during the autumn of 1992.

Waters were examined for electrical conductivity (EC) and pH on four occasions; sampling in July 1989 and August 1990 represented watertable recession after significant autumn rainfall, while sampling in February 1990 and April 1991 reflected the irrigation season after severely restricted summer rainfall, which typified the years 1988 to 1991. Waters from the July 1989, August 1990 and April 1991 samplings were sorted on the basis of EC; every third sample was analysed for calcium, magnesium, sodium, potassium, chloride, sulfate, bicarbonate, iron and manganese; nitrate analyses were performed only for the last two sampling occasions. Sub-samples for nitrate analysis were preserved in the field with phenyl-mercuric acetate, while those for iron and manganese analysis were acidified with hydrochloric acid. Phosphate analyses were conducted on most samples, but values were too low to measure accurately.

Inclusion of EC and water level data from another 17 shallow wells, installed in the period 1985 to 1988, resulted in a network of 211 shallow observation bores. Data were also taken from 13 regional groundwater bores at nine sites on the same measurement frequency to study potential for interaction between shallow and regional groundwater. Data were also available from 26 shallow bores at a seepage site from March 1986 to September 1988, after which a change of ownership and landuse to aquiculture precluded further data acquisition. This site was used for development of a model to describe response of shallow watertables to precipitation (Kingston, 1993).

Daily rainfall data were obtained from the Elliott River Forest Station, Childers Post Office, and seven raingauges installed on farms throughout the Isis area in July 1988 to cover the network of 194 shallow bores.

4. SHALLOW GROUNDWATER HYDROLOGY

4.1 Behaviour of shallow watertables

In Table 2, watertable depths for four measurement times are shown to represent typical conditions experienced during the project. February 1989 data were chosen because preceding rainfall in 1988 was average and well distributed throughout the year; June 1989 data reflect watertable elevations after a significant, but late, wet season from February to May; data in February 1990 were taken after a severe drought in the spring and summer of 1989-90, while June 1991 data also reflect drought conditions in the previous spring, but with 329 mm of rain in January to February followed by the most severe drought on record.

Table 2

Percentage of 210 shallow observation bores in the Isis District in each of six classes for watertable depth on four occasions

Watertable depth below ground surface (m)	27/02/89	2/06/89	5/02/90	25/06/91
< 0.49	7.9	66.8	2.3	1.0
0.50 - 0.99	22.9	19.6	9.3	7.0
1.00 - 1.49	24.3	1.4	15.9	11.8
1.50 - 1.99	12.1	3.3	20.1	14.6
> 2.00	13.6	2.8	22.4	29.1
Dry	17.3	5.1	29.0	33.7
Not measured	1.9	1.0	1.0	2.8

The data for February 1989, in Table 2, show that approximately 30% of bores had watertables within the surface metre of soil after a year of average and well distributed rainfall. After the prolonged wet season of 1989, 66.8% and 86.4 % of bores had watertables within 0.5 and 1.0 m, respectively, of the soil surface.

In June 1989 only 5.1%, or 11 bores, did not have a shallow watertable after the wet season. Two bores in a low-landscape position remained dry until May 1990; appearance of water in these bores was attributed to a change from burnt cane agronomy to conservation of leaf residues and more extensive irrigation of a farm some 400 m up-slope. Waterlevel in a small dam, at a similar position in the landscape to the bores, also responded to the up-slope irrigation. Only 1.4% (3 bores) had never expressed a watertable by June 1991. These dry bores were located in very sandy alluvium, heavy clay and at an upland site.

On average only 31% of bores dried in 1990-91, after two very dry summers. During this period 27% of sites maintained watertables deeper than 2 m from the surface, while 41 % had water within 2 m of the surface. Ten percent of sites had watertables within the surface metre of soil. Most of the watertables maintained within 2 m of the surface during this extended dry period were in the irrigation area.

4.2 Influence of landscape position on shallow watertables

Locations for 29 bores in 11 landscape transects were rationalised into upper slope, break of slope/mid-slope and lower slope/lowland positions, relative to the landform for each transect. Data for the number of days watertables at each site were shallower than 0.5 and 1.0 m are recorded in Appendix I, along with average salinity of the water and geology of the transect.

These data show increased duration of watertables within the two depth categories with progression down the landscape. Salinity of groundwater, measured as EC, also increased in lower landscape positions; this deterioration in water quality was most evident in landscapes with Cretaceous geology.

A summary of watertable duration data from Appendix I, in Table 3, shows that watertables were within the surface 0.5 m of soil for 50 to 134 days in mid- and low-landscape positions, respectively, for the wetter year of 1989. Even though 1990 was much drier than 1989, a watertable was still present from 9 to 63 days below mid-landscape. A second year of low rainfall reduced the period of very shallow watertables to 11 days in lowland positions during the first half of 1991. Watertables were within 1.0 m of the surface for much longer periods in all years at all landscape positions.

Statistics in Table 3 show that within year variation of watertable duration between sites decreases with progression down the landscape. A significant ($p<0.05$) and negative correlation ($R^2=0.39$) existed between the range in watertable height and the mean depth of water below the soil surface. These two sets of statistics and data from Table 3 confirm that higher landscape positions tend to act as intake areas, with deeper and more variable watertables, whereas lower positions have shallower and less variable watertables and tend behave as discharge zones.

Table 3

Summary statistics for the number of days watertables were shallower than 0.5 and 1.0 m below groundlevel at three positions, in 11 landscape transects, in the Isis District from 1988-91

Landscape position	Year	Watertable > - 0.5 m			Watertable > - 1.0 m		
		N (bores)	Mean (days)	CV %	N (bores)	Mean (days)	CV %
Lowland	1988*	3	67	67	3	184	33
	1989	13	134	69	13	291	25
	1990	13	63	97	13	172	70
	1991**	13	11	191	13	104	110
Break of slope/ mid-slope	1988*	4	42	86	4	79	70
	1989	13	50	88	13	136	74
	1990	13	9	133	13	51	114
	1991**	13	0	0	13	18	244
Upper slope	1988*	1	0	0	1	0	0
	1989	3	24	154	3	95	41
	1990	3	0	0	3	37	97
	1991**	3	0	0	3	5	160

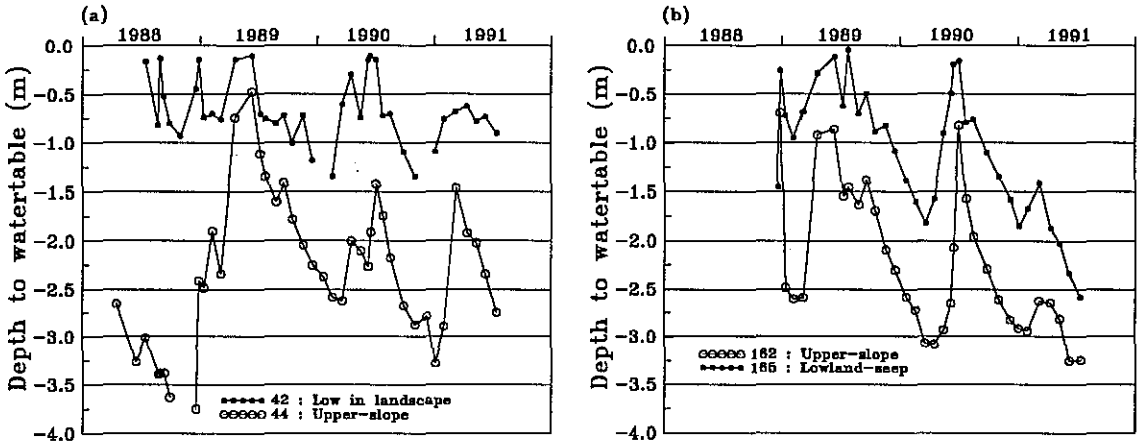
N = the number of bores contributing to the mean at each location; CV% = the coefficient of variation expressed as %; * indicates data were available only from bores installed in April 1988, no data were used in 1988 from bores installed October - December; ** indicates records for 1991 end on 25/6/91.

4.3 Typical water level data for shallow watertables

Shallow watertables were classified into *non-seepage, permanent seepage and seasonal seepage* categories on the basis of seasonal variation in water level data; each category can be further subdivided into saline and non-saline types.

Watertables in *non-seepage areas* are usually deeper than 1.5 m, but may rise to within 1 m of the surface for short periods during major rainfall events. Response to rainfall and subsequent recession are rapid in these sites, which are usually in upper slope locations. While there is no on site seepage at these elevations, the hydraulic gradient ensures that the watertable will contribute to off-site seepage lower in the landscape.

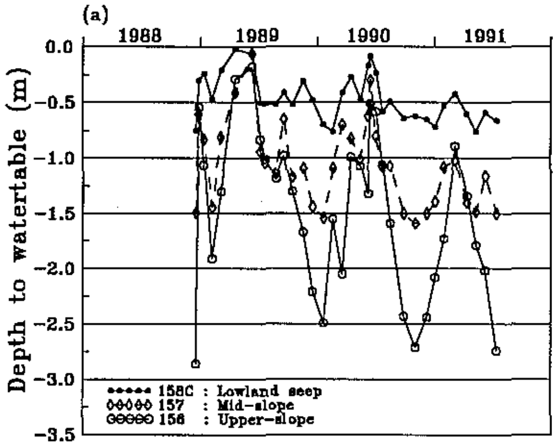
In Tertiary landscapes the watertable is usually non-saline, typically < 0.75 dS m^{-1}, while in Cretaceous areas EC of the watertable may be as high as 6.00 dS m^{-1}. Bore 44 in Figure 3(a) represents non-saline, non-seepage watertable in Tertiary landscapes, while bore 162 in Figure 3(b) is a saline non-seeping watertable in a Cretaceous landscape.

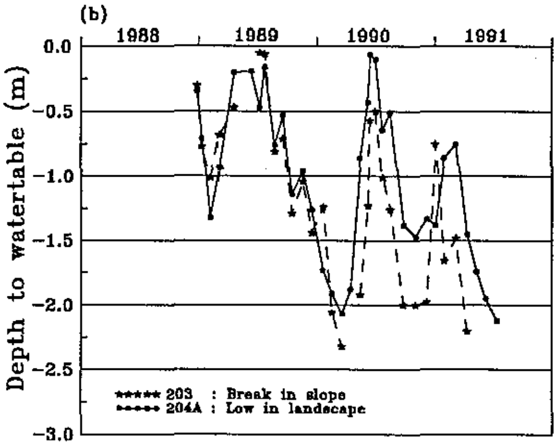


Figures 3(a)-(b) Depth of the watertable, below groundlevel, for shallow bore sites in the lateritic zone of sedimentary soil profiles on transects which include non-seepage and permanent seepage sites; (a) represents a Tertiary Elliott Formation landscape and (b) a Cretaceous Burrum Coal Measures landscape.

In *seasonal seepage areas*, watertables may be shallower than 0.5 m depth for up to three months during a major wet season; however, the watertable recedes rapidly after cessation of rainfall to remain below 1.0 m depth for drier periods of the year. Such sites may be found high in landscapes but towards the edge of a geological unit, in mid-landscape positions, or where deeper xanthozem soil types have formed in colluvial material from more elevated structured soils. In Tertiary areas, such as at bore 156 in Figure 4(a), the water is non-saline; whereas bores 203 and 204 in Figure 4(b) are in colluvial material in Cretaceous areas and contain saline water with EC of 5.4 and 11.88 dS m^{-1}, respectively. The latter area could develop into a permanent seepage area as the bores are located below an area which will be irrigated from early 1992. Seasonally high saline watertables have already caused crop losses from soil salinity in this locality.

Bore 165, in Figure 3(b), is located in an area of Burrum Coal Measures which is severely degraded by saline seepage; the groundwater has an EC of 28 dS m^{-1}. The data in Figure 3(b) show that the site behaved as a permanent seep during the wet year of 1989, but was reduced to seasonal seepage during 1990-91. This site reinforces the concept advanced later (in section 4.5) that short duration of very saline watertables can lead to high levels of soil salinity.





Figures 4(a)-(b)Depth of the watertable, below groundlevel, for shallow bores at seasonal seepage sites in the lateritic zone of sedimentary soils in the Isis District; (a) shows a seasonal seep on upper slopes with Tertiary geology above a permanent saline seep in Cretaceous sediments and (b) shows seasonal saline seepage in xanthozem soils in a Cretaceous landscape.

Watertables in *permanent seepage areas* exhibit damped seasonal variation in depth. The watertable is within 0.5 m of the soil surface in wet periods, and within 1.0 m of the surface for most of the year. Seepage salting has been observed in the vicinity of seeps where the watertable has an EC as low as 0.75 dS m^{-1}. Bore 42, in Figure 3(a), is located low in a Tertiary landscape and has a 1.68 dS m^{-1} watertable which has caused extensive seepage salting as well as yield reduction from waterlogging.

Most *permanent seeps* occur low in the landscape and are quite saline, with EC often > 3.00 dS m^{-1}. Bore 158C, in Figure 4(a), is in clay and weathered mudstone from Cretaceous Burrum Coal Measures below the eastern edge of the Tertiary landscape. The 11.63 dS m^{-1} water is permanently within the 0.75 m of the soil surface and has caused seepage salting nearby. Bore 196, in Figure 5, is located in the lowland of a Burrum Coal Measures landscape and has an extremely saline 24.63 dS m^{-1} water causing soil salinity from a permanent seep.

Permanent non-saline seeps are quite rare. Bore 124, in Figure 6, is an example of such a seep. Water at this mid-slope site is forced into surface layers by a band of heavy clay at 1.5 m depth. The site has been under cultivation and supplementary irrigation for 15 years and full irrigation since late 1988, but to date salinity has not developed. This may be due to the high quality of the water (EC of 0.34 dS m^{-1}) and its continued flux through sandy loam and sandy clay A and B-horizons. Cane yield and trafficability at this site are affected by waterlogging. Similar situations exist at soil type boundaries throughout the region where there is a marked decrease in hydraulic conductivity down the catena.

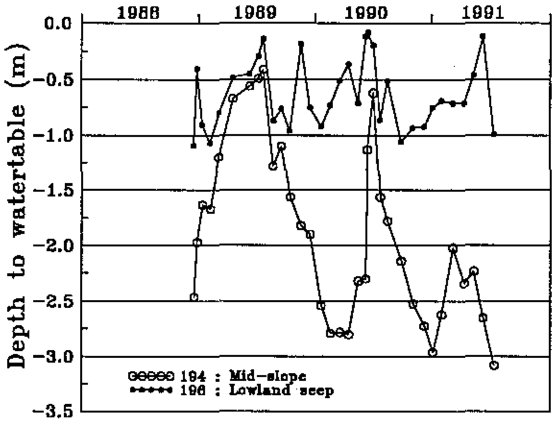


Figure 5 Depth of the watertable, below groundlevel, for shallow bores in the lateritic zone of soil profiles in permanent (bore 194) and seasonal saline seepage (bore 196) areas for a transect in a Cretaceous landscape in the Isis District.

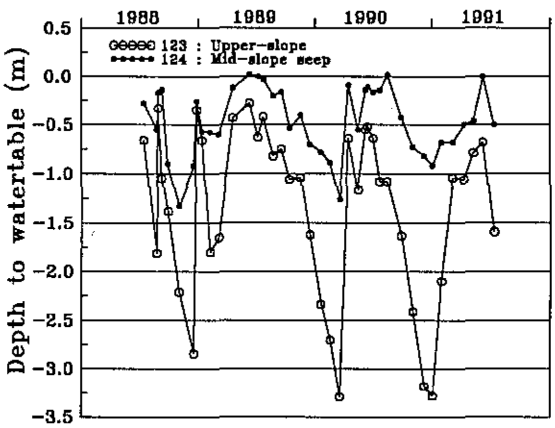


Figure 6 Depth of the watertable, below groundlevel, for shallow bores in the lateritic zone of soil profiles in non-saline permanent (bore 124) and seasonal seepage (bore 123) sites for a transect in Tertiary Elliott Formation in the Isis District.

The extent to which non-seepage or seasonal seep areas develop into permanent saline or non-saline seeps will depend on the degree of hydrologic imbalance caused by additional deep drainage from the full use of the completed irrigation system. Shaw (personal communication) has estimated that an additional 150 mm year^{-1} of deep drainage could be generated by the irrigation area. Effective porosity of the hydromorphic zone in nodular sedimentary soils has been estimated to have an upper value of approximately 15% (Kingston, 1993); therefore the 150 mm of additional deep drainage has the potential to raise watertables by 1.0 m in a theoretical closed basin situation. The strong surface relief and lateral drainage that takes place throughout much of the area suggests that the theoretical closed basin site does not exist, and that further significant watertable rise may only be a problem in the lowlands in years of at least average rainfall. However, in wet years seepage could be expected from mid-slope or the break in slope positions.

4.4 The nature of shallow aquifer materials

4.4.1 Location of shallow aquifers

Presence of a watertable within such close proximity to the soil surface for the three years of the project indicates the shallow groundwater may be regarded as a perennial, rather than a perched seasonal watertable. The enduring presence of this water is not a recent feature due to deep drainage from more extensive irrigation. The phenomenon was observed previously in a network of watertable observation wells, over a two-year period in 1986-88, at the seepage site with 26 bores described in the Methods section 3.3. This site received slightly below average rainfall and only three irrigations during the study period.

Bore logs for shallow wells in sedimentary soils in the Isis District show that shallow groundwater was observed in the lower profile of soils which contained a major lateritic zone. The lateritic zone commenced with development of pisolitic concretionary ironstone nodules in the mottled and/or gleyed clay matrix of the B-horizon. Pit exposures and large undisturbed cores showed that nodules could range from 5 to 50 mm in diameter. In the lower B-horizon, usually below 1.50 m, nodules were often irregularly shaped and/or cemented together. There are examples of the cementing process continuing until boulders, up to 0.5 m in diameter, are developed in low-landscape positions.

The lateritic layer in Isis soils usually is most developed between 1.5 and 2.0 m, and terminates between 2.5 and 3.0 m depth on a zone of heavy pallid clay, which can be up to 1.5 m thick. In areas with Elliott Formation geology, the pallid clay caps the regional aquifer; zones of water bearing gleyed and pallid sandy clays and clayey sands then alternate with clay bands until gravel beds of the production aquifer are encountered between 12 and 20 m depth. At sites with Cretaceous geology, the pallid clay usually rests on a zone of weathered mudstone.

Nodules are formed by a series of alternating redox reactions in which ferro-aluminosilicates are precipitated as groundwaters rise and fall (Brewer *et al.*, 1983). The lateritic zone in some soils, especially in Cretaceous areas, contains an indurated layer of lateritised sandstone or mudstone.

Stable macropores of 1 to 4 mm diameter have developed in the gleyed clay matrix around and between nodules. These macropores could lead to the lateritic zone having a higher hydraulic conductivity than would be inferred from the medium to heavy clay matrix. This type of macropore structure is distinct from that reported by Johnston *et al.*

(1983) who were studying flow in macropores filled with permeable material in the pallid zone of lateritic profiles in southern Western Australia.

4.4.2 Hydraulic conductivity

Hydraulic conductivity data in Table 4 reflect the highly variable nature of this parameter. Mean and median values of hydraulic conductivity show a tendency for higher values at high- and low-landscape than at mid-landscape; these differences were not significant on the basis of paired a *t-test*. The highest value of 5.15 m day^{-1} was obtained for a watertable in a high-landscape position with 15 to 35 mm diameter nodules in a sandy clay loam matrix, while the lowest value of 0.08 m day^{-1} was obtained at mid-landscape in a heavy clay and weathered mudstone zone.

The trend to lower values of hydraulic conductivity at mid-landscape positions is supported by observations in sections 5.1.1 and 5.1.2 that the greatest changes in watertable elevation and development of new seepage areas appears to be in mid-slope positions. It is inferred that lower hydraulic conductivity in these locations reduces the hydraulic gradient and watertable rise has resulted from the additional quantities of water moving in the landscape. Higher hydraulic conductivity of upper and lower landscape positions may be sufficient to allow discharge of the extra water, without significant watertable rise at this stage.

Table 4

Hydraulic conductivity data (m day^{-1}) for the hydromorphic zone of lateritic soils in the Isis Irrigation Area in relation to landscape position

Statistical parameter	Upper-slope	Mid-slope	Lower-slope	All positions
No. of samples	7	19	10	36
Mean	1.93	0.53	0.79	0.87
Std deviation	1.69	0.38	0.42	0.95
Minimum	0.31	0.08	0.21	0.08
Median	1.09	0.43	0.68	0.64
Maximum	5.15	1.44	1.43	5.15

4.4.3 Significance of the nodular zone

Data in Table 5 show that lateritic gravel or ironstone layers were encountered within drill depth in representatives of all soil types in which bores were installed. These sites represented 69% of holes drilled during the project. The drilling program focussed more on mid- and lower slopes because of the hypothesised effect of shallow watertables on soil morphology. The data therefore are not a balanced sample of district soils, but do reflect the importance of lateritisation and precipitation of ferruginous material from the soil solution in the genesis of hydromorphic sedimentary soils. Average bore depth was 2.90 $\pm$ 0.95 m and nodular material ranged between 6 and 91% by weight of samples taken from different depth intervals, but the average for layers containing the material was 44 $\pm$ 18.6%.

Table 5

Allocation of shallow bore sites by Great Soil Group (GSG), and the proportion of sites containing lateritic material > 2 mm diameter within bore depth

Great Soil Group (GSG)	No. of bores	% of bores in each GSG with laterite > 2 mm	% each GSG with > 20% nodules in the surface 1.0 m
Krasnozem	4	100.0	25
Xanthozem	16	81.3	31
Yellow podsolic	13	84.6	15
Red yellow podsolic	4	100.0	0
Earthy yellow podsolic	1	100.0	0
Nodular yellow podsolic	7	100.0	14
Yellow earth	4	100.0	0
Nodular yellow earth	1	100.0	0
Bleached yellow earth	4	75.0	0
Grey earth	15	60.0	6
Nodular grey earth	1	100.0	0
Bleached grey earth	1	100.0	0
Earthy sand	1	100.0	100
Nodular earthy sand	1	100.0	0
Bleached earthy sand	3	33.0	0
Gleyed podsolic	43	62.8	7
Nodular gleyed podsolic	24	83.3	29
Rudimentary podsol	7	57.1	14
Podsol	2	50.0	0
Soloth	42	59.5	29
Totals	194	69.0%	16%

The significance and distribution of soils with major lateritic layers are not recognised from rapid reconnaissance soil surveys. During such a survey the profile is examined only to the depth which is considered sufficient to make use of diagnostic features of the B-horizon, namely colour, texture and pH trend. This depth is typically 0.75 to 1.0 m. If this procedure is followed, a Great Soil Group name (Stephens, 1962) will not be prefixed with the term *nodular* unless at least one of the diagnostic horizons contained at least 20% of lateritic nodules, based on visual rating. No information will be obtained for the morphology of the lateritic profile above the pallid zone and its significance as a shallow aquifer. Reconnaissance soil survey data were used to generate soil type classifications for this project (Forster and Macnish, 1987).

Examination of the distribution of the lateritic gravel fraction by depth in the profile, summarised in Table 5, showed that 69% of all bores contained nodular material. In 16% of bore sites the surface metre of soil contained more than 20% by weight of gravel; 53% of bores contained less than 20% gravel in this zone, but the lateritic layer commenced below 1.0 m in 51% of sites.

Table 5 also shows that nodular material of the gravel fraction was separated from the surface metre in only 29% of soils classified as nodular gley podsolic, but 83 % of this classification contained significant lateritic material in the solum. Similarly nodules were sieved from the likely diagnostic depth of only 14% of nodular yellow podsolic soils, and no nodules were recovered from this zone for the lesser represented nodular phases of the yellow and grey earths or the earthy sand. The high degree of variability in soils in the region (Kingston, personal observation; Macnish and Wilson, personal communication) may account for some of these discrepancies.

The 1987 land resources survey (Forster and Macnish, 1987) clearly was successful in diagnosing the problems associated with the hydromorphic soils in the Isis District. There was, however, no indication of the significance of the lateritic process which had a major influence on solum morphology in 69% of profiles located throughout the district. As a result, no soils in the Great Soil Group called lateritic podsolic were recognised during the survey. A soil would be placed in this group if:

- the mottled B-horizon overlies a coarsely mottled, light grey to white, yellow and red clay horizon which may or may not be the material from which the solum has developed;
- ironstone or ferruginous nodules are dominant in at least the A_2-horizon and usually extend into the upper B-horizon. They may extend throughout the solum;
- the profile is gradational or duplex;
- an A_2-horizon, bleached or unbleached, is present;
- the profile is acid throughout (unpublished report on Soil Classification Workshop - Bundaberg to Maryborough, 6 to 9/11/84).

The strong influence of the lateritic process in the project area soils suggests that the requirement for nodules to be *"dominant in at least the A_2-horizon ....* ", may be too severe a criterion for recognition of the influence of the lateritic process. Especially when the above report recommended that *"..The term lateritic be restricted to podsolic soils only."* The prefix nodular was to be appended in all other cases as indicated above. The importance of this inadequacy for classification of soils is demonstrated by the gley podsolic, nodular gley podsolic and soloth groups of soils. Such soils usually occur in mid- to low-landscape positions and are often associated with seepage salting. Data in Table 5 show that between 63 and 83% of these soils contained significant lateritic material, which points to higher hydraulic conductivity and potential for more rapid wetting of the solum than would be inferred from properties of B-horizon clay.

There appears to be a strong case for implementation of one of the *observations* of the 1984 Workshop that *"...Deep borings to at least 2.0 m will be necessary in a variety of soil survey situations. Some examples are, characterisation of salinity profiles and identification of horizons likely to cause perched watertables in proposed and developing irrigation areas......The deep borings are required not only to more accurately describe the soils, but because knowledge of some soils to these depths is essential to understand their behaviour on development...* ". Examination of the solum to a depth of 1.5 m, at the rate of four or 16 sites per 250 ha for 1:24 000 and 1:12:000 scale mapping, respectively, and to a depth of 3 m at one site, is standard practice by the US Bureau of Reclamation during classification of land resources for long-term suitability for irrigation (Anon., 1982). This intensity of investigation is justified by the heavy investment of public funds in large irrigation schemes in which significant land degradation can challenge the viability of the investment by both public and private sectors. The cost of rehabilitating waterlogged and saline land in the USA is approximately twice that of planning for, and installation of appropriate irrigation techniques and removal of excess drainage water at scheme inception (J. Christopher, personal communication).

A program of deeper investigation of the solum would have revealed the extent and behaviour of shallow groundwater systems within the Isis area, and by correlating observations in similar landscapes, throughout the Maryborough Basin. Construction of the necessary drainage and irrigation systems could then have proceeded in parallel, supported by guidelines for the irrigation efficiency required to sustain watertables within acceptable bounds. While this did not happen prior to establishment of the irrigation area, guidelines are being finalised for establishment of a Drainage Board to approve and coordinate installation of sub-surface drainage systems in the Isis District (unpublished Interim Report to Water Resources Commission, Isis Area Drainage Board Study : Isis Steering Committee, April 1991).

4.5 Effect of shallow groundwater on soil salinity

Water level data from 55 shallow bores were used to determine the number of days that watertables occurred in the following depth categories; 0 to 0.5 m, 0 to 1.0 m and 0 to 1.5 m. Regression analysis was used to examine the association between average EC of shallow groundwater and depth duration of the watertable on soil salinity in the surface 0.5 m of soil,at each site.

$EC_{1:5}$ of the surface 0.5 m of soil was involved in a significant multiple regression relationship with average EC of shallow groundwater and the interaction of the latter term with the number of days the watertable was shallower than 0.5 m; R^2 was 0.65. The duration of the watertable alone made no significant contribution to the regression.

$EC_{1:5}$ of the surface 0.5 m of soil also was involved in a significant multiple regression relationship with average EC of shallow groundwater and the interaction of the latter term with the number of days the watertable was between 0.5 and 1.0 m below the soil surface; R^2 was 0.59.

Simple regression analysis between $EC_{1:5}$ of the surface 0.5 m of soil and EC of shallow groundwater showed that 49% of the variation in $EC_{1:5}$ was attributable to variation in salinity of the groundwater. Comparison of this R^2 value with those in the previous two paragraphs, and the failure of duration of the watertable within the two depth ranges to be a significant variable, shows that salinity of groundwater was the most important factor governing $EC_{1:5}$ of the surface 0.5 m of soil.

The data do not allow recognition of a critical depth to the watertable which is associated with seepage salting. The regression relationship between soil salinity and groundwater salinity was improved more by interaction with duration of the watertable shallower than 0.5 m, than by interaction with duration of the watertable between 0.5 and 1.0 m. This feature supports field observations that seepage salting is most often associated with watertables closer to the soil surface than 0.5 m. The interaction term implies that longer duration of a low salinity watertable is required to produce effects on soil salinity similar to those which result from shorter duration of more saline groundwater.

4.6 Areas affected by shallow groundwater

Thompson (personal communication) used maps of Forster and Macnish (1987) to estimate that 1650 ha of Isis caneland faced an existing seepage hazard, and that a further 5700 ha faced a potential seepage hazard. Interpretation of data acquired during this project were combined with observations of Mr C D Jones and the author, by Mr W P Thompson, to arrive at extent and distribution of seepage locations shown in Figure 2. A total area of 1910 ha was estimated as being affected by seepage; 680 ha were affected by non-saline seepage and a further 1230 ha were affected by varying degrees of saline seepage.

4.7 Conclusions from the study of shallow groundwater hydrology

Research discussed in this section has shown that shallow watertables contained in the lateritic zone of the solum of hydromorphic soils, which were formed during the Quaternary/Tertiary period in the Maryborough Basin, represent a perennial source of shallow groundwater. The shallow aquifer was contained in the clay matrix and in stable macropores in the pisolitic ironstone zone of the sedimentary soil profile, which extended from approximately 0.75 m to around 2.5 m in depth. In areas with Tertiary Elliott Formation geology, the lateritic zone rested conformably on a narrow band of pallid clay capping the regional groundwater aquifer; in areas where lateritic soils have formed from other sediments deposited on Cretaceous sediments the lateritic zone rests unconformably on weathered mudstone.

The widespread occurrence of shallow watertables in the lateritic zone led to the suggestion that insufficient emphasis has generally been placed on profile examination beyond 1 m depth during classification of soils for suitability for irrigation.

During the 24 to 30 month study period, which included one of the driest years on record, 41% of shallow bores supported perennial watertables within 2 m of the surface and 27% were perennial and often deeper than 2 m. Duration of the shallow watertable and salinity of the water increased with progression from mid- to low-landscape positions. Shallow watertables were classified into *non-seepage, permanent seepage* and *seasonal seepage* waters on the performance of bore water levels. These categories also contained saline and non-saline groundwaters, but non-saline *permanent seeps* were rare.

Salinity of the 0 to 0.5 m zone of the profile was best described as a function of salinity of the shallow groundwater and the interaction of the latter term with the duration of the watertable shallower than 0.5 m. This relationship confirmed the field observation that seepage salting usually was associated with watertables shallower than 0.5 m depth.

Figure 7 Locations for shallow and regional groundwater bores in areas of Tertiary geology in the Isis District.

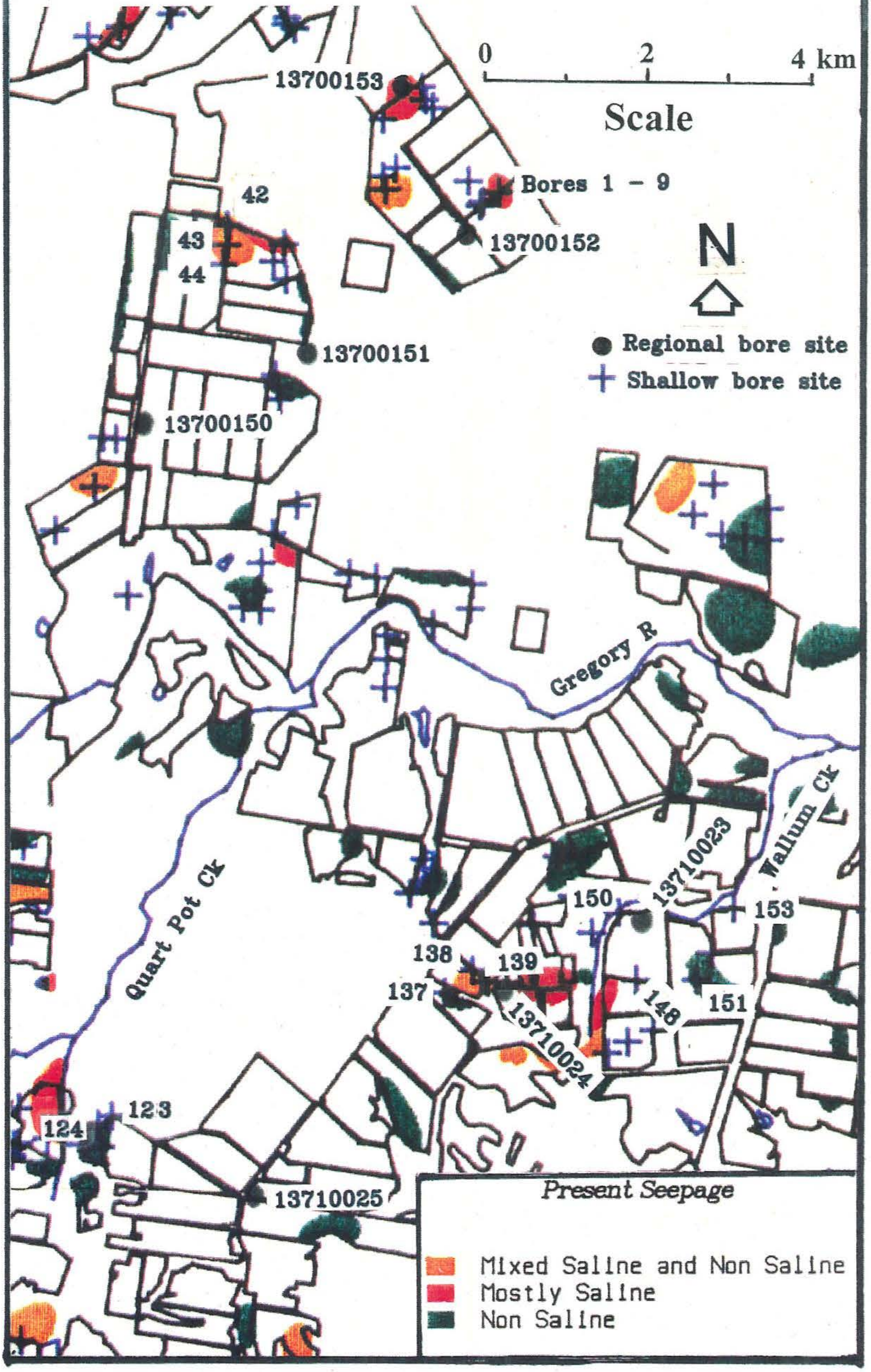
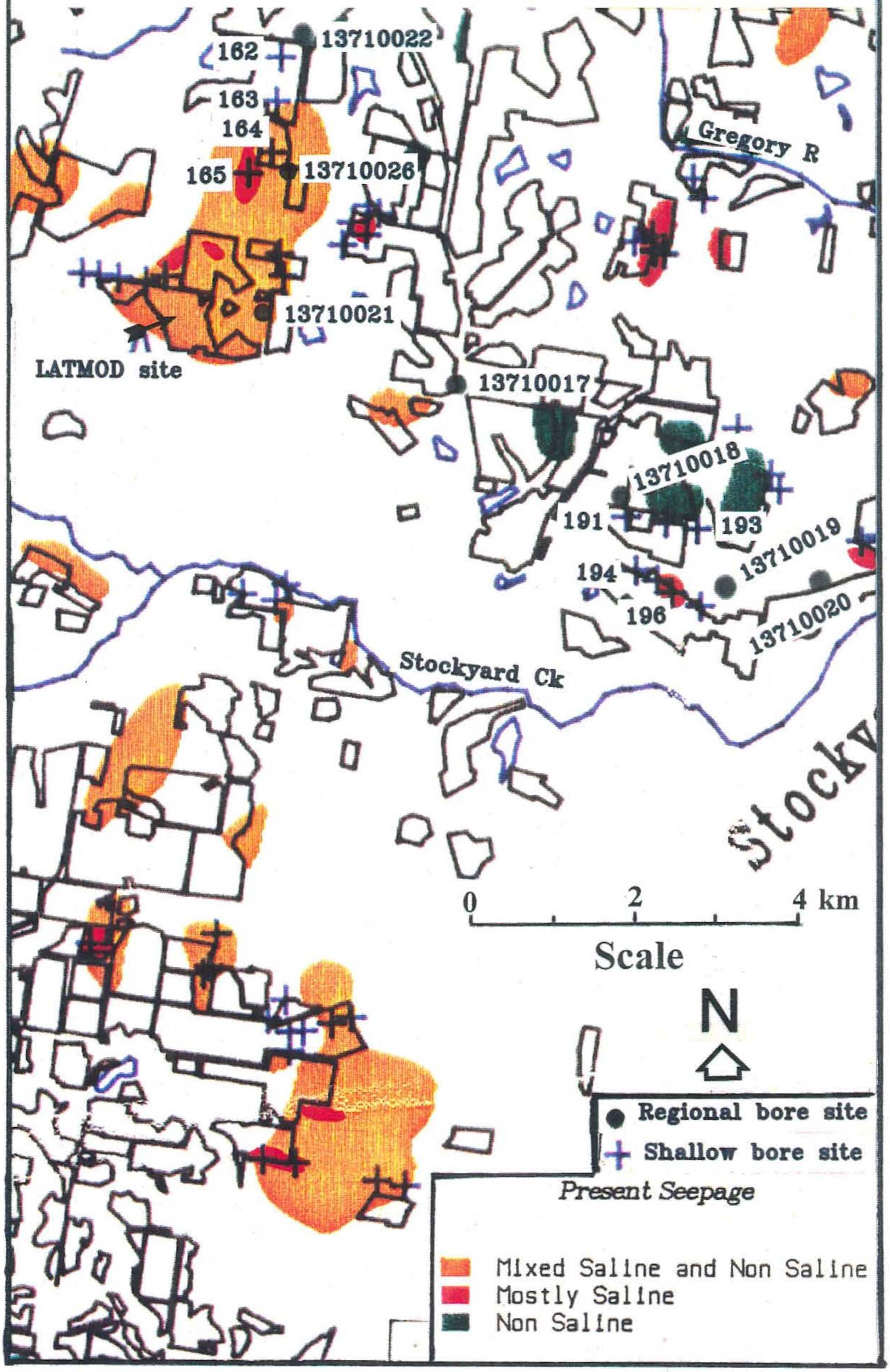


Figure 8 Locations for shallow and regional groundwater bores in areas of Cretaceous geology in the Isis District.



5. POTENTIAL FOR INTERACTION BETWEEN REGIONAL AND SHALLOW GROUNDWATER

Figures 7 and 8 show the locations of regional and shallow groundwater monitoring bores which were used to assess potential for interaction between regional and shallow groundwaters.

Potential for discharge from deep to shallow groundwater was assessed in the first instance by comparison of the elevation of the piezometric water surface of the deeper bores with elevation of watertables in the shallow lateritic zone aquifer. An upward and sustained shift in elevation of shallow water matched by an increase in head of deeper water was taken as evidence of actual discharge.

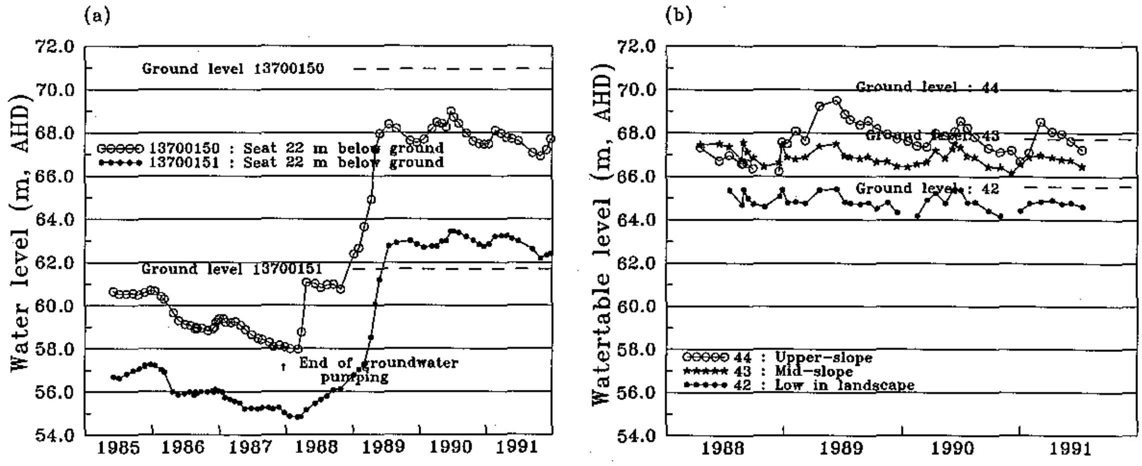
5.1 Areas on Tertiary sediments

5.1.1 Former production aquifers

The major water level response of North Gregory Tertiary aquifers to cessation of pumping, and possible returns of deep drainage water from more extensive irrigation, is demonstrated by the water level data for the deep bore 13700150, in Figure 9(a). Since mid-1989 the piezometric surface has varied around 68 m elevation. This response was mirrored by that of deep bore 13700151, some 2.5 km to the north-east of the previous bore on Figure 7. Increased water level in the aquifer, and location of 13700151 at a break in slope 9.2 m lower in the landscape than 13700150, resulted in artesian pressures at the lower bore site. A seep to the soil surface has been observed across the slope near this bore site.

Water level data for shallow bores in Figure 9(b) were derived from a 500 m transect which commences 2.5 km to the NNE of bore 13700150, as shown in Figure 7. The watertable at site 44, an upper-slope position, has fluctuated around 68 m elevation since the major recharge of mid-1989. Even with the extremely dry conditions of early 1990 and 1991 the watertable had not receded to pre-1989 elevations. The gap in the water level record for this site in Figure 9(b) in late 1988 is due to recession of the watertable below the seat of the bore. Similar gaps in the data for bore 42 in 1990 and 1991 also indicate absence of a watertable in the well zone.

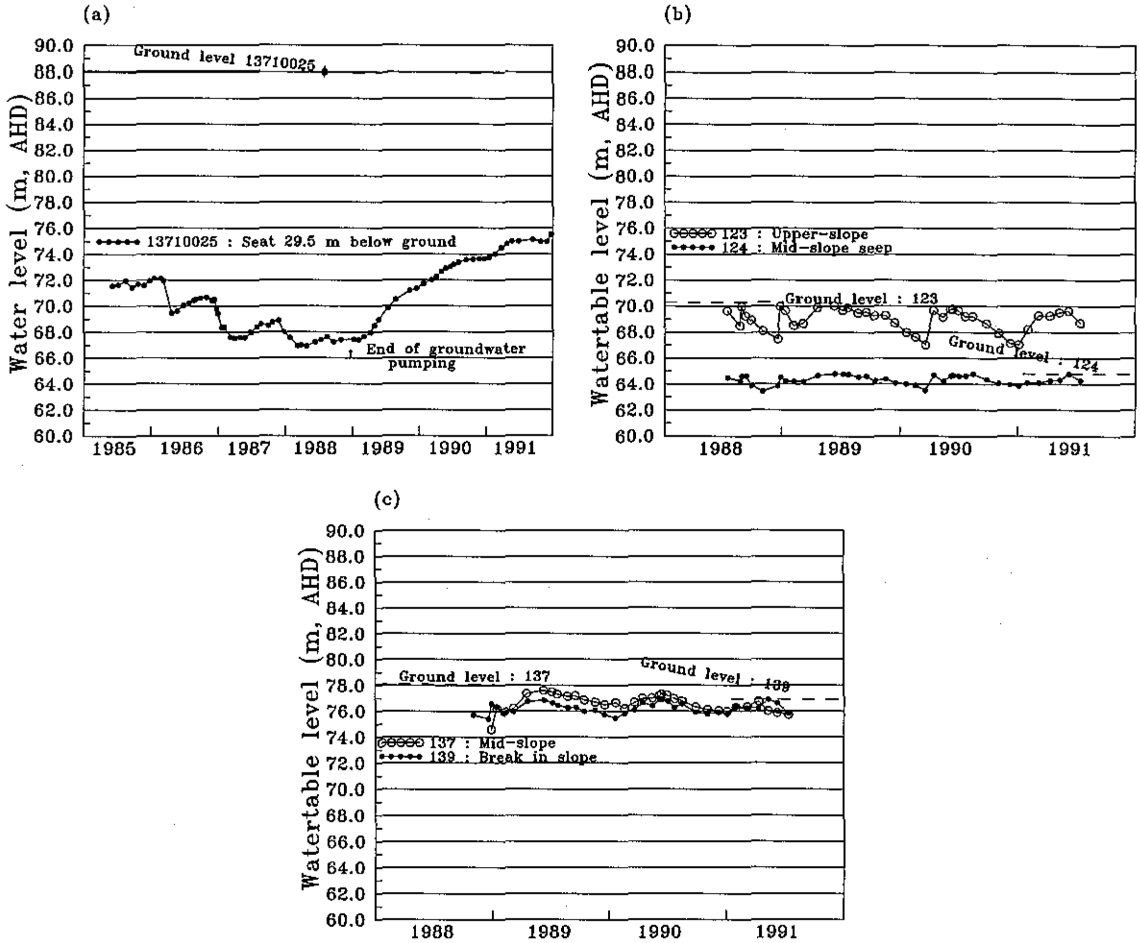
Comparison of water surface elevation and duration of the response for bores 13700150 and 44, in Figures 9(a)-(b), show that the criteria for potential and actual discharge of deeper groundwater were achieved at site 44. The discharge has inflated head in the shallow bore, but the site is not regarded as a seepage site because the watertable depth below the soil surface did not meet seepage criteria established in section 4.3. Water level data for sites 42 and 43, at lower and mid-slope positions, respectively, are typical of the lower amplitude variation in water level noted for seepage locations. Lack of any appreciable increase in watertable elevation at these sites in response to the increased water level in the deep aquifer, and the upper slope bore, is interpreted as an indication that flow pathways in the solum are coping with the current level of aquifer discharge.



Figures 9(a)-(b) AHD elevation of water level data for regional and shallow lateritic zone groundwaters in the North Gregory area of the Isis District; (a) is the regional groundwater and (b) is the shallow groundwater.

Bore 13710025 is located within the main aquifer zone to the south of the Gregory River in Figure 7. The water level data for this bore in Figure 10(a) show a more gradual and sustained recharge pattern compared to data from other bores in the former production aquifers in Figures 9(a) and 11(a). The more gradual rise in water level is attributed to the higher location of this bore site at 88 m in the landscape. There is therefore potential for aquifer flow to lower landscape positions, such as 13710023 in Figure 11(a) which is at 48.9 m elevation.

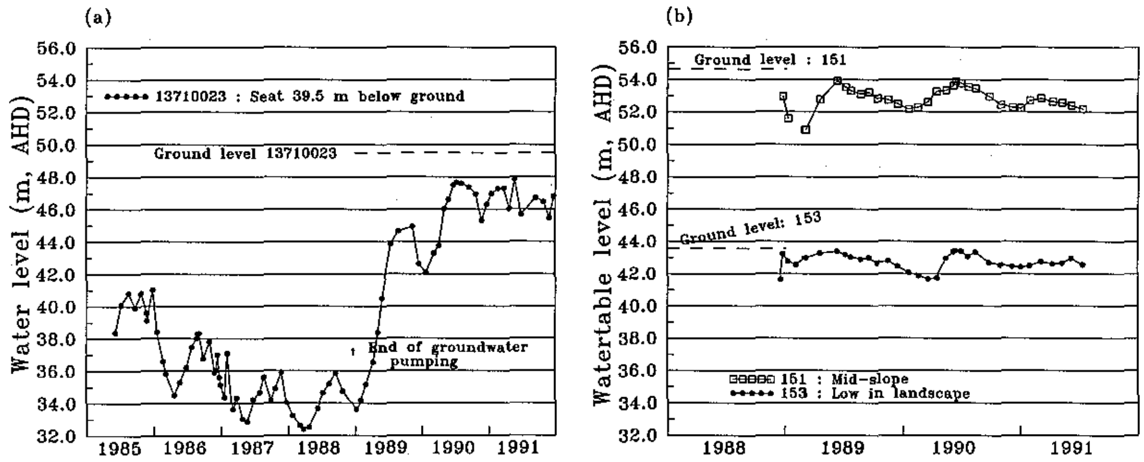
Water level data in Figure 10(b) are for two shallow bores located 1.5 km to the NWW and 18 to 23 m down slope from 13710025, as shown in Figure 7. Comparison of piezometric and watertable elevations in Figures 10(a) and (b) shows that there has been potential for discharge of deep groundwater at site 124 since commencement of the regional groundwater record in 1985. The water level data for tube 124 is typical of a permanent seepage site, but has shown no substantial response to increased head in the regional aquifer. Site 123 is 5.5 m higher on the slope and 70 m closer to 13710025 than is site 124. The water level record for site 123 in Figure 10(a), which is typical of a seasonal seep, also showed no substantial response to the higher head in the deep aquifer, even though potential for discharge has existed since early in 1989. These responses suggest that existing wetland areas marked by *Banksia robur* (Swamp banksia) and *Melaleuca quinquenervia* (Tee tree) communities, between elevations of 55 and 60 m in the vicinity of bores 123 and 124, may be coping with aquifer discharge; or the majority of the flow is to the north-east where regional bores 13710023 and 13710024 have both shown recharge.



Figures 10(a)-(c) **AHD elevation of water level data for regional and shallow lateritic zone groundwaters, high in the Tertiary landscape to the south of the Gregory River, in the Isis District; (a) is the regional groundwater and (b)-(c) are for shallow groundwater.**

Figures 10(a) and (c) show that head in bore 13710025 was below the elevation of shallow watertables at sites 137 and 139 for the duration of measurement. The latter two bores are located on a transect 3.4 to 3.7 km to the north-east of the deep bore. The water level data for site 139, which is characteristic of a permanent seepage area, has shown no departure from variation around 76 m elevation. However, the seasonal seep at site 137 had not receded to the December 1988 elevation by June 1991, despite extremely dry weather in late 1990 and early 1991. The data for regional and shallow groundwater levels suggest that only a small additional rise in regional groundwater level may be required to determine whether an impact on shallow groundwater will be registered in this area, where humus podzol and gleyed podzolic soils and remaining forest species suggest a long history of wet soil.

The deep bore 13710023 and shallow bores 151 and 153 are a further 2 km to the north-east beyond bore 139, and are 25 m lower in the Tertiary landscape in Figure 7. The water level data for 13710023, in Figure 11(a), showed a similar response to the regional groundwater bores in Figure 9(a). It should be noted that the greater variation water level in Figure 11(a), compared to those shown for other bores in the main Tertiary aquifer in Figures 9(a) and 10(a), is attributed to continued intermittent use of a groundwater pump 100 m away from the bore.



Figures 11(a)-(b) **AHD elevation of water level data for regional and shallow lateritic zone groundwaters, low in the Tertiary landscape to the south of the Gregory River, in the Isis District; (a) is the regional groundwater and (b) is for shallow groundwater.**

Figure 11(b) shows that the watertable at site 151 has been maintained above 52 m elevation, or less than 2.5 m below ground level, since early 1989. Therefore, this non-seepage site must have been receiving additional water from the aquifer or from higher in the landscape to maintain this level during the 1990-91 drought. In August 1990 a piezometer was installed at site 151 to sample water at the top of the main aquifer, below the pallid clay zone of the solum. Bentonite clay was used to seal the void around the PVC tube in the pallid clay zone. The piezometer and watertable bore at this site have exhibited identical elevations of head since installation. This response indicates water level in the shallow aquifer at site 151 is being controlled by discharge from the regional aquifer, as there is no reason to suspect a leak in the piezometer seal. The piezometric heads at 13710023 and site 151 indicate that the main aquifer is exhibiting unconfined behaviour, with the water surface representing a subdued image of ground levels. Any partial confinement of the aquifer would result in artesian head, as there is a 25 m difference between the level of the watertable at site 151 and elevation of head at bore 13700125 and the watertable at sites 137/139.

In the autumn of 1990, the watertable rose to the surface over an area of 10 ha which commenced 100 m north of site 151. This area is 0.3 to 0.5 m lower than site 151, but is characterised by a decrease in gradient of the soil surface in the waterlogged area. The area remained waterlogged until a sub-surface drainage system was installed in August 1990. The drainage system serviced the immediate 10 ha of waterlogging and an adjoining 4.5 ha with similar problems. The impact of this drainage system on the 1990 recession and subsequent behaviour of the shallow watertable at site 151 in Figure 11(b) cannot be measured precisely. Water level data are available, but not shown, for shallow bores at sites 148 and 149 in a similar landscape position and elevation to site 151 but on an adjoining farm. Response of the three bores was similar to the end of 1990. The difference between data for 148/149 and 151 for the 1991 recharge suggest that the drainage system may have reduced peak watertable height at site 151 by approximately 0.75 m. It is of interest to note that a major sub-surface drainage system was installed adjacent to bores 148 and 149 in the spring of 1992 to control waterlogging.

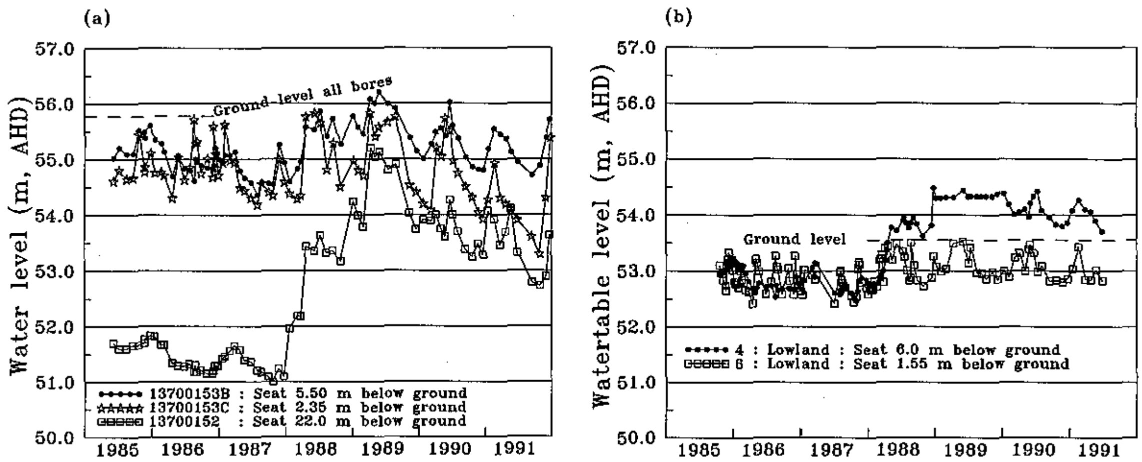
In Figure 11(b) shallow bore 153 demonstrates a water level variation typical of a permanent seepage area. The watertable at this site has varied around 43 m elevation since late 1988, and in accordance with unconfined aquifer performance does not appear to have responded to the 4 to 5 m of additional head now present in the deep aquifer at bore 13710023. Site 153 is adjacent to an extensive area of *Banksia robur* (Swamp banksia) and *Melaleuca quinquenervia* (Tee tree) vegetation in wetland in the Wallum Creek drainage depression.

Seepage at the soil surface has been observed along the edge of the Wallum Creek drainage line adjacent to bore 13710023 and site 153 after significant rainfall events in early 1990 and 1991. The Wallum Creek drainage line therefore may be one of the areas for direct discharge of groundwater and for receipt of higher landscape discharge from the deeper aquifer *via* the shallow lateritic zone aquifer.

5.1.2 Distal sections of the Tertiary aquifer zone

Data in Figure 12(a) are the record of variation in water level of bores 13700152 and 13700153 at the same elevation, but 1.5 km apart, on the north-eastern edge of the North Gregory aquifer zone in Figure 7. The difference in water level between these two bores was attributed to a decrease in hydraulic gradient between the bore sites caused by a bedrock high in the Burrum Coal Measures which was described by Kingston (1993). Bore 13700153B is a piezometer seated at 5.5 m below ground level and has an identical water level to regional bore 13700153 which is seated at 8 m below ground level with filter gravel down to 13 m depth. Bore 13700153C is a watertable observation bore seated at 2.35 m below ground level, on top of the pallid clay band which caps the aquifer. All three tubes are installed in separate bores 5 m apart.

The relative water levels at bore sites 13700153B and 13700153C indicate there has been potential for continued discharge of groundwater at this site since early 1989, after



Figures 12(a)-(b) **AHD elevation of water level data for regional and shallow lateritic zone groundwaters, near the edge of the Tertiary aquifer zone in the North Gregory area, in the Isis District; (a) is regional groundwater and (b) is for shallow groundwater.**

which recharge in the regional aquifer raised average head to above 55 m elevation. This elevation was associated with more extended periods during which the shallow watertable was within 1.0 m of the surface during 1989 to 1990, inclusive. There is extensive seepage salting in the vicinity of this site.

Further evidence for discharge of regional groundwater was obtained at a 3 ha seepage salting site 1.2 km east of bore 13700153 and 400 m to the north-east of bore 13700152 in Figure 7, but 2.1 m lower in the landscape than the two regional bore sites. The bore at site 4 is a piezometer sampling the top of the regional aquifer, whereas site 6 is a watertable observation bore seated on top of the pallid clay zone. Data in Figures 12(a) and (b) show that bores 13700152 and 4 have maintained heads at similar elevations since 1989; however, head at the latter site is artesian because of lower location of the site. There also has been an increase in the average elevation of the watertable of the shallow aquifer, in bore 6, to the extent that minimum recession levels have increased by 0.5 m.

5.1.3 Conclusions from analysis of interaction between regional and shallow groundwater in Tertiary sediments

It was hypothesised that regional groundwater of the Elliott Formation may be able to discharge into the shallow aquifer of the lateritic zone when deep groundwater developed sufficient head to force water through the pallid clay zone separating the shallow and regional aquifers. Evidence to support this hypothesis was quite conclusive at several locations in the North Gregory and Wallum Creek areas. The evidence is much less convincing at higher landscape positions on the southern side of the river where further monitoring of water levels in the deep and shallow groundwater systems will be required to determine the impact of any further recharge of the deep aquifer.

It is of considerable interest that water level in most permanent seepage areas in the Tertiary landscape has not elevated in response to recharge of the main aquifer, as at June 1991. These observations may indicate that lower landscape discharge structures, adjacent to natural drainage depressions, are coping with current levels of discharge. Site 6, in Figure 12(b), is in a discharge zone adjacent to a bedrock high in the Burrum Coal Measures and is an exception to this observation. However, watertables at mid-slope sites have shown a small upward response in elevation. This occurrence is most likely where hydraulic gradient is reduced by a break in slope of the land surface.

Further evidence to support the proposition of groundwater discharge in mid-landscape positions has been gathered from observation of three sub-surface drainage installations which have been constructed in Tertiary mid-landscape positions since 1990. These installations were made necessary by a significant increase in waterlogging since 1989. One installation, involving approximately 1.5 km of drainage pipe at 1.5 m depth, commences approximately 100 m away from site 151 which was discussed in section 5.1.1. This installation has discharged water since installation in September 1990. The system has a base flow discharge of 1 L sec^{-1}, but a flow of 2.4 L sec^{-1} has been measured on several occasions. The installation is directly benefiting an area of 14.5 ha. If it is assumed that the drain discharge is generated within the benefited area, the flow rate range translates into contribution of 2.2 to 5.2 ML ha^{-1} yr^{-1} from the above area. These values are of the same order of magnitude as estimates of 2.25 to 4.75 ML ha^{-1} yr^{-1} derived from a modelling approach by Kingston (1993) of flow in the lateritic zone aquifer at another site.

The above estimates of drainage flows from the lateritic zone range form approximately 50 to 100% of the average allocation, and application, per hectare of irrigation water to sugarcane in the region. The relative magnitude of the drainage and irrigation figures suggest that deep drainage from sprinkler irrigation in the benefited area is unlikely to be largely responisible for the drainage values.

Use, in equation 1, of flow rate from the above drainage system, dimensions of the intercepting area of the trench and head for watertable heights relevant to the flow rate, yielded an estimate of hydraulic conductivity of 0.12 m day^{-1}. This value is towards the lower end of the range of hydraulic conductivities measured for the lateritic zone throughout the Isis District (Table 4).

The benefited area of 14.5 ha was determined from measurement of the area affected by waterlogging prior to installation of the drainage system. However it was not clear whether the drainage flow was generated solely within the benefitted area, or whether more widespread seepage also contributed to drainage outflow. A semi-quantitative answer to this question was provided by applying equation 1 to the following data :

> Assume that the drainage flow Q is generated from an unknown area A, that the hydraulic gradient is the slope across the drainage system, hydraulic conductivity is the calculated value of 0.12 m day^{-1} .

$$Q = -(K\ i\ A) \quad (1)$$

where: Q = flow in $m^3\ day^{-1}$, K = hydraulic conductivity in m day^{-1}, i = hydraulic gradient and A = contributing area in m^2.

Results of the calculation for the low and high drainage flow cases, in Table 6, show that the calculated area for the high flow/high watertable case is in good agreement with the observed 14.5 ha of benefit, and that it is possible for drainage flow to be generated within the benefited area. The flow may come from discharge of regional groundwater. The smaller contributing area, of 7.2 ha, during periods of lower flow/lower watertable implies either the discharge area contracts during drier periods or that 7.2 ha is the actual area of discharge which spreads water over a larger area when the watertable is elevated.

Table 6

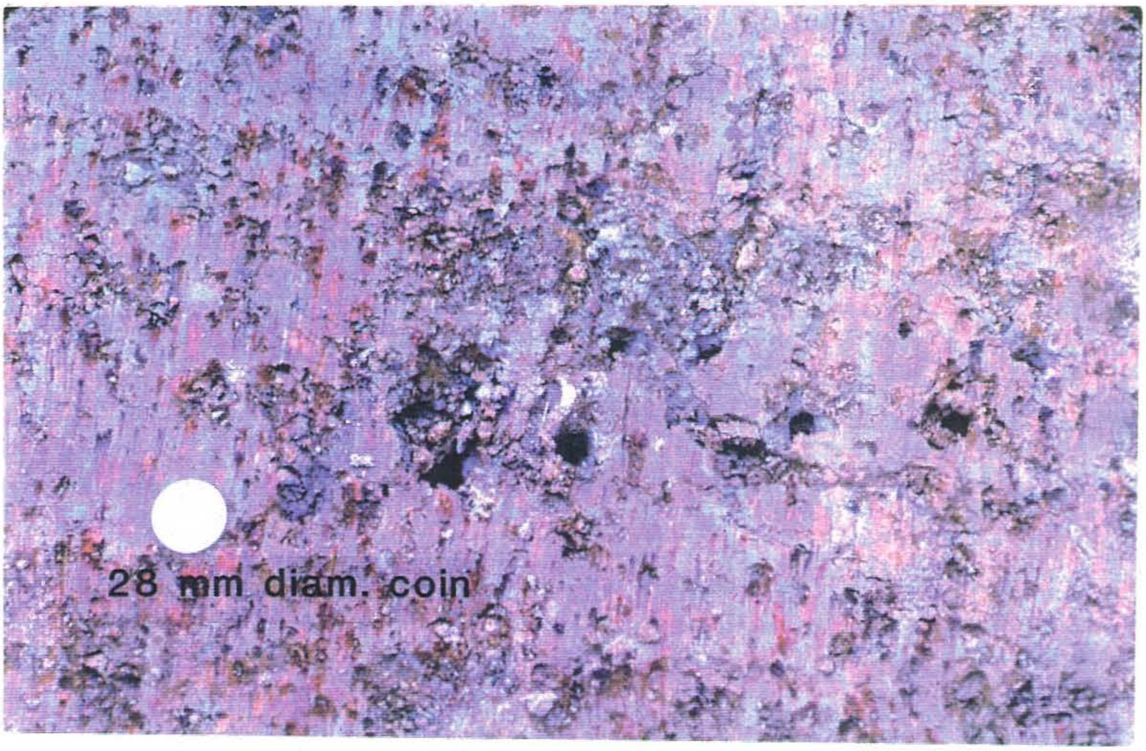
Calculation of areas required to supply measured flow (Q) for the drainage system; K, i and A are defined for equation 1

Parameter	Flow @ 1 L sec^{-1}	Flow @ 2.4 L sec^{-1}
Q ($m^3\ day^{-1}$)	86.4	207.4
K (m day^{-1}) i	0.12 0.01	0.12 0.01
A (m^2) A (ha)	72 000 7.2	172 833 17.3

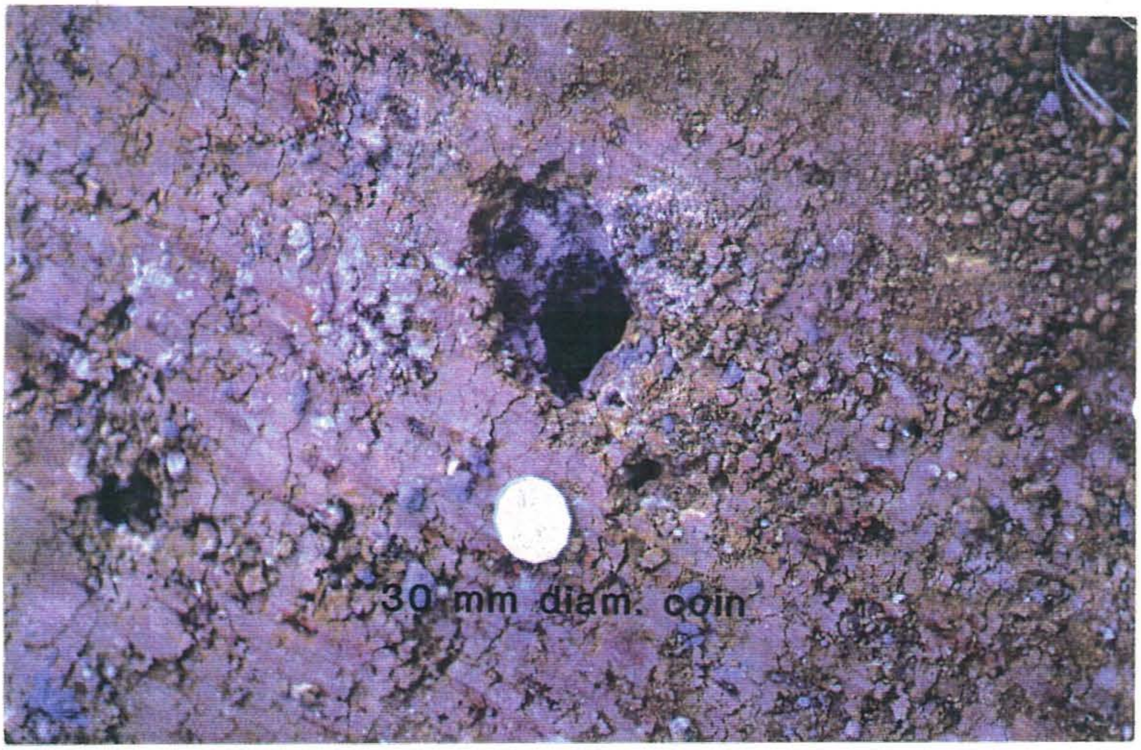
The mechanism for transfer of water through the pallid clay zone which caps the main Tertiary aquifer has not been demonstrated. Johnston *et al.* (1983) demonstrated the existence of macropores in the pallid clay zone at the base of lateritic profiles in southern Western Australia. Macropores to 35 mm diameter have been observed in the lower B-horizon of lateritic soils in the Maryborough Basin. The macropores shown in Plates 1 (a)-(b) were exposed during construction of a drain in an area that had been cleared of timber 25 years earlier. The holes were presumed to have been made by rotting of a tree root. It is possible that roots also penetrated the pallid zone to access underlying moisture in dry periods; old root channels may now facilitate hydraulic connection of lateritic and deeper aquifers.

Seepage salting in Tertiary landscapes generally has been restricted to lower slopes and drainage lines. It has already been shown that discharge from the main Tertiary aquifer zone is having an impact on watertable elevation in the shallow lateritic aquifer in upper and mid-slope positions at several locations. If aquifer recharge continues and shallow watertables are elevated to within 0.5 to 0.75 m of the surface at these locations for extended parts of the year, it is anticipated that there will be an increase in the area affected by waterlogging. This increase probably will be accompanied by an up-slope movement of the seepage salting areas.

(a)



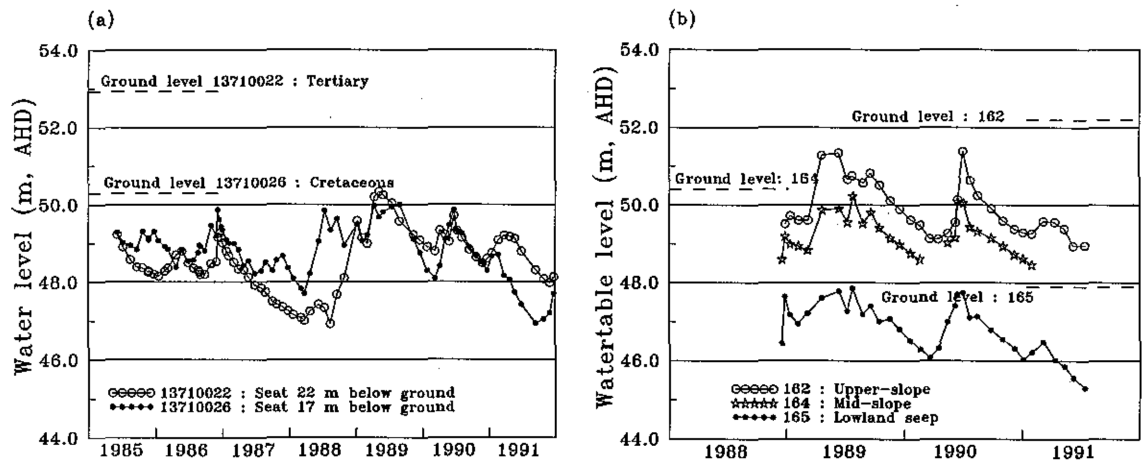
(b)



Plates 1(a)-(b) Macropores in the lower section of a lateritic profile in the Maryborough Basin.

5.2 Areas with Cretaceous geology

Figures 13(a)-(b) contain water level data for deep and shallow bores installed on a transect from an elevated Tertiary area down into the Cretaceous landscape. Bore 13710022 is drilled in Elliott Formation, while Bore 13710026 is drilled in Burrum Coal Measures, a distance of 1.5 km south and further down the slope, as shown in Figure 8. The difference between water level response patterns for these two bores in 1985-86 and 1987 and the delayed response in 13710022 to rainfall in late 1986 and 1988 cannot be explained adequately. The bores showed generally similar responses for 1989-90, but 13710022 maintained a higher water level elevation than did 13710026 throughout the dry weather of 1991. This may have been due to deep drainage from reticulated irrigation. There are no groundwater pumps in the area because of the low transmissivity of the clayey sand material in the Tertiary aquifer zone.

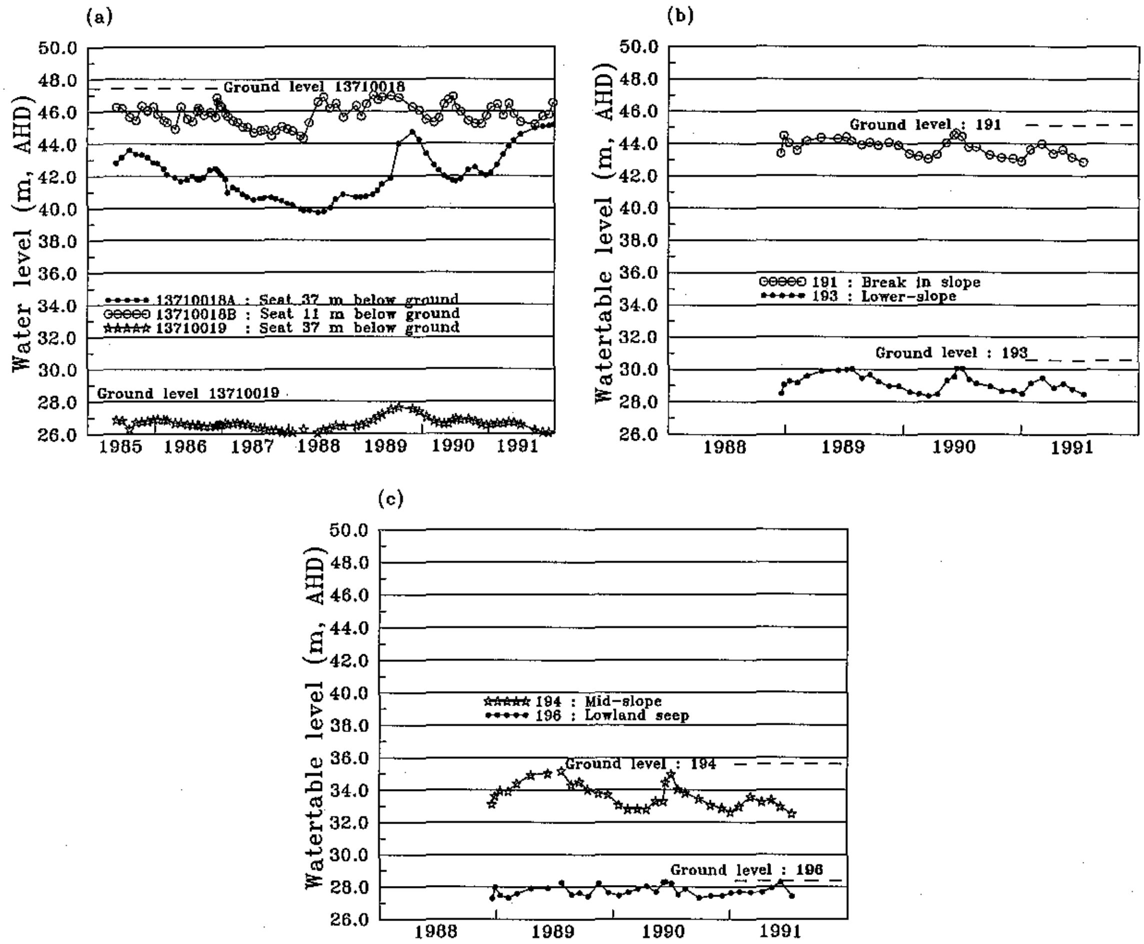


Figures 13(a)-(b) **AHD elevation of water level data for regional and shallow lateritic zone groundwaters, for a transect from Tertiary to Cretaceous geology, in the Farnsfield area of the Isis District; (a) is regional groundwater and (b) is for shallow groundwater.**

The shallow bore at site 162, in Figure 8, is in the shallow Tertiary landscape while sites 164 and 165 are in the Cretaceous unit. Comparison of water levels in Figures 13(a) and (b) shows that the shallow groundwater at site 162 is unlikely to be affected by regional groundwater at the current level of recharge. There is sufficient head in both regional groundwaters for potential discharge situations to exist at sites 164 and 165. The water level in these two shallow bores do not show any impact of post-1989 irrigation. However, numerous outbreaks of seepage salting already exist within a 200 m radius of bore 164, which has water with an EC of 13.7 dS m^{-1}. Bore 165, with 28.1 dS m^{-1} water, is located on the edge of a 300 m^2 saline seep; several similar seeps lower in this landscape are shown on Figure 8.

Bores 13710018 and 13710019 are 5 and 6 km, respectively, to the east of the above sites (see Figure 8) and are drilled in Burrum Coal Measures. Bore 13710018B is seated at

11 m depth, below ground. Figure 14(a) shows that recharge since 1988 has elevated the water level by approximately 0.5 m above 1985-86 values in 13710018B, and by approximately 1 m over the 1987-88 situation. The recovery is due to higher rainfall in 1988-89 and presumably more extensive irrigation since December 1989. Relative head for the deep and shallow bores at this site suggest infiltration from the shallow aquifer to the deeper aquifer. The rate of recharge in the deep bore may have been assisted by the small increase in pressure of shallow groundwater and the cessation of limited groundwater pumping 400 m to the north of the bore site.



Figures 14(a)-(c) **AHD elevation of water level data for regional and shallow lateritic zone groundwaters, for a transect in a Cretaceous landscape, in the Redridge area of the Isis District; (a) is regional groundwater and (b)-(c) are for shallow groundwater.**

There is no significant time-based trend in elevation of the piezometric surface at 13710019 in Figure 14(a), where the head is always within 2 m of the soil surface.

Shallow bores 191 and 193 are located on a transect between 13710018 and 13710019 and also show no significant trends in watertable elevation. Site 193 is classified as a site with potential for permanent seepage. Even though there is no actual discharge at site 193, the difference of 15 m in elevation between this and the previous up-slope sites may be contributing to the seasonal seepage of water into the roadside table drain 60 m to the north of site 193.

Sites 194 and 196, in Figure 14(c), are located 600 m to the south of site 193 in the Burrum Coal Measures landscape. Bore 194 is at a timbered saline non-seepage site, while bore 196 is in a permanent saline seepage area. Neither of these sites show any significant trend in elevation of the watertable.

5.2.1 Conclusions from analysis of hydraulic interaction between regional and shallow groundwater in Cretaceous sediments

With the exception of one bore at a mid-landscape position, there was no evidence of a response in elevation of the piezometric surface to more extensive irrigation since 1989 in Cretaceous aquifers in the eastern section of the Isis District. Similarly there was no significant response in the shallow unconfined aquifers.

The possible impact of high pressure saline waters on development of salt stores in the surficial 8 m of earth in Cretaceous landscapes was discussed by Kingston (1993) and quantitative evidence for discharge of saline water at one site was presented. Data in Figures 14(a)-(b) show that water in saline regional bore 13710019 is within 0.5 to 1 m of developing sufficient water level to present a potential discharge hazard to a least two sites where highly saline groundwater was encountered within 0.5 m of the soil surface.

The impact of extensive irrigation of elevated Tertiary volcanic uplands on hydrology of Cretaceous aquifers cannot be predicted, as there is no understanding of hydrological links between the two groundwater systems. A more extensive drilling program and groundwater monitoring will be essential to understanding the hydrology of Cretaceous landscapes.

The present extent of seepage salting, known location of salt stores in the solum and poor quality of shallow groundwater in Cretaceous landscapes indicate that additional clearing of these landscapes is likely to result in further land degradation. It is extremely unlikely that economic subsurface drainage systems can be installed in Cretaceous landscapes because of lower hydraulic conductivities associated with heavy sodic clay B-horizons. Approval for installation of drainage schemes in such landscapes by a gazetted Drainage Board would be unlikely because the highly saline nature of most drainage waters would prejudice existing stream water quality. Management options may therefore be constrained to efficient use of irrigation water on intake areas and only restricted clearing of lower landscape locations.

6. GROUNDWATER QUALITY

Salinity and chemical composition of regional and shallow groundwater were studied to determine whether these data could be used to corroborate the hydraulic links recognised between the two water bodies, and also to provide the baseline data for regional and shallow groundwater quality in the early days of the irrigation scheme.

6.1 Aquifers in the Maryborough Basin

The nature of water bearing strata in geologic formations in the Maryborough Basin have been interpreted by Hendry and Pearce (personal communication), but assessments of water quality were restricted to electrical conductivity data.

Jurassic Tiaro Coal Measures (Jt) generally yielded poor quality waters from fractured shale and clay aquifers in the Maryborough and Childers areas.

The texture of Cretaceous Graham's Creek Formation (Jkg) in the Maryborough area varies from medium grained micromonzonite and microsyenite to fine grained andesite, basalt and andesitic tuff; in the Childers area the formation was represented by fine grained andesite with limited inter-beds of andesitic conglomerate. The formation was not vesicular and aquifers were located mostly in fractured rock.

The predominant aquifer in Cretaceous Maryborough Formation (Klm) consisted of highly fractured hard dark grey shale. A number of bores in the Maryborough and Isis areas exhibited artesian flow.

Aquifers in Cretaceous Burrum Coal Measures (Klb) occurred mostly in highly fractured zones in grey and red mudstone and grey shale. Some water supplies were obtained from porous carbonaceous sandstone bands interbeded with shale and mudstone.

Aquifers in the Tertiary Elliott Formation (Te) varied considerably in nature throughout the area, but can be put into two broad categories:

1. In the Maryborough area and the southern part of the Isis area aquifers were contained predominantly in clayey semi-consolidated sands and some mudstone, which were reasonably fractured and porous. These aquifers occupied elevated positions in the landscape and did not contain much groundwater.

2. In the Bingera District and on an the North Gregory plateau between the Gregory and Elliott rivers in the Isis district, (see Figure 1), the aquifer consisted of sandstone and siltstone with subordinate interbeds of conglomerate. These sediments yield significant good quality groundwater supplies which are pumped for irrigation.

Pearce (personal communication) considers the aquifers in the Graham's Creek Formation to be unconfined; that aquifers in Maryborough Formation were confined, while aquifers in Elliott Formation and Burrum Coal Measures were unconfined.

The nature of materials supporting perched or shallow groundwaters in the region was addressed in section 6.2 of this report. Water level data for selected shallow and regional aquifers were discussed in 4.3, 5.1.1, 5.1.2 and 5.2. Hydrochemistry of shallow and regional groundwater has not been reported in the literature.

6.2 Groundwater chemistry

6.2.1 Composition of regional groundwater

Means and standard deviations for detailed water quality parameters for regional and shallow groundwaters from the Isis district which were subjected to chemical analysis are shown in Table 7. Data in Table 8 provide a summary of the salinity status of all samples of groundwater in the Maryborough Basin, as EC is the water quality parameter most relevant to this study.

Shallow and Elliott Formation aquifers contain the lowest salinity waters, but there are also some very saline shallow waters in seepage areas, with EC as high as 29.0 dS m^{-1}. Waters in the Cretaceous and Jurassic (Klb, Klm, Jkg and Jt) formations were variable in level of dissolved solids, with most waters falling into the moderate and high salinity categories. The two samples of very saline water came from the Quaternary alluvia in the tidal reaches of the Mary River.

Data for major ionic composition of regional groundwaters are summarised in trilinear and Langlier diagrams in Figures 15(a) to (c). Waters of all formations are dominated by sodium ions; potassium represented a very low proportion of cations. The relatively tight distribution of samples in the lower right hand corner of the cation triangle, in Figure 15(a), does not allow clear recognition of sample grouping by geology of the aquifer. However, it would appear that most samples of water from the Elliott Formation contained less than 5% of cations as calcium; several samples from Burrum Coal Measures, Maryborough and Graham's Creek Formations also fell into this category. With the exception of one sample from Tiaro Coal Measures, changes in composition which decreased the proportion of sodium ions were related to an increase in magnesium rather than calcium ions.

Table 7

Number of samples, mean and standard deviation for water quality parameters in relation to regional groundwater aquifers of the Maryborough Basin and for shallow groundwater in the Isis District

Geology	n	pH	EC mS m^{-1}	Ca me L^{-1}	Mg me L^{-1}	Na me L^{-1}	K me L^{-1}	Cl me L^{-1}	$SO_4^{=}$ me L^{-1}	HCO_3^- me L^{-1}
Qa	2	6.17±0.17	27.3±3.5	29.6±20.9	93.8±41.0	195.0±94.8	2.37±3.16	293.0±23.9	22.6±13.3	4.4±1.5
Te	34	5.53±0.58	0.8±0.6	0.2±0.3	1.0±0.8	6.3±4.8	0.05±0.04	7.3±5.9	0.4±0.3	0.6±0.6
Klb	15	5.86±1.43	6.9±7.3	3.6±6.4	15.1±21.6	62.8±63.3	0.16±0.10	75.4±84.9	4.3±5.1	3.8±3.7
Klm	13	6.35±1.12	9.0±6.2	6.4±7.3	15.9±15.8	75.8±54.8	0.14±0.11	85.9±70.4	9.3±9.2	5.5±3.2
Jkg	13	6.67±0.46	5.3±3.9	5.0±5.1	10.9±10.4	36.6±24.6	0.07±0.03	44.0±35.3	2.9±2.5	6.0±4.0
Jt	6	7.10±0.38	4.6±4.4	3.7±2.1	9.5±10.5	36.7±37.9	0.26±0.34	37.8±47.4	5.5±4.9	6.6±3.8
Shallow	79	5.06±1.08	4.0±5.5	1.0±2.5	5.1±8.5	33.3±49.5	0.09±0.17	36.5±56.2	2.4±5.3	0.6±1.6

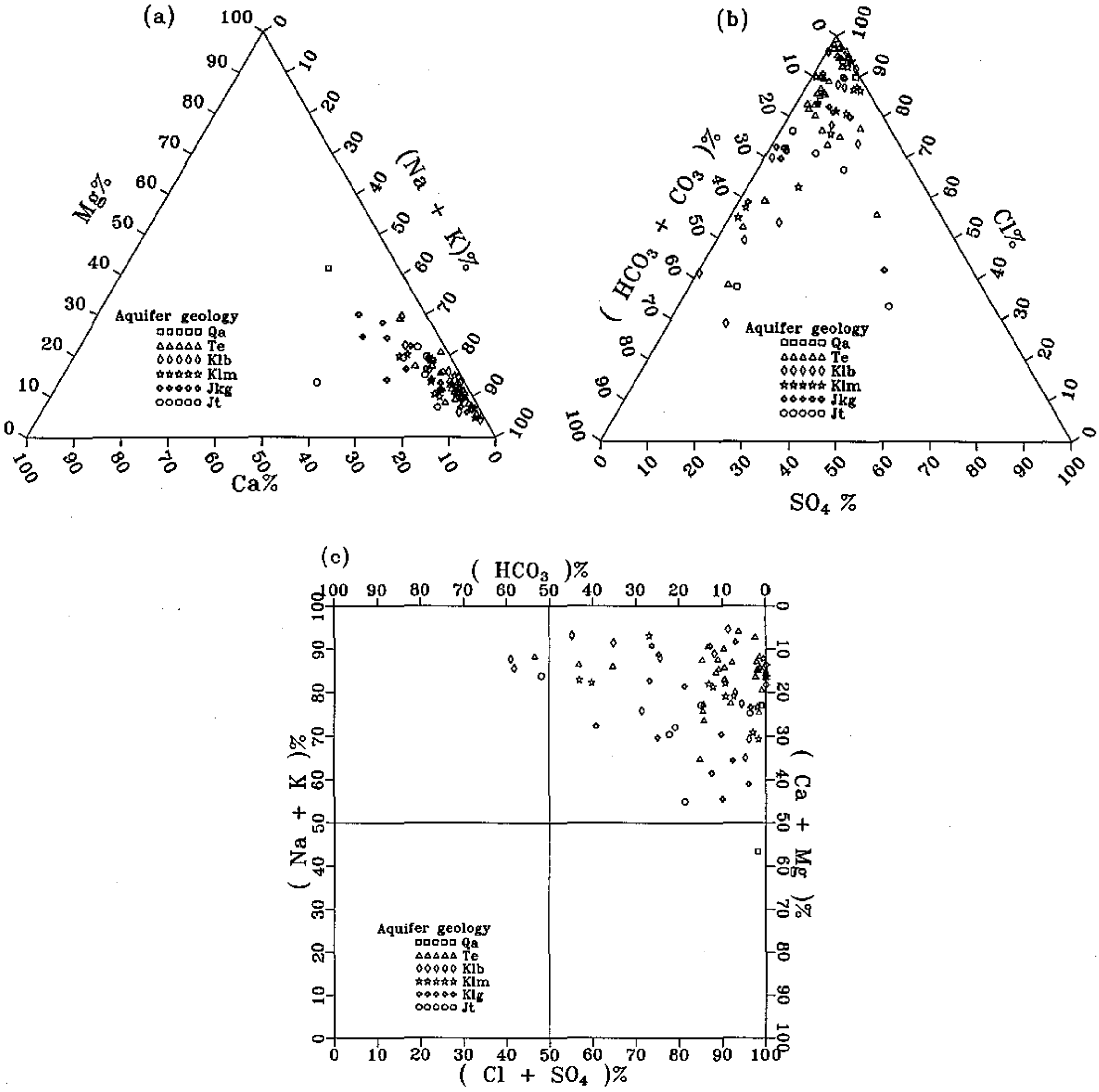
Qa = Quaternary alluvia, Te = Elliott Formation, Klb = Burrum Coal Measures, Klm = Maryborough Formation, Jkg = Graham's Creek Formation and, Jt = Tiaro Coal Measures

Table 8

Mean and range of salinity levels (EC dS m^{-1}) in regional groundwaters in relation to geology of aquifers in the Maryborough Basin and shallow groundwaters of the lateritic zone in the Isis area

Aquifer Geology	EC of groundwater (dS m^{-1})			Number of samples
	Mean	Maximum	Minimum	
Qa	27.3	29.8	24.8	2
Te	0.8	2.8	0.1	34
Klb	6.9	24.3	0.4	15
Klm	9.0	19.9	1.0	13
Jkg	5.3	10.5	0.8	13
Jt	4.6	12.1	0.8	6
Shallow waters of the lateritic zone in the Isis area.	3.3	29.0	0.1	160

Qa = Quaternary alluvia, Te = Elliott Formation, Klb = Burrum Coal Measures, Klm = Maryborough Formation, Jkg = Graham's Creek Formation and Jt = Tiaro Coal Measures



Figures 15(a)-(c) **Trilinear and Langlier diagrams of cation and anion composition for regional groundwaters in the Maryborough Basin, in relation to geology of aquifers.**

The anion triangle, in Figure 15(b), shows chloride to be the dominant anion for most waters, especially those from Elliott Formation. Decreases in chloride proportions were associated more with a higher level of bicarbonate than of sulfate ions. Cretaceous and Jurassic waters showed higher levels of bicarbonate ions than did Tertiary waters. No bicarbonate was detected in seven of the 83 samples of regional groundwater. The seven samples were very acidic; four of the samples had pH values between 3.01 and 3.60 and EC values between 8.28 and 15.46 dS m^{-1}, while the remaining three samples had pH between 4.14 and 5.18 and EC between 0.27 and 1.49 dS m^{-1}.

Most regional waters were located in the NaCl quadrat of Figure 15(c), which is a Langlier plot of cation/anion composition. There is no clear definition of discrete geological groupings of waters within sedimentary aquifers of the Maryborough Basin, when overall composition of the major ions is examined graphically. However, Figure 15(c) does indicate a general tendency for Elliott Formation waters to be the most dominant of the NaCl-type waters, located in the upper right-hand corner of the graph. Burrum Coal Measures water had a wide distribution of composition within the quadrat. Waters from Maryborough, Graham's Creek and Tiaro Formations appear to lie within two broad lineations at 45° to the HCO_3 and (Ca+Mg) axes in Figure 15(c).

There was a low but significant positive correlation ($R^2 = 0.17$, $p<0.01$) between (Ca+Mg)% and $Log_{10}(EC)$. However, the low but significant correlation ($R^2=0.18$, $p<0.01$) between HCO_3% and $Log_{10}(EC)$ was negative for regional waters; this was attributable to higher proportions of chloride in saline waters. Twenty-four samples of water demonstrated residual alkalinity; 14 of the 17 samples which showed levels greater than 0.5 me L^{-1} were from Cretaceous aquifers.

Higher proportions of calcium, magnesium and bicarbonate ions in most Cretaceous, as opposed to Tertiary, waters may represent an equilibrium with minerals in the sediments without precipitation. The trend to higher divalent ion percentages with concentration of regional groundwaters is contrary to trends reported by Hardie and Eugster (1970) and Shaw *et al.* (1987), where it was shown that precipitation of less soluble ion species increased the proportion of sodium and chloride ions in saline waters. However, Kingston (1993) used a study of disequilibrium indices to show that most common minerals were unlikely to precipitate from groundwaters of the Maryborough Basin.

Analysis of 31 regional groundwaters for nitrates in April 1991 showed no samples exceeded the recommended maximum level, in water for human consumption, of 10 mg L^{-1} of NO_3 - N. Nitrate was not detected in 15 samples, 13 samples contained less than 2 mg L^{-1}, two samples fell in the 3 to 4 mg L^{-1} range and one sample contained 5.9 mg L^{-1}.

6.2.2 Composition of shallow groundwaters

Shallow groundwaters in this discussion were sampled mainly from the nodular zone of lateritic sedimentary soils in the Isis District; similar soil types occur throughout the Maryborough Basin. The nodular zone aquifer was described in section 4.4.1.

In lower landscape positions, and in areas with Cretaceous geology, shallow groundwaters were encountered also as perched waters on heavier clay B-horizons, on mudstone, or within macropores in clay or fractured mudstone.

Means and standard deviations for detailed water quality parameters for shallow groundwaters in the Isis area were obtained from the partial data set which was

Table 9

Number of samples, mean and standard deviation for water quality parameters for shallow groundwater in relation to geology of the weathered zone in the Isis District

Geology	n	pH	EC mS m^{-1}	Ca me L^{-1}	Mg me L^{-1}	Na me L^{-1}	K me L^{-1}	Cl me L^{-1}	$SO_4^{=}$ me L^{-1}	HCO_3^- me L^{-1}
Tb	7	5.16±0.52	1.0±0.9	0.7±0.6	1.7±2.0	6.9±7.3	0.17±0.37	7.6±7.6	0.6±0.5	0.2±0.3
Te	51	5.35±0.96	2.2±3.0	0.4±1.3	2.8±4.6	17.4±25.5	0.08±0.16	19.3±28.7	0.9±1.7	0.5±1.3
Klb	13	4.22±1.17	9.7±6.4	2.9±4.9	12.5±13.9	85.1±66.1	0.06±0.04	90.6±73.3	6.2±6.1	0.9±2.1
Klm	8	4.45±1.21	9.2±9.1	1.8±2.7	11.3±10.7	73.4±75.8	0.07±0.05	86.3±95.2	7.2±12.4	1.0±2.8

Tb = Tertiary basalt, Te = Elliott Formation, Klb = Burrum Coal Measures, Klm = Maryborough Formation and n = number of samples

Table 10

Range of salinity levels, expressed as EC (dS m^{-1}), in shallow groundwaters of the lateritic zone of soils in the Isis area, in relation to geology of the weathered zone

Geology of the weathered zone	EC of groundwater (dS m^{-1})			Number of samples
	Mean	Maximum	Minimum	
Tb	1.5	5.2	0.3	11
Te	1.3	10.1	0.1	109
Klb	8.6	28.0	0.5	30
Klm	7.4	29.0	0.9	8
Jkg	4.5	-	-	1
Jt	4.6	-	-	1

Tb = Tertiary basalt, Te = Elliott Formation, Klb = Burrum Coal Measures, Klm = Maryborough Formation, Jkg = Graham's Creek Formation and Jt = Tiaro Coal Measures.

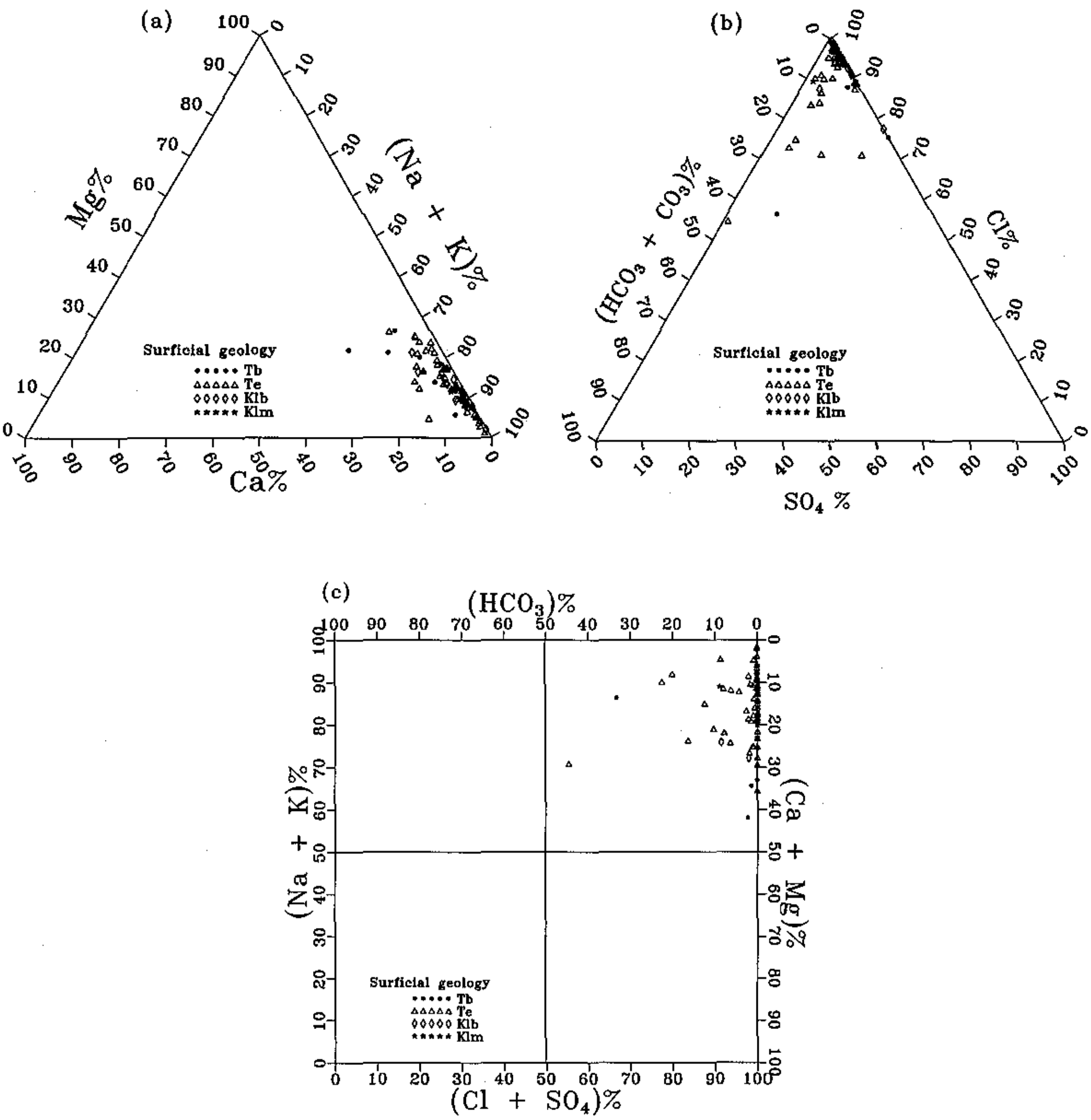
subjected to chemical analysis and are shown in Table 9. The mean and range in salinity levels for all shallow groundwaters sampled in the Isis District are shown in Table 10.

Tables 9 and 10 show that lowest salinity shallow groundwaters were associated with profiles developed on Tertiary basalt and Tertiary Elliott Formation. Shallow groundwaters in the two Cretaceous formations were generally saline; 85% of the samples in weathered material from Burrum Coal Measures were of moderate to high salinity, while 63% of Maryborough Formation seepage waters fell into the same category.

Trilinear and Langlier diagrams in Figures 16(a)-(c) summarise composition of the shallow groundwater with respect to the major ions. Comparison of corresponding diagrams in Figures 15(a)-(c) and 16(a)-(c) show that regional and shallow groundwaters demonstrate marked similarities in composition. This graphical analysis of composition of the shallow groundwaters provided no clear delineation of groups of waters in relation to geology.

Cations, in Figure 16(a), were ranked in the order $Na^+ > Mg^{++} > Ca^{++}$ for per cent reacting value (Piper, 1944), while Cl^- dominated anion composition in Figure 16(b). Bicarbonate ions were not detected in 43 and 39%, respectively, of Tertiary basalt and Elliott Formation waters and in 85 and 88%, respectively, of shallow waters from Burrum Coal Measures and Maryborough Formation. More samples from Tertiary profiles were associated with increased HCO_3^- and $SO_4^=$ ions in Figure 16(b) than were samples from

Cretaceous areas. The only three samples which exhibited residual alkalinity came from Tertiary profiles. Data in Table 9 show that all shallow groundwaters were acidic.



Figures 16(a)-(c) **Trilinear and Langlier diagrams of cation and anion composition for shallow groundwaters of the lateritic zone of soils in the Isis District.**

Nitrate-nitrogen data were available for 44 shallow groundwater bores from sampling in August 1990 and April 1991. Data in Figure 17 show that 93 and 87% of the 1990 and 1991 samples, respectively, contained less than 4 mg L^{-1} NO_3 - N. On average 97% of samples contained less than the maximum recommended level of 10 mg L^{-1} NO_3 - N, in water for human consumption. Comparison of NO_3 - N levels in individual bores for the two sampling times showed that 1991 values were higher than 1990 values in 59% of bores, lower in 39% and unchanged in 2%. There was no consistency between years for the few bores which showed moderate to high nitrate levels.

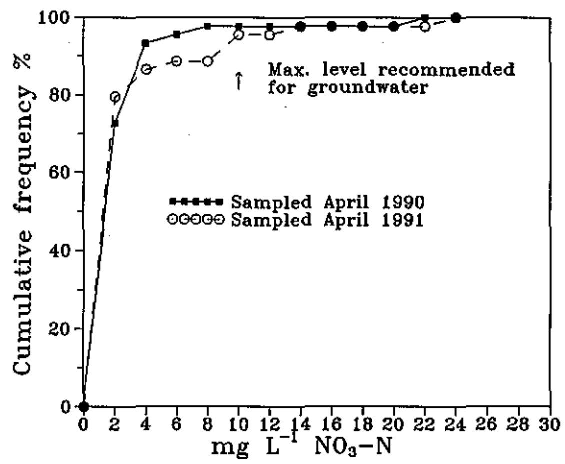


Figure 17 **Cumulative frequency of occurrence of nitrate-nitrogen levels, in 2 mg L^{-1} increments, in shallow groundwater samples in the Isis District in 1990 and 1991.**

Data from SRDC Project CSC2S *"Improving nitrogen management in sugarcane in south Queensland and trash management effects on nitrogen use by sugarcane"* have shown rapid leaching of bromide and nitrate from the root zone of lateritic soils in the Isis area. The presence of more samples in the 4 to 12 mg L^{-1} NO_3 - N range in April 1991 samples than in August 1990 samples may be a reflection of nitrate movement from the autumn planting operation in 1991, but only two of the 44 samples contained more than 10 mg L^{-1} NO_3 - N.

Phosphate assays were conducted on most samples of shallow groundwater. In 1990, PO_4 - P values ranged between 0.06 and 0.78 mg L^{-1} in waters where phosphorus was detectable, while in 1991 all waters showed less than 0.06 mg L^{-1} PO_4 - P. The low values for phosphorus in shallow groundwater is not surprising as phosphorus is strongly bound to clay platelets; soil loss is usually required for significant movement of phosphorus.

6.2.3 Origins of soluble salts in groundwaters

Kingston (1993) showed that composition of shallow and regional groundwater in the Maryborough basin is influenced heavily by oceanic salt; either from aerosols mixed with rainwater, or from connate salts mobilised from shales and mudstone of the Maryborough Formation. Conserved species such as sodium and chloride ions showed a close relationship to a theoretical mixing model proposed between sea water and rainfall. However, magnesium, calcium and potassium ions were shown to be increasingly susceptible to departures from the above model as a result of possible enrichment from aquifer minerals and depletion by ion exchange reactions. Departures of sulfate ions in groundwater from the mixing model were attributed to oxidation and absorption reactions. Enrichment of shallow groundwaters with bicarbonate ions was attributed to biological activity of the solum, while higher level of bicarbonate in some Cretaceous waters was attributed to interbedding of calcite, or oxidation of carbonaceous material in sediments.

6.2.4 Interpretation of groundwater classification in terms of geo-hydrochemistry

Classification of waters by principal components analysis (PCA) and cluster analysis has shown that low salinity/low Ca^{++}, Mg^{++} and HCO_3^- waters of the Elliott Formation (Group 1) can be discriminated objectively from most Cretaceous / Jurassic waters (Group 4), (Kingston, 1993). Both multivariate classification techniques also allowed recognition of another two groups of waters; one with moderate to very high salinity, and zero to low values of HCO_3^- (Group 3), and a second group (Group 2) which was intermediate in factor space among the previous three groups.

Groups 2 and 3 contain 61% of the shallow groundwater samples. Location of samples in PCA factor space had a basis in geology of aquifer materials and the degree of mixing between waters. An understanding of processes or factors which lead to the trend in increasing salinity of shallow groundwaters, from PCA group 1 through groups 2 and 3, may have significant implications for understanding the dynamics of seepage salinity development in the Basin.

Both classification systems contributed to a large reduction in the conceptual extent of the water quality data set so that possible relationships between the groups of waters could be hypothesised more readily from additional field data.

Principal components analysis of groundwater composition in the Isis District suggested that moderate and higher salinity shallow groundwaters in areas with Cretaceous geology could be explained on the basis of different mixing proportions between infiltrating meteoric waters and discharge of saline water from Cretaceous materials. Degree of separation of water samples from Tertiary and Cretaceous zones at the same site in PCA factor space was interpreted as an indication of the magnitude and source of the mixing components.

Water quality of the low salinity shallow groundwaters, in the nodular zones of sedimentary soils developed on Tertiary Elliott Formation, is similar to that contained in the sands and gravels of the major regional aquifers in the formation. In section 5.1.1 piezometric evidence from four localities in the Isis district shows hydraulic connection between the shallow and regional aquifers. The heavy clay aquitard between the two zones may contain windows of more permeable material, or may be perforated by channels from decayed tree roots. The regional aquifer can discharge into the shallow zone when pressure head in the former aquifer is within 2.5 to 3.m of the soil surface.

Hydraulic connection may also allow rapid recharge of the regional aquifer by rainfall or irrigation.

Higher salinity of regional waters in areas with cretaceous geology was interpreted to have come from leaching of marine salts trapped in sediments of the Maryborough Formation. Hydraulic pressures and deformation of Graham's Creek Formation and Tiaro Coal Measures, during the late Jurassic or early to mid-Cretaceous, may have allowed fractured and weathered zones in these formations to approach and equilibrium with sea water in which the overlying Maryborough Formation was being deposited. Salts in Burrum Coal Measures may also have originated from periodic marine incursions (Ellis and Whitaker, 1976) and from weathering of minerals in carbonaceous deposits.

It is proposed that oxidation of carbon from laminations in Burrum Coal Measures, Maryborough Formation and Tiaro Coal Measures provided the strong continental signature of higher concentrations of HCO_3^- ions in these waters which was recognised from PCA (Kingston, 1993). Displacement of sodium, magnesium and calcium concentrations above the rainfall / sea water mixing line proposed by Kingston (1993) for most waters from Graham's Creek Formation suggests further continental effects from weathering of sodium and calcium feldspars and pyroxenes from the volcanics of this formation.

7. TEST OF THE HYPOTHESIS FOR DISCHARGE AND MIXING OF GROUNDWATERS

Membership of PCA groups by shallow and regional groundwaters was determined largely by EC, and concentration of Ca^{++} and HCO_3^- ions, but it also had a firm basis in geology of the aquifers. The group of waters which lay between the other three groups in PCA factor space was hypothesised to result from discharge and/or mixing of waters from aquifers of different geology.

The hypothesis of discharge of Cretaceous groundwater and mixing with low salinity Tertiary waters, to create saline seepage, was tested by Kingston (1993) against a 1986-87 shallow groundwater data set that was not used in PCA or cluster classifications.

7.1 Conclusions for discharge of Cretaceous groundwater and subsequent mixing

Four conclusions were drawn from analysis of the hydrochemical data set used to test the hypothesis that saline water contained in Cretaceous mudstone was discharging upwards through a semi-confining clay layer into the nodular zone of lateritic soils developed on a thin sheet of Tertiary Elliott Formation. These conclusions were:

- Classification of waters by K-means cluster analysis and trilinear composition diagrams showed that the saline water below the clay layer and water around the potential discharge site were classified in a group which also contained waters from nearby bores which were known to originate in the Burrum Coal Measures. Low salinity waters of the nodular zone were classified into a second group. Thus waters in the seepage area could be objectively recognised as being chemically different from waters of the surrounding nodular zone.

- There was sufficient hydraulic potential for the saline water to discharge upwards into the nodular zone.

- EC data from the 18 shallow bores in the nodular zone at this site showed a focus of more saline water around the potential discharge site. There was a trend in a north-easterly direction indicating dilution of the saline water by flow of low salinity water in the nodular zone.

- Hydraulic and EC data from the study area were used in a simple models to show that the dilution plume could be explained by Darcian flow and mixing of saline water with low salinity water of the nodular zone. Similar calculations were employed to show that the vertical discharge of saline water could occur through preferred pathways in the semi-confining clay layer.

The conclusion that Cretaceous waters can discharge and mix with lower salinity Tertiary waters, under certain conditions, is relevant to discussion of composition and increasing salinity of waters in the classification provided by PCA. It is possible that the processes outlined above are involved in raising salinity of groundwaters in Tertiary materials, and saline seepage in the Bingera district. This mechanism will also apply in the Isis and Maryborough area where the Tertiary sheet is thin and where Cretaceous waters exhibit confined or semi-confined pressure heads. Sites in mid- to low-landscape positions are most likely to be affected by this process of seepage salting.

8. IMPLICATIONS OF GROUNDWATER DISCHARGE FOR MANAGEMENT OF SALINITY

Recognition of potential for discharge and mixing of more saline groundwater has significant implications for future management of seepage salting in the Maryborough Basin.

Higher hydraulic conductivity of Tertiary profiles, especially the nodular zone, offers hope that irrigation scheduling and cropping strategies, which minimise the deep drainage component and improved subsurface drainage of the nodular zone, could allow management of watertables and seepage salting in this landscape.

However, individual farm management strategies are unlikely to be successful where regional Tertiary aquifers are recharged with sufficient head to cause discharge into the

However, individual farm management strategies are unlikely to be successful where regional Tertiary aquifers are recharged with sufficient head to cause discharge into the nodular zone. Data presented in section 5.1.1 show hazardous levels of recharge have occurred in former production aquifers on Elliott Formation. An integrated management approach therefore will be required to manage the deep regional groundwater resource through groundwater extraction for irrigation, integrated use of imported irrigation water and more efficient irrigation techniques to minimise recharge of groundwater.

Examination of shallow bore logs and pit exposures of the waterbearing nodular zone and consideration of techniques available for installing sub-surface drains suggested that drains could be installed between 1.5 and 1.8 m depth. The Hooghoudt steady-state drainage equation was used with median hydraulic conductivity of 0.64 m day^{-1}, a lower value of 0.5 and higher value of 1.0 m day^{-1} from Table 4, to calculate design drain spacing, for drains at 1.5 or 1.8 m depth. Results are shown in Table 11.

Table 11

Design drain spacings (m) for 65 mm slotted pipe in the lateritic zone of sedimentary soils in the Isis area for three values of hydraulic conductivity and two depths of drain. The impermeable layer was assumed at 2.5 m, mid-drain height of watertable was designed at 0.75 m and required daily drainage was 6 mm day^{-1}

Hydraulic conductivity (m day^{-1})	Drain depth = 1.5 m	Drain depth = 1.8 m
0.50	25	28
0.64	28	32
1.00	35	40

Use of 100 mm instead of 65 mm pipe made only small differences to calculated drain spacings. Choice of pipe size for lateral drains depends on length of the lateral, gradient and estimated water flow. Standard tables can be used to assist this determination. Diameter of drainage mainline should also be sized from the standard tables.

Identification of opportunity for deeper than normal placement of sub-surface drainage pipe posed difficulty with respect to the Workplace Health and Safety legislation. Pits or trenches deeper than 1.5 m must have walls reinforced by shoring before workers enter. BSES imported a dedicated drainage machine from Victoria, and demonstrated its operation at a field day. This step was indicated to ensure that the benefits of the project were not constrained by lack of information on safe installation of deeper drains or concern for significant additional costs of deeper drain placement. This machine can dig a trench to 2 m depth, lay the pipe and filter material at up to 800 m per day, and save approximately $1.50 per metre of drain. Workers do not have to enter the trench.

Soils developed on Cretaceous sediments have finer textured B-horizons, are often sodic and therefore have lower hydraulic conductivity and poorer drainage prospects than do soils derived from Tertiary sandstones. Poor quality groundwater and effective discontinuity of aquifers limits the option for head control by pumping. It would therefore appear that best prospects for management of discharge of Cretaceous groundwaters and their mixing with better quality shallow waters may be through minimising aquifer recharge and development of higher pressure head.

Consideration should also be given to realistic landuse planning through control of forest clearing and intensity of development in areas with potential for discharge of groundwater. Kingston (1993) showed that clearing of catchments with Cretaceous geology is associated with deterioration in stream water quality. Discharge areas can be recognised from electromagnetic induction data supplemented by hydrology and geochemical data.

Locations of recharge areas for the Cretaceous aquifers have not been identified, nor has the relationship between intake and discharge zones.

9. ACHIEVEMENT OF OBJECTIVES AND APPLICATION OF RESULTS

9.1 Achievement of objectives

All objectives established for this project were achieved. The results have provided much greater knowledge of the problem and possible courses for future action within research / extension agencies and the sugar industry. Major findings of the project have been used to justify the need for, and to underpin establishment of the Isis District Drainage Board.

A summary of achievements within the four project objectives is shown below :

1. Seasonal persistence of shallow watertables was measured over the three-year project in conditions which included a heavy wet season, major drought and progressive expansion of the irrigation area. The perennial persistence of the watertables and recognition of the shallow lateritic aquifer zone showed that the watertable at most sites should be classified as shallow rather than the normal interpretation of a perched watertable.

   Watertables were classified into *non-seepage, seasonal seepage and permanent seepage* categories.

2. Presence of a well developed nodular zone between 0.75 and 2.5 m depth in mid- or low-landscape positions in areas with Tertiary Elliott Formation geology was a good indicator of potential for waterlogging problems and requirement for improved drainage.

New expressions of waterlogging hazards developed in mid-landscape positions, rather than only in low-landscape positions. Low-landscape positions remain wet, but there was no significant elevation of watertables in this zone. An explanation for this phenomenon included allowance for differences in hydraulic conductivity and gradient.

Areas in which seepage may have an impact on waterlogging and/or soil salinity are mapped on Figure 2.

3. The conceptual model for drainage design in Tertiary lateritic landscapes included the recognition that sub-surface drainage pipe should be located in the nodular zone, between 1.5 and 1.8 m depth, rather than in or on top of the clayey B-horizon. Design drain spacings were based on typical hydraulic conductivity data.

   It was shown that regional groundwater was leaking upwards into the nodular zone aquifer. Specific hazard areas for such discharge were identified. It is unlikely that sub-surface drainage installations could be economically designed to cope with this discharge in addition to rainfall and irrigation percolation.

   In Tertiary landscapes the discharging water is of high quality and should be regarded as a resource rather than a liability. A strategy was proposed for integrated use of this groundwater with reticulated surface water to enable draw down of the groundwater surface to an appropriate level. Details of the strategy will be the subject of further research by the Queensland Department of Primary Industries (Water Resources) and BSES.

4. Detailed chemical analyses for regional and shallow groundwater data on three occasions throughout the project provided the first comprehensive study of groundwater quality in the area. It was shown that high quality regional and shallow groundwaters from Tertiary landscapes could be objectively discriminated from poorer quality water from Cretaceous and Jurassic landscapes. These data will be useful as baseline data for observation of any changes in water quality associated with downstream effects of the irrigation scheme.

   Concentrations of soluble phosphorus in the shallow groundwaters were very low, while on average 97% of samples contained less than the recommended level of nitrate in drinking water for humans.

Project findings have been extended to the Sugar Industry through two field days, articles in the BSES Bulletin and two addresses to the District Canegrowers Executive. Cooperating growers received an annual summary of water level and EC data for bores on their farms. Data were used extensively to justify formation of the Isis District Drainage Board and in planning farm drainage works. A further series of shed meetings will be held in May-June 1993 to discuss results.

9.2 Publications arising from the project

Scientific papers, with the following title proposals, will be prepared for the journals identified with each paper :

- Soil colour and ferriginous nodules as indicators of waterlogging hazard in hydromorphic sedimentary soils. *Aust. J. Soil Sci.*

- Interaction between groundwaters from deep and shallow aquifers in landscapes with Tertiary or Cretaceous geology in the Isis Irrigation Area of south-east Queensland. *J. of Hydrology*

- Geochemistry of regional groundwater in the Maryborough Basin of south-east Queensland. *Groundwater*

- Geochemistry of shallow groundwater in the Maryborough Basin of south-east Queensland. *Groundwater*

- Origins of soluble salts in groundwater in the Maryborough Basin of south-east Queensland. *Groundwater*

- Relationship of seepage salting of soil to depth and salinity of watertables in south-east Queensland. *Aust. J. Soil Sci.*

9.3 Difficulties encountered

The major difficulties encountered during this project were of a logistic nature where weather conditions upset or significantly delayed planned operations. For example rainfall in the autumn and winter of 1988 caused delays to installation of shallow bores, and drought in 1990 and 1991 precluded measurement of hydraulic conductivity because the watertable had dropped below bore depth for some bores in key transects. Acquisition of watertable data was often difficult and time consuming during wet periods because the only access to some sites was on foot.

10. FUTURE RESEARCH

This project has resulted in identification of several areas in which further research is required to assist with implementation of management strategies which will ensuure the sustainability of the irrigation area and production systems on hydromorphic soils.

1. Further research is needed to quantify the volume of groundwater extraction required from Tertiary aquifers to control seepage into the base of lateritic soil profiles. In most cases extracted water would be of high quality and could be reused for irrigation. This research would most appropriately be carried out by

QDPI-Water Resources, with possible collaboration with CSIRO Division of Water Resources.

2. There is a good opportunity for rural sociology research to be undertaken in association with the above project to suggest the most efficient, and acceptable, manner of administering the groundwater pumping operation. A major objective of this work will be deriving a management system which has most chance of success, through fostering a greater sense of community ownership and participation in defining benefits of managing aquifer levels. This work would be relevant to other irrigation areas in Queensland where conjunctive use of surface and groundwater has a role in managing high groundwater levles.

3. Prospects are poor for gravity outfall of sub-surface drains in many low-landscape positions. This problem is common to other irrigation areas in Australia and overseas. There is a need to develop alternative strategies, which are efficient and low-cost, for pumping and possible reuse of drainage waters.

4. Drainage water from irrigation of the volcanic uplands had no apparent impact on recharge of Cretaceous aquifers during the term of the project. There is no understanding of recharge mechanisms for the Cretaceous aquifers. This knowledge may be important for the long-term consequences of the irrigation system. Monitoring of bore water levels will be maintained, but a more significant study of groundwater hydrology is indicated.

11. ACKNOWLEDGMENTS

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Appendix I Duration of watertable height shallower than 0.5 and 1.0 m for shallow bores in nodular zone aquifers from 1988-91, in relation to position in the landscape transect, surficial geology and average salinity of the watertable.

Transect No.	Bore No.	Position	Year	Days >-0.5 m	Days >-1.0 m	EC mS m^{-1}	Geology
1	14	Mid slope	1988*	0	0	0.26	Tertiary
			1989	87	96		
			1990	0	0		
			1991**	0	0		
1	15	Break of slope	1988*	43	125	0.51	"
			1989	82	159		
			1990	0	29		
			1991**	0	0		
1	16	Lowland	1988*	48	130	0.32	"
			1989	91	216		
			1990	19	48		
			1991**	0	0		
2	B8	Mid slope	1988*	38	91	0.55	Tertiary
			1989	111	341		
			1990	19	139		
			1991**	0	72		
2	B2	Lowland seep	1988*	38	173	6.90	"
			1989	312	365		
			1990	212	365		
			1991**	43	365		
3	44	Upper slope	1988*	0	0	0.30	Tertiary
			1989	5	82		
			1990	0	0		
			1991**	0	0		
3	43	Mid slope	1988*	87	100	0.59	"
			1989	82	288		
			1990	29	163		
			1991**	0	149		
3	42	Lowland seep	1988*	120	250	1.68	"
			1989	101	336		
			1990	34	202		
			1991**	0	187		
4	156	Upper slope	1988*	-	-	0.35	Tertiary
			1989	67	139		
			1990	0	38		
			1991**	0	14		
4	157	Mid slope	1988*	-	-	0.51	"
			1989	67	202		
			1990	10	144		
			1991**	0	0		
4	158	Lowland seep	1988*	-	-	11.63	Cretaceous
			1989	312	365		
			1990	135	365		
			1991**	48	202		

Appendix I continued

Transect No.	Bore No.	Position	Year	Days >-0.5 m	Days >-1.0 m	EC mS m^{-1}	Geology
5	151	Mid slope	1988* 1989 1990 1991**	- 0 0 0	- 29 34 0	0.19	Tertiary
5	152	Mid slope	1988* 1989 1990 1991**	- 43 0 0	- 87 29 0	0.26	"
5	153	Lowland	1988* 1989 1990 1991**	- 120 106 0	- 351 183 159	0.67	"
6	198	Mid slope	1988* 1989 1990 1991**	- 0 0 0	- 111 21 0	12.58	Cretaceous
6	199	Lowland	1988* 1989 1990 1991**	- 19 0 0	- 144 14 0	28.63	"
7	220	Mid-lower slope	1988* 1989 1990 1991**	- 0 0 0	- 82 0 0	1.50	Cretaceous
7	221	Lower slope	1988* 1989 1990 1991**	- 65 0 0	- 197 43 0	23.25	"
8	203	Break of slope	1988* 1989 1990 1991**	- 120 0 0	- 216 38 12	5.40	Cretaceous
8	204	Lowland	1988* 1989 1990 1991**	- 135 43 0	- 255 120 58	11.88	"
9	206	Break of slope	1988* 1989 1990 1991**	- 0 0 0	- 84 24 0	0.58	Cretaceous
9	205	Lowland	1988* 1989 1990 1991**	- 168 34 0	- 346 149 0	2.63	"

Appendix I continued

Transect No.	Bore No.	Position	Year	Days >-0.5 m	Days >-1.0 m	EC mS m^{-1}	Geology
10	162	Upper slope	1988* 1989 1990 1991**	- 0 0 0	- 65 72 0	5.55	Tertiary
10	164	Mid slope	1988* 1989 1990 1991**	- 24 24 0	- 202 48 0	13.68	Cretaceous
10	165	Lowland seep	1988* 1989 1990 1991**	- 142 35 0	- 351 130 0	28.08	"
11	194	Mid slope	1988* 1989 1990 1991**	- 29 0 0	- 149 19 0	8.18	Cretaceous
11	195	Lowland seep	1988* 1989 1990 1991**	- 115 82 0	- 288 171 111	5.71	"
11	196	Lowland seep	1988* 1989 1990 1991**	- 146 91 53	- 312 346 202	24.63	"
11	197	Drainage line	1988* 1989 1990 1991**	- 10 19 0	- 260 111 67	2.28	"

where: * indicates data only for bores installed February - April; no data shown for bores installed October - December 1988.

** Records for 1991 end on 25/06/91.