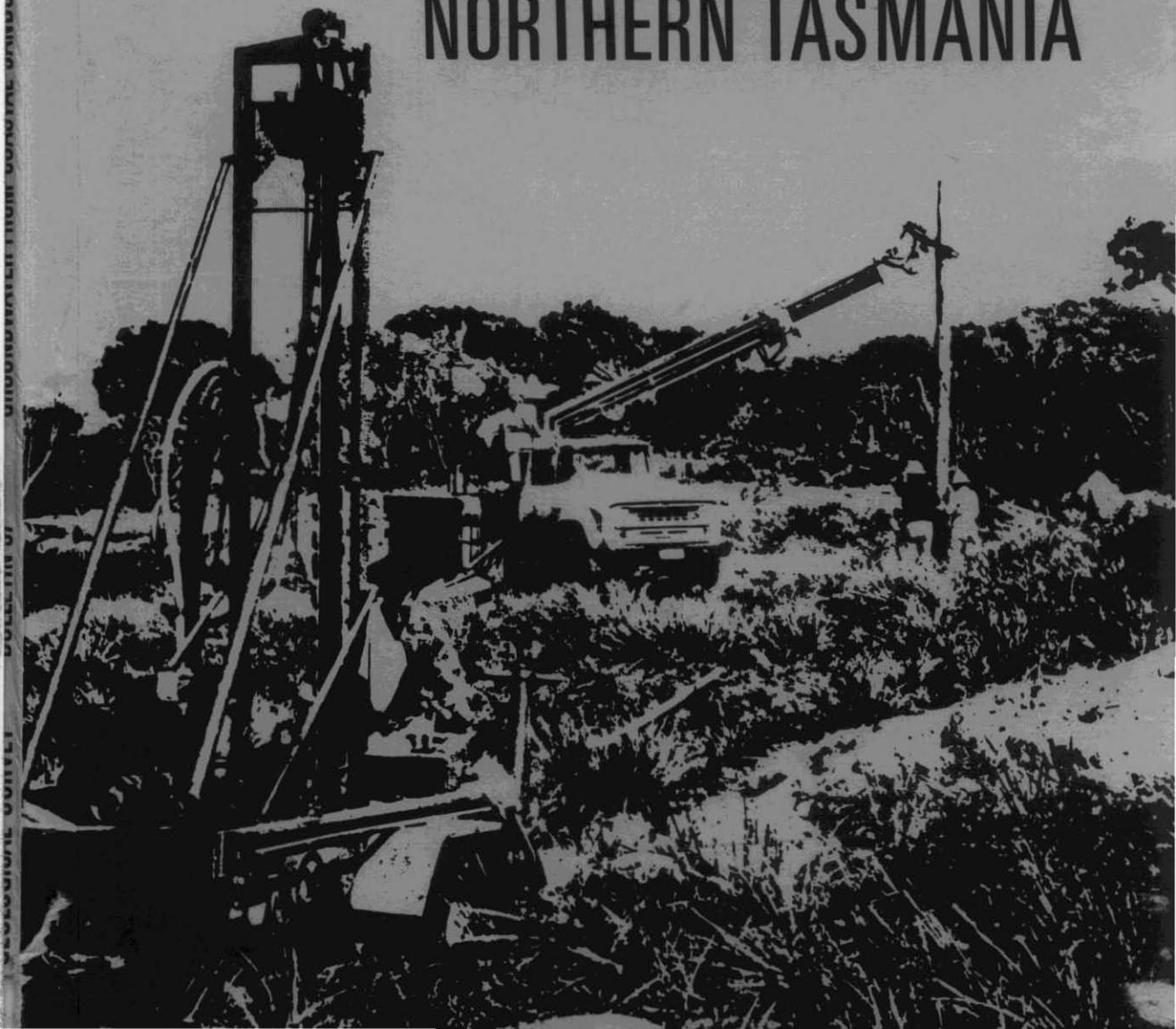




**GEOLOGICAL SURVEY
BULLETIN 57**

**GROUNDWATER
FROM COASTAL SANDS
AT GREENS BEACH,
NORTHERN TASMANIA**



DEPARTMENT OF MINES TASMANIA
BULLETIN 57
GEOLOGICAL SURVEY

GSB57



1979

TASMANIA DEPARTMENT OF MINES

GEOLOGICAL SURVEY
BULLETIN 57

GROUNDWATER
FROM COASTAL SANDS
AT GREENS BEACH,
NORTHERN TASMANIA

by W.C. CROMER, B.Sc. (Hons),



TASMANIA DEPARTMENT OF MINES
GEOLOGICAL SURVEY
BULLETIN 57

GROUNDWATER
FROM COASTAL SANDS
AT GREENS BEACH,
NORTHERN TASMANIA

by W.C. CROMER, B.Sc. (Hons.)

CROMER, W.C. 1979. Groundwater from coastal sands at Greens Beach,
northern Tasmania. *Bull.geol.Surv.Tasm.* 57.

ISBN 0 7246 0485 5 : ISSN 0082-2043

PREFACE

Landowners and Municipal and State authorities are becoming increasingly aware of the availability and importance of groundwater in Tasmanian coastal sands. This publication, one of a series dealing with groundwater assessments, is the first to report solely on a restricted coastal area.

The study has shown that the groundwater contained in the small coastal sand aquifer at Greens Beach forms a major component of the total water available in the district. At present the town has no reticulated surface water system, and properly managed, the aquifer has the potential to usefully supplement existing domestic and garden supplies.

J.G. SYMONS, Director of Mines

CONTENTS

ABSTRACT	9
INTRODUCTION	11
<i>Location, access and present water use</i>	11
<i>History of groundwater investigations</i>	11
 PART 1: REGIONAL INVESTIGATIONS	 13
Introduction	14
Geology	14
<i>Jurassic dolerite</i>	14
<i>Tertiary basalt</i>	14
<i>Tertiary(?) sediments</i>	15
<i>Quaternary sediments</i>	15
Refraction seismic survey	18
Hydrogeology	20
<i>Introduction</i>	20
<i>Kelso-Friend Point area</i>	20
<i>Sea Hill - Wentworth area</i>	21
<i>Badger Beach area</i>	21
<i>Greens Beach area</i>	24
Quality of the groundwater	25
<i>Introduction</i>	25
<i>Regional salinities</i>	25
<i>Nature of the groundwater</i>	25
<i>Origin of dissolved species</i>	29
<i>Acceptability of the groundwater for domestic use</i>	29
<i>Acceptability of the groundwater for agricultural and garden use</i>	34
Recommendations	34
 PART 2: SITE INVESTIGATIONS	 35
Introduction	37
Resistivity survey	37
Drilling	37
<i>Drilling in unconsolidated sediments</i>	37
<i>Drilling in Tertiary basalt</i>	37
Pump testing the unconfined aquifer	38
<i>Installing and pump testing the initial 5-bore array</i>	38
<i>Results and predictions</i>	38
<i>Installing and pump testing the 12-bore array</i>	38
Analysis of the pump test results	41
<i>Symbols, notation, definitions</i>	41
<i>Drawdown against time</i>	42
<i>Drawdown against radial distance from array centre (Q constant, t variable)</i>	45
<i>Drawdown against radial distance from array centre (t constant, Q variable)</i>	47
<i>Main conclusions of the graphical analysis</i>	47
Comparative determination of transmissivity and specific yield	47
<i>Thiem equilibrium equation</i>	47
<i>Modified Theis non-equilibrium equations</i>	50
<i>Boulton's non-equilibrium equations for unconfined aquifers showing delayed yield</i>	51

<i>Stallman's non-equilibrium equations for partially penetrating bores in unconfined aquifers</i>	51
<i>Calculating specific yield from first principles</i>	51
<i>Discussion of transmissivity and specific yield values</i>	51
<i>The problem of array geometry</i>	52
Water balance in the aquifer	55
<i>Precipitation</i>	55
<i>Evapo-transpiration</i>	56
<i>Surface run-off</i>	56
<i>Discharge from the aquifer</i>	59
<i>Discussion</i>	60
<i>Management of the aquifer</i>	61
Quality of the groundwater	63
Introduction	63
CHEMICAL QUALITY	63
<i>Presentation and accuracy of the analytical results</i>	63
<i>Total dissolved solids</i>	65
<i>pH</i>	65
<i>Iron</i>	65
<i>Hardness</i>	67
<i>Dissolved hydrogen sulphide</i>	68
<i>Domestic water use - experience during the 13-day pump test</i>	68
EFFECT ON GARDENS AND THE GOLF COURSE	68
<i>Total dissolved solids</i>	68
<i>Sodium</i>	69
<i>Bicarbonate</i>	69
<i>Chloride</i>	69
<i>Iron</i>	69
Biological quality	69
<i>Summary of water quality</i>	69
GENERAL CONCLUSIONS AND RECOMMENDATIONS	70
ACKNOWLEDGEMENTS	71
REFERENCES	71
APPENDICES	
1. Geological logs of augered holes and drilled holes	74
2. Wells in the Kelso area	80
3. Wells in the Greens Beach area	84
4. Chemical analyses of water in Quaternary sediments at Greens Beach	86
5. Chemical analyses of water in Tertiary(?) sediments at Greens Beach	88
6. Chemical analyses of water in Tertiary sediments at Kelso	90
7. Water analyses of groundwater from Tertiary basalt near Greens Beach	94
8. Geological logs of augered and drilled holes, Greens Beach pump test site	95
9. Chemical analyses of groundwater samples collected during the 13-day pump test at the Greens Beach test site	98
10. Technical and installation details of the 12-spear array at Greens Beach	105

LIST OF PLATES

1. Bailing from 100mm PVC casing to 7m	107
2. Complete spear	107
3. View of test site, showing parts of radial trenches and central manifold position	107
4. Spear installed in trench prior to back-filling	107
5. Valve assembly prior to fitting to screen	107
6. View of trench showing T-junction, horizontal 25mm pipe and spear positions	109
7. T-junction showing 40mm radial pipe connected to two spears by 25mm pipe	109
8. Manifold showing radial 40mm pipes, valves and outlets	109
9. Manifold - pump assembly	109

LIST OF FIGURES

1. The Greens Beach area	10
2. Geological map, Greens Beach - Kelso area	<i>In pocket</i>
3. Location of seismic spreads, bores and wells, Greens Beach - Kelso area	<i>In pocket</i>
4. Section along survey line A, Greens Beach	16
5. Section along coast at Greens Beach	17
6. Chemical analyses of water from (a) Quaternary and (b) Tertiary(?) sediments near Greens Beach, represented as Stiff diagrams	26
7. Chemical analyses from Quaternary sediments near Kelso, represented as Stiff diagrams	27
8. Triangular diagrams of water analyses from the Greens Beach - Kelso area	28
9. Suitability of groundwater for agricultural use. Per cent sodium criterion	31
10. Suitability of groundwater for agricultural use. S.A.R. criterion	32
11. Site plan of the Greens Beach test site	<i>In pocket</i>
12. Apparent resistivity curves for the Greens Beach unconfined aquifer	33
13. Grain size distribution curves for Greens Beach sand samples, and artificial gravel packs used in production bores	36
14. Geometry of 12-spear array	39
15. Symbols and terms used in unconfined pump test analysis	40
16. Log - log plot of drawdown against radial distance for each of 13 observation holes for the 12-bore array at Greens Beach	43
17. Log - linear plot of drawdown against radial distance from centre of Greens Beach array for observation bores 13, 7, 6, 5, 4 and 3 for various times. Q is constant	44
18. Log - linear plot of drawdown against radial distance from centre of Greens Beach array	46
19. Variation of transmissivity and specific yield during the 13-day pump test at Greens Beach	48
20. Log - linear plot of drawdown against time for ob- servation bore 5, showing calculation of T and S_y using the modified Theis non-equilibrium equations	49

21. The Greens Beach aquifer drainage basin	53
22. Block diagram of Greens Beach aquifer drainage basin	54
23. Flow patterns near a beach in an unconfined aquifer	57
24. Variation in depth to water table, and rainfall at Greens Beach during 1978-1979	58
25. Variation diagrams showing changes in concentration of various components of the groundwater at the Greens Beach test site during the 13-day pump test	64

ABSTRACT

The Quaternary unconfined coastal aquifer at Greens Beach in northern Tasmania is an arcuate deposit of aeolian and marine sand about 9 m thick. Within a catchment area of about 1.5 km² the aquifer crops out over 1 km² and contains a groundwater reserve of about two million cubic metres.

A circular array of twelve gravel-packed small-diameter screened bores installed to a depth of 6 - 7 m and radially connected to a central pump yielded 350 m³/day under test for thirteen days. Drawdowns accurate to the nearest millimetre were measured in each of thirteen observation bores. Analysis of the pump test results by various standard techniques - including equilibrium and non-equilibrium methods - produced overlapping values for transmissivity and specific yield. The precision of the results (T in the range 55 - 100 m²/day; S in the range 0.16 - 0.33) is more a function of the duration of the pump test rather than any particular method. The value of S considered most reliable (0.33) was obtained from independent calculations; Boulton's method accounting for delayed yield produced the next most reliable estimate ($S = 0.29$). The aquifer - superficially lithologically homogeneous - has a horizontal hydraulic conductivity about 8 - 11 times greater than the vertical hydraulic conductivity. The array can be pumped continuously at 350 m³/day for at least one and probably two months, when maximum drawdown at its centre will be about 2 m, and the radius of influence will not exceed 150 m.

Water budget estimates indicate that despite these yields from individual bore arrays, the aquifer is capable of supplying on average at least 180 m³/day, and no more than 800 m³/day. No further refinement of these figures is yet possible, but it is clear that if the aquifer is to provide a reliable, permanent town supply for Greens Beach it must be continuously monitored, and carefully managed on a sustained yield basis, so that reserves are essentially not depleted and this safe yield is not exceeded. Most efficient use of all available water implies a management plan which allows for continuous low-yield pumping from two or three arrays to a storage dam, and a capacity to increase yield at short notice to intercept surface runoff. Even so, it is clear that the aquifer is too small to produce the maximum anticipated peak daily demand of 2500 m³. Other aquifers will be needed to supplement the supply if and when urban development occurs.

Chemically and biologically the groundwater is a medium salinity, hard water suitable for most uses. Salinity will remain within the range 450 - 650 mg/l T.D.S. Most (90%) of the hardness (270 mg/l CaCO₃) is temporary and calcium and magnesium carbonate precipitation will be a problem in hot water cylinders unless the supply is treated. The water also contains dissolved H₂S and probably a high total iron content. Both are readily removed by aeration and the reticulated supply will be free of H₂S and contain less than 0.1 mg/l Fe.

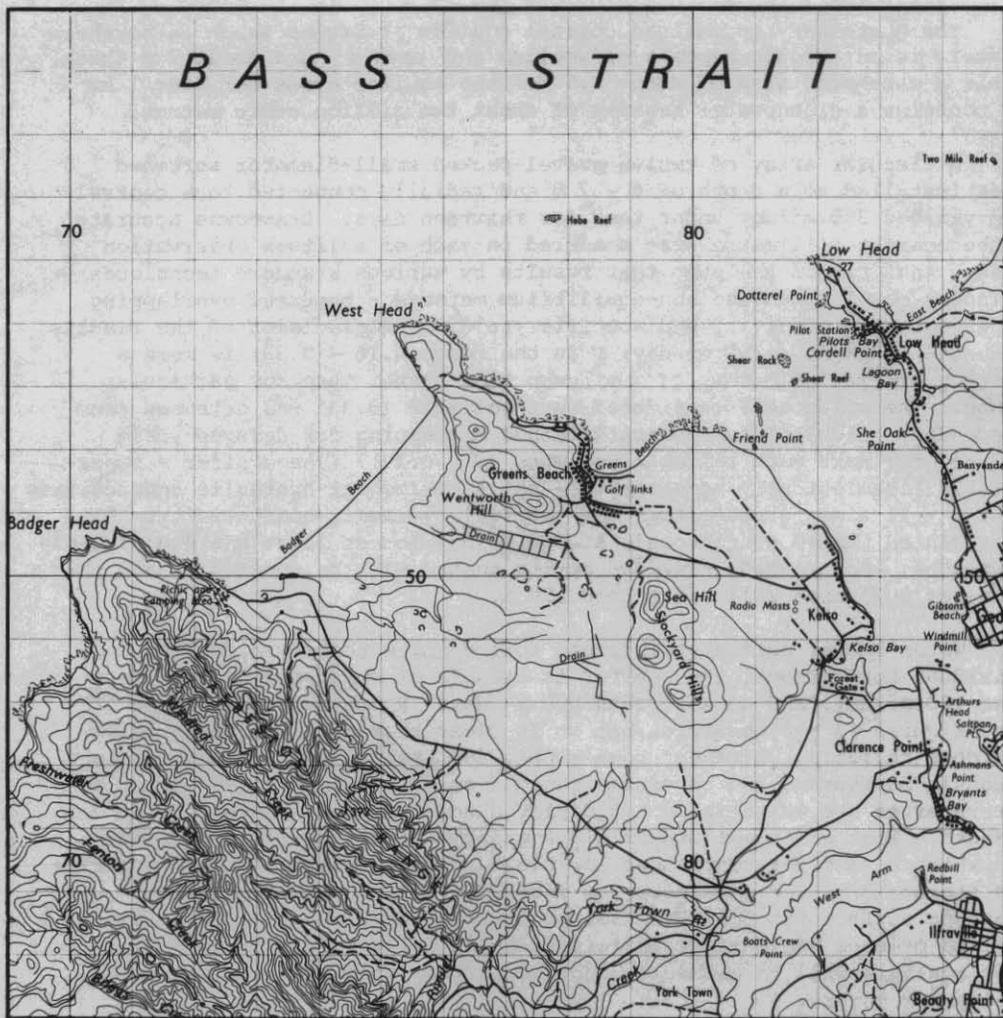
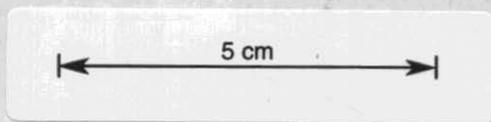


Figure 1. The Greens Beach area (grid lines at one kilometre intervals).



INTRODUCTION

LOCATION, ACCESS AND PRESENT WATER USE

Greens Beach is a small coastal settlement near the western mouth of the River Tamar in northern Tasmania. The only access is by way of the West Tamar Highway to Beaconsfield, and thence by 20 km of sealed secondary road through Kelso.

The township has long been regarded as a holiday resort, and its population fluctuates markedly throughout the year. Even now, its permanent residents are few; the number is slowly increasing but expansion and development await a reticulated water system. The West Tamar Regional Supply ends at Beaconsfield, and most residents at Greens Beach must rely on water from tanks collecting roof runoff. At least six homes use groundwater from shallow wells. A permanent spring draining Tertiary sediments in the township feeds toilet facilities at the council caravan park (and also serves the adjacent golf course), but until recently the annual influx of holiday-makers imposed unacceptable demands on the available water reserves. A shallow council well dug in the caravan park helped alleviate the shortage, but drinking water was often trucked to the park during summer.

Since there are no permanent surface supplies in the area, and extending the West Tamar supply might impose high rate charges on residents, there seems little chance of a reticulated water system to the town unless suitable groundwater is obtained.

HISTORY OF GROUNDWATER INVESTIGATIONS

Investigations started in the summer of 1974 when the Beaconsfield Council requested an examination of groundwater possibilities at the Greens Beach caravan park. The park suffered from insufficient water during the holiday season, and supplies were only available for toilets and wash-basins. By March 1974, the Council had installed a concrete-lined well three metres deep in the sand underlying the park, and this partly alleviated the seasonal water shortage. The well remains capable of yielding 10 - 12 l/min, and chemically the water is suitable for human consumption. Unfortunately, it was sited too close to the toilet block, and a biological water analysis indicated that the septic tank effluent was causing undesirable contamination. That the well was unable to supply drinking water for the park was not known when the Department of Mines prepared an initial report (Cromer, 1974) on the area. It concluded that the sand and clay deposits in the area were 25 m thick, and that *'Large quantities of water appear to be present in the beach sand underlying the caravan park. The water is of good quality and is suitable for toilet and shower usage. It is suitable for drinking purposes provided that a test for bacterial content is satisfactory'*. It recommended that water could be obtained by digging additional wells in the park as the need arose, or by using sufficient spear bores. These conclusions remain valid.

Subsequently, in late 1975 the Beaconsfield Council and the Rivers and Water Supply Commission jointly requested that the general Greens Beach area be investigated with the aim of supplying the township of Greens Beach with reticulated groundwater. It was thought that future residential needs may be about 250 000 m³ a year, with a daily maximum in summer of 2500 m³.

Regional mapping, surveying, seismic work, drilling and spear bore pump tests were made in the Kelso, Greens Beach and Badger Beach areas from

late 1975 to May 1976. The results were presented in a report by Cromer and Sloane (1976) which forms the basis of the first part of this Bulletin.

The Council and the Commission then asked that further detailed testing be made at the site recommended from the regional survey, and if results were favourable to proceed with the installation and testing of a permanent battery of spear bores. Such a system would form the first production stage of the town water supply. The second part in this Bulletin deals with these site investigations, begun in April 1977, and describes the results of a 13 day pump test made on a 12-spear circular array in October and November 1977.

Part 1:

Regional Investigations

INTRODUCTION

The request for a regional groundwater survey covering the Greens Beach, Kelso and Badger Beach areas resulted from the initial site investigations at the Greens Beach caravan park (Cromer, 1974).

Aspects of the regional geology were revised, and the original geophysical and drilling work extended to include twenty-two seismic spreads and thirty mechanically augered holes. Some of these holes were pump-tested by shallow bores, and groundwater samples were collected for analysis. A survey was made of existing residential groundwater use at Kelso and Greens Beach. On these bases a favourable groundwater area was selected for further detailed work.

GEOLOGY

The area (fig. 1,2) has been mapped by Gee and Legge (1971) and Sutherland (1971) described the geology and petrology of the Tertiary basalts in the Tamar Valley.

Jurassic dolerite

The western boundary of the Tamar Graben is delineated by a series of partly buried dolerite horsts extending south-east from West Head to Kelso. The western side of Wentworth Hill and West Head appears to be fault-controlled, and may represent the eastern boundary of a small graben south-east of Badger Beach. Generally, the lower slopes of the dolerite hills are buried beneath Tertiary(?) sediments. Behind Greens Beach and at the eastern end of Badger Beach, where the dolerite extends almost to sea level, it is overlain by Quaternary deposits. A previously unrecorded dolerite body occurs near 793513*.

Tertiary basalt

Sutherland (1971) described in detail the petrology of the basalts in the lower Tamar Trough. He established the presence of two major volcanic episodes, represented by a Lower Basalt and an Upper Basalt. The Lower Basalt overlies Eocene sediments and is in turn overlain by inter-basaltic post-Upper Eocene gravel, sand and clay. Quaternary and Upper Tertiary sediments overlie the Upper Basalt. The volcanism disrupted the course of the ancestral Tamar, and Sutherland (1971, p. 5) suggests the river was once diverted north of Beaconsfield between West and Badger Heads.

The Lower Basalt and derived basalt boulder beds are exposed on extensive shore platforms between Friend Point and Kelso. Basalt occurs at shallow depth beneath the flat, low-lying coastal plain north-west of the township, where it was intersected in profile Holes 6 - 12 (fig. 3). Drilling shows that the upper surface of the basalt is irregular, but in general dips westward. According to Sutherland (1971, p. 21) its base rises gently inland, but drilling control to support such a premise is lacking.

The drilling and seismic programmes suggest the presence of a shallow buried erosional channel extending north-west from Kelso along the base of the Tertiary escarpment towards Greens Beach. Such a feature may delineate a former diversion of the Tamar. The basement geology along Greens Beach is shown in Figure 7.

* All localities lie within the 100 kilometre grid square DQ.

Tertiary(?) sediments

Post-basaltic sediments, considered by previous workers to be Tertiary in age, mantle the dolerite horsts south of Greens Beach and form an extensive almost level surface about 20 m above sea level extending south-east from Wentworth Hill. Low-lying areas behind Badger Beach and north-west of Kelso have previously also been mapped as Tertiary, but such areas were almost certainly inundated during Quaternary higher sea levels. As a result, parts of the original Tertiary sequence have been reworked and these are included among the Quaternary deposits (fig. 2) in this Bulletin.

These rocks consist mainly of unconsolidated fine to medium-grained slightly clayey sand. Clay and gravel are ubiquitous but generally minor constituents. Behind Badger Beach the sequence contains clayey gravel and grit derived from the Asbestos Range and Wentworth Hill. The only material considered to be Tertiary in age is a small isolated lag(?) deposit of laterite boulders at 774501.

Quaternary sediments

While it is sometimes difficult to unequivocally distinguish between Tertiary and Quaternary sediments in the Greens Beach area, the youngest rocks exhibit a sequential series of deposits consistent with a marine transgressional origin. Accordingly they are considered to be of Late Last Glacial and Holocene age. The underlying sediments may be Pleistocene or Late Tertiary.

At Greens Beach, such a sequence overlies a variable (8 - 15 m) thickness of Tertiary(?) clay and sandy clay. The Holocene deposits are interpreted as:

- (4) aeolian
- (3) beach or near-shore
- (2) marine
- (1) lagoonal or backwater

A similar sequence probably occurs at Badger Beach, where an extensive system of longitudinal blow-out dunes overlies a well-developed Late Last Glacial palaeosol (N. Chick, pers. comm.) developed on marine sand. Elsewhere in Tasmania, coastal deposits exhibit the same transgressional sequence. Thus, at Chinamans Bay on Maria Island, 4 m of aeolian, marine and lagoonal sand rest on shelly grey clay (Cromer, 1977). At Seven Mile Beach a similar sequence 10 - 12 m thick contains a shell-rich horizon at its base, and overlies Tertiary(?) clay (Cromer and Sloane, 1976). At Barnbougle near Bridport 11 m of sediments overlie alluvium and Interglacial marine deposits (Bowden, 1978). At Barnbougle the upper 1.5 m (fine sand) is interpreted as a regressional lagoonal or backwater deposit overlying the transgressional sequence.

Basalt boulder beds form extensive shore platforms between Friend Point and Kelso and extend inland beneath the narrow strip of aeolian Holocene sand at Kelso. The beds apparently exist beneath the Kelso-Friend Point area designated in Figure 3, and reach their maximum thickness of about 3 m near the radio masts where they rest on Tertiary basalt. They were not encountered in hole 13 near the western boundary of the area. On Friend Point they are overlain by a thin clay layer, which in turn is overlain by Holocene aeolian and marine sand. At Greens Beach, the thin pebbly clay beneath the transgressive sequence is correlated with the boulder beds.

COMPOSITE SECTION ALONG SURVEY LINE A, GREENS BEACH

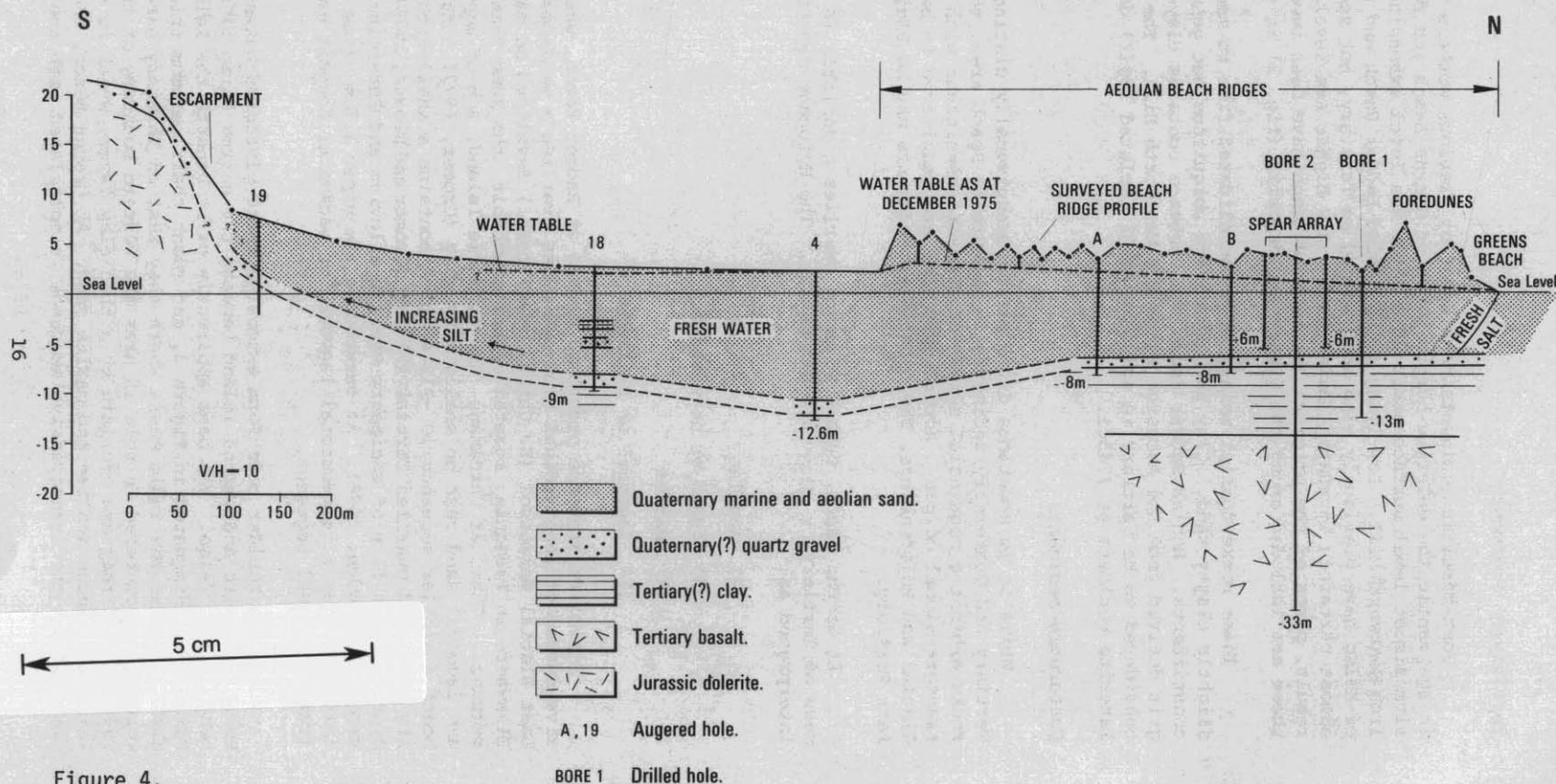


Figure 4.

SECTION ALONG COAST AT GREENS BEACH

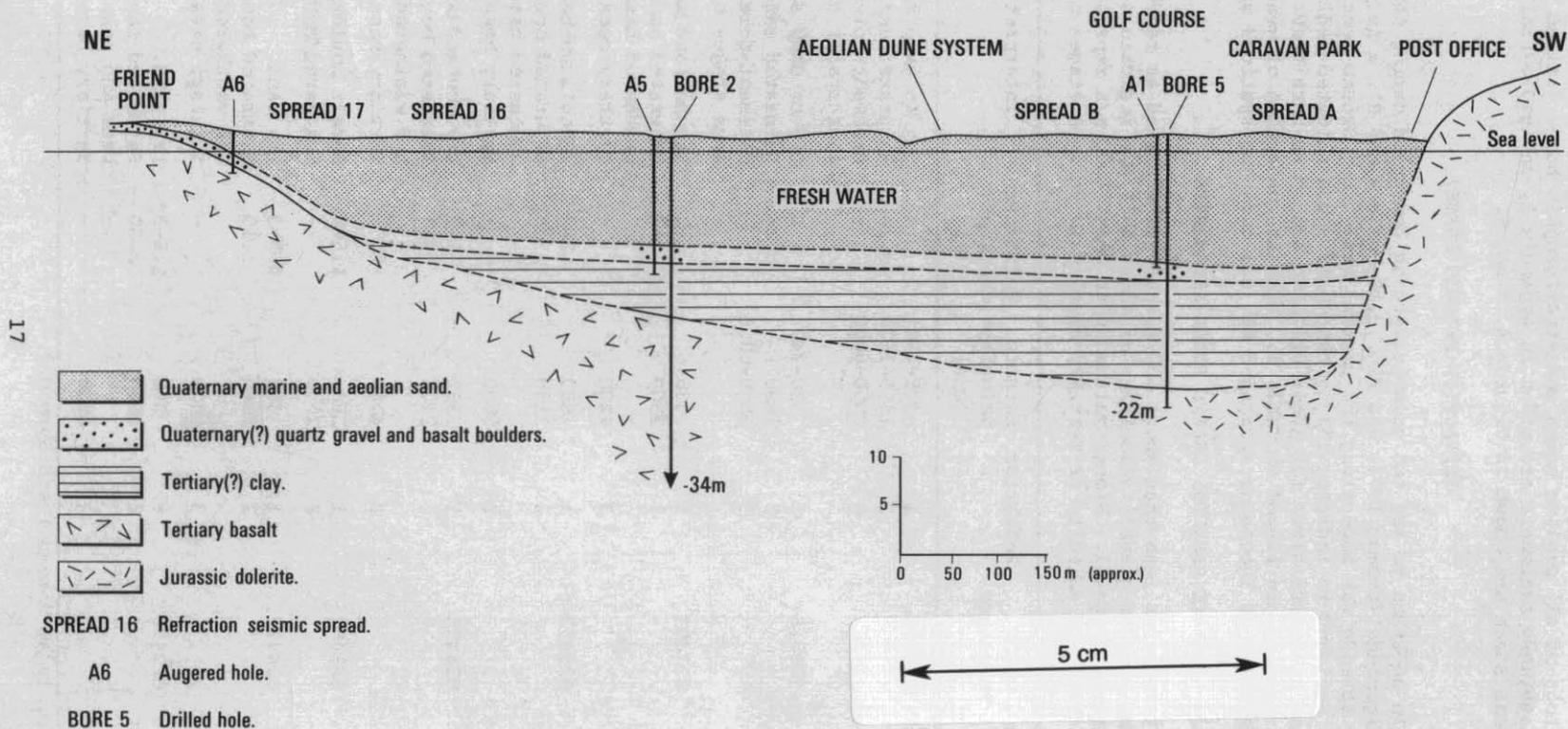


Figure 5.

Logs of all proline holes and stratigraphic bores drilled in Tertiary and Quaternary sediments are given in Appendix 1, and geological sections of Greens Beach are shown in Figures 4, 5 and 6.

REFRACTION SEISMIC SURVEY

In addition to the two seismic spreads conducted during the initial investigations (Cromer, 1974; and fig. 3, Spreads A and B), a survey of twenty spreads was made along the coastal strip from Greens Beach to Kelso. It was designed to indicate the thickness of unconsolidated sediments in the area and to locate sites for auger drilling and spear-bore tests. Details of all spreads are listed in Table 1. With the exception of weathering Spreads 9 and 12 (geophone spacing 3 m), all geophone spacings were 7.6 m.

Table 1. SEISMIC RESULTS, GREENS BEACH-KELSO AREA

Velocities less than about 500 m/s are interpreted as representing dry-damp sand or gravel; velocities of about 1500 m/s indicate saturated sand, clay or gravel. Higher values up to about 6000 m/s represent basement rocks (Jurassic dolerite or Tertiary basalt) in various stages of weathering.

Spread number	AMG reference	Refractor	Seismic velocity (m/s)	Refractor thickness (m)	Interpretation
A*	787515	1	375-470	3	Dry to damp sand.
		2	1590-1620	c.24	Saturated sand and clay.
		3	3500-6000	-	Basement-dolerite in various stages of weathering.
B*	790516	1	330-340	4	Dry to damp sand.
		2	1600	c.25	Saturated sand and clay.
		3	3500-6000	-	Basement-dolerite in various stages of weathering.
1	827493	1	330	1-2	Dry sand and basalt boulders.
		2	2300	2-3	Saturated boulder beds and weathered basalt.
		3	4200	-	Tertiary basalt.
2	828493	1	380	1-2	Topsoil and basalt boulders.
		2	3160	-	Saturated boulder beds and weathered basalt.
		3	5600	-	Tertiary basalt.
3	826495	1	380	1-2	Dry sand and boulder beds.
		2	2135	3-9	Saturated boulder beds and weathered basalt.
		3	4080	-	Tertiary basalt.
4	828492	1	380	1.5-4	Basalt boulder beds.
		2	2570	-	Weathered Tertiary basalt.
5	824497	1	380	0.5-3	Dry sand.
		2	2640	c.10	Saturated boulder beds and weathered basalt.
		3	4270	-	Tertiary basalt.
6	823496	1	380	1.5-3	Dry sand.
		2	1660	c.30	Saturated sand, boulder beds and possibly clay.
		3	4270	-	Tertiary basalt.

*Cromer, 1974; Spread 1 and Spread 2.

Table 1. (continued)

Spread number	AMG reference	Refractor	Seismic velocity (m/s)	Refractor thickness (m)	Interpretation
7	821494	1	390	2-2.5	Dry sand.
		2	1500	8-10	Saturated basalt boulder beds, and clay.
		3	2700	-	Weathered Tertiary basalt.
8,10	818501	1	380	3-4	Dry sand.
		2	3290	-	Weathered Tertiary basalt.
9,10	813507	1	300	3-4	Dry sand.
		2	3000	-	Weathered Tertiary basalt.
11	809511	1	495	3-4	Dry-damp sand.
		2	2900	-	Weathered Tertiary basalt.
12,13	809513	1	380	3-4	Dry sand.
		2	3300	-	Tertiary basalt.
14	814513	1	380	3-4	Dry sand.
		2	3000	-	Weathered Tertiary basalt.
15	793517	1	300	3-4	Dry sand.
		2	1500	15	Saturated sand.
		3	4200	-	Tertiary basalt.
16	795520	1	380	2-3.5	Dry sand.
		2	1800	12	Saturated sand.
		3	5000	-	Tertiary basalt.
17	798522	1	380	3-4	Dry sand.
		2	1500	8-10	Saturated sand.
		3	3500	-	Tertiary basalt.
18	795518	1	300	3-4	Dry sand.
		2	1500	10-15	Saturated sand.
		3	4050	-	Tertiary basalt.
19	796515	1	335	4-5	Dry sand.
		2	1550	c.30	Saturated sand.
		3	4200	-	Tertiary basalt or Jurassic dolerite.
20	797514	1	300	2-3	Dry sand.
		2	1400	-	Saturated sand.
		3	4500	-	Tertiary basalt or Jurassic dolerite.

Introduction

All the major rock types - dolerite, basalt and sediments - contain groundwater, but only the Tertiary and Quaternary deposits will yield economic quantities. Jurassic dolerite remains largely unexplored as a groundwater source - despite its widespread occurrence - mainly because of the discouragingly high failure rate of the few water bores drilled in it. The rock has a very low primary porosity and usually a small storage capacity; yields from successful bores are generally less than 10 l/min and are due to well-developed secondary porosity (continuous interconnecting fractures) in favourable topographic areas.

Tertiary basalts - especially unweathered varieties with well-developed vesicularity and primary fracturing - are reliable aquifers almost everywhere in Tasmania. Usually the water quality is medium to good, and sometimes excellent. Average yields are in the range 75 - 150 l/min, but some basalt bores are among the most successful in the State, with yields of more than 1000 l/min. In favourable topographic areas, some are artesian. During the regional survey, the basalts in the Greens Beach area remained unexplored as aquifers (mainly because drilling rigs were unavailable), but bores drilled later, in the basalt at Kelso and Greens Beach, produced moderate yields but unsuitable groundwater.

The unconsolidated sediments offer the most promising groundwater prospects for many reasons. Their porosity and storage capabilities are large (so that even a small volume of material contains economic amounts of water); water tables are shallow, and the resource can be easily extracted by simple and cheap methods without using drilling rigs. More importantly, the groundwater quality is usually good to excellent. Accordingly, the drilling and seismic surveys were confined to these rocks, and encouraging thicknesses of water-bearing deposits were proved. Seismically favourable sites were investigated further by spear-bore pump tests, and less favourable areas excluded from consideration.

Regionally the area has been divided into five groundwater areas (fig. 3).

Kelso-Friend Point area

This flat low-lying area consists of a veneer of Quaternary and probably reworked Tertiary (?) sediments overlying Tertiary basalt. The sediments include aeolian and marine sand, clay, shelly grit, gravelly clay and basalt boulder beds. The eroded upper surface of the basalt generally dips gently south-west but steepens near the base of the escarpment at the western boundary of the area.

The area includes the township of Kelso, where about half the residents supplement domestic tank water with groundwater from shallow wells (fig. 3, appendix 2). The aquifer is a narrow deposit of aeolian and shelly marine sand only a few metres thick. It wedges out rapidly west of the residential strip where some deeper wells obtain water from underlying basalt boulder beds.

The wells are generally sited from 3 - 6 m above high water mark, and in summer water is struck at depths less than 2.5 m. Residents report that groundwater levels approach the ground surface during winter.

Without exception the water is used for gardening and domestic (excluding drinking) purposes. Chemically (appendices 2 and 6) it is too hard for drinking, and in any case nearby septic tanks are probably contaminating the aquifer.

Because the unconsolidated sediments are thin, and variable in lithology, groundwater reserves are small and are best used - as at present - for gardens. Future wells or bores drilled in the sand or boulder beds will be successful but low yielding, and there is little chance of depleting the supply.

The underlying Tertiary basalt which crops out in places in Kelso has been drilled for both investigation and private water bores (fig. 3). The basalt is a reliable aquifer (all holes struck useful amounts of water) but the water is marginal in quality and not suitable for drinking without treatment. Yield varies from 4 to more than 300 l/min, and is related to the depth of aquifer penetrated.

Sea Hill - Wentworth Hill area

This area includes the more elevated dolerite horsts which are covered by extensive but thin deposits of unconsolidated sediments. On the Wentworth Hill headland and on the south-western side of Sea Hill, these sediments consist mainly of aeolian sand. In small cuttings on the saddle between the two hills, the sand displays a well developed soil profile consisting of about 0.3 m of dark grey A₁ horizon, a white leached A₂ horizon about 0.6 m thick, and a well developed and partly cemented dark brown humic B horizon. Such a profile may indicate a pre-Late Last Glacial age.

Most of these sand deposits (which mainly occupy the higher areas) are too thin and restricted to contain permanent groundwater (holes 28, 29 and 30 in fig. 3 were dry) although temporary water tables will persist after heavy continuous rain. In a few places the sand is thick enough to provide domestic water, and at least six wells at Greens Beach tap the supply.

The remainder of the area comprises an extensive flat area about 20 m A.S.L. at the rear of a prominent escarpment, for the most part poorly drained and consisting of a variable thickness (<3 to >15 m) of sandy and silty clay, clay gravel, grit and boulder beds. These sediments overlie fresh Jurassic dolerite and appear to thicken westward along the Greens Beach - Kelso road towards Wentworth Hill. Their age is unknown.

Because the sediments are variable in lithology, it is difficult to select suitable bore sites. Three sites (holes 3, 19 and 20, see fig. 3) were tested but the results (table 2) were unfavourable. Spear bores were jetted and bailed to depths of 6 - 7 m and in short pump tests none sustained a yield greater than 8 l/min. Deeper penetration and longer screens will increase these yields in favourable areas, but the sediments are clearly of low permeability and restricted storage and are not a favourable aquifer for a town supply.

Badger Beach area

This large gently sloping area extends from West Head to Badger Head and south to the Stockyard Hills, and includes not only the extensive aeolian sand dunes along Badger Beach but also the relatively unexplored sediments behind it. More work is needed to satisfactorily evaluate its potential, but early tests suggest that the groundwater is in places unacceptable for a town supply.

Table 2. RESULTS OF SPEAR BORE PUMP TESTS, GREENS BEACH AREA.

Hole No.	AMG reference	Approximate standing water level (m)	Discharge rate (l/min)	Pumping duration (min)	Total draw-down (m)	Approximate safe yield* (l/min)	WATER QUALITY			Aquifer	Remarks	
							T.D.S.†	Colour	Taste			Smell
1	789516	1.5	30	400	c.3	40	730-800	None	Slight H ₂ S	Slight H ₂ S	Quaternary marine sand	Water initially grey and muddy; clears rapidly. Salinity increased slightly during pumping.
22 3	785510	1	8	<5	6	<3		Muddy yellow	None	None	Tertiary(?) clayey sand and clay	Failure.
5	794518	1.5	30	90	1	40-50	480	None	None	Slight H ₂ S	Quaternary marine sand	Water initially cloudy; clear after 5 min. Sustained a discharge of 60 l/min for short period: drawdown 1.6 m
15	770504	1	3	15	c.3	<5	520	Initially muddy	None	None	Tertiary(?) clayey sand	Water gradually clears on pumping.

Table 2. (continued)

Hole No.	AMG reference	Approximate standing water level (m)	Discharge rate (l/min)	Pumping duration (min)	Total draw-down (m)	Approximate safe yield* (l/min)	WATER QUALITY			Aquifer	Remarks	
							T.D.S.†	Colour	Taste			Smell
16	778504	0.6	30	95	c.3	30	350	Initially muddy	None	None	Tertiary(?) clayey sand	Water clears rapidly on pumping. Unacceptably high iron content.
19	801508	0.5	10	60	c.6	10		Initially muddy	H ₂ S	H ₂ S	Tertiary(?) clayey sand	Recovers strongly. Strong H ₂ S smell; water clears gradually.
20	792506	1	6	60	5	6		Initially muddy	None	H ₂ S	Tertiary(?) clayey sand	Clears gradually.

Notes:

* Safe yield is considered to mean the pumping rate which a bore can sustain indefinitely.

† T.D.S. = Total dissolved solids; obtained from chemical analyses in appendices 4 and 5.

Most of the area is underlain by Quaternary and Tertiary (?) sediments which have filled a shallow basin-like structure presumably underlain by Jurassic dolerite and Precambrian quartzite. The sediments are mainly fine sand, silty sand, clay and gravelly clay. Grey-green textured clay considered to be weathered Jurassic dolerite was struck at 4.6 m in proline hole 14 (appendix 1), and generally the basin probably deepens towards the south-west. Rounded cobbles of Tertiary(?) laterite occur over a restricted area near 774502 but the material does not crop out. The laterite may be more extensive than the surface evidence indicates, since water from proline Holes 15 and 16 contains high iron and aluminium levels.

Proline holes 15 and 16, drilled into Tertiary sediments, were pump tested by spear bore. Hole 15 sustained a low yield (<5 l/min) for only a few minutes before pumping air, and Hole 16 was pumped at 30 l/min for 96 minutes. These figures reflect the variation in stratigraphy and permeability of the sequence, and also show that unless more work is done successful bores will be more the result of good luck than good management.

Nevertheless, the area has potential as a source of groundwater. The sediments are a large reservoir extending over about 15 km² and are at least 15 m thick in places. The extensive longitudinal sand dunes behind Badger Beach seem especially favourable in this respect, but nothing is known of their groundwater potential.

Greens Beach area

This area includes the aeolian beach ridge system and the underlying marine sand south of Greens Beach. The unconfined aquifer is everywhere underlain by clay or sandy clay which in turn rests on Tertiary basalt or Jurassic dolerite. The aquifer is about 9 - 10 m thick and extends west beneath the caravan park and south to the base of the escarpment (fig. 3). Its effective eastern limit is somewhat arbitrary but has been placed on the western side of Friend Point where the dipping bed of quartzite gravel and basalt boulders approaches the surface (fig. 6). The unconsolidated sequence attains its maximum thickness beneath the Greens Beach caravan park, where 25 m of sand and clay rest on dolerite (fig. 6). The sequence becomes lithologically more variable along the southern border of the area where material has probably been derived from Tertiary (?) sediments and Jurassic dolerite on the escarpment.

Surveyed sections (A, B and D in fig. 3 and figs. 4 and 5) across the area indicate the general shape of the water table and the extent of the aquifer. The water table is a smooth gently sloping surface which beneath the beach ridge system exhibits a seaward gradient of about 1:250, or 0.004 m/m (in December 1975). At the time of the survey, its maximum elevation was 2.5 - 3 m A.S.L. at the rear of the dunes. Subsequent monitoring reveals a probable annual maximum fluctuation of about 0.5 m* suggesting that in dry periods the relative water-table head difference between the dunes and the adjacent flatter area to the south (fig. 4) disappears and the table shows a uniform sloping surface from the escarpment north to the coast.

Two sites (hole 1 and 5) were pump tested with spear bores. Yields (table 2) from both were encouraging. Each sustained only a small drawdown when pumped at 30 l/min, and the safe yield is probably greater than this. Since the quality of the groundwater is good-moderate, this area offers the region's best prospects for obtaining a reliable town groundwater supply.

* A 0.53 m drop in water level in the period October 1977 - June 1978 was monitored near the spear bore test site in the dunes. Over the same period rainfall was 30% below average. Annual fluctuations of the water-table are unlikely to exceed this value on average.

QUALITY OF THE GROUNDWATER

Introduction

Samples of water for chemical analysis (appendices 4, 5, 6) were collected during the period December 1975 - April 1976 from six pumped proline holes, thirteen wells, a spring and a lagoon. None should be considered totally representative of the aquifer from which it was taken, and salinity variations at the same locality (e.g. Greens Beach well, appendix 4), may reflect changes in water quality due to seasonal distribution of rainfall, degree of use of the well or bore, or method of sampling. The chemistry of the groundwater at the Greens Beach test site is discussed more fully in Part 2.

None of the samples from the regional survey was tested for biological purity during this period although contamination is known to occur at the Greens Beach caravan park, and undoubtedly is present at Kelso where effluent is discharged directly to the aquifer. Contamination is not expected in bores removed from residential areas, although it is always wise to test any water intended for human consumption.

Analytical results are presented in the appendices as milligrams per litre (mg/l, approximately equal to parts per million), milligram equivalents per litre (meq/l, i.e. equivalents per million) and percentage milligram equivalents per litre (% meq/l). The first of these units is determined by laboratory methods. The second is derived from mg/l by dividing by the equivalent weight of the species involved. This is useful since in an analysis expressed in meq/l unit concentrations of all ions are chemically equivalent. This means that the chemical behaviour of the water, and of the mixing of water, can be more easily understood. It also serves as a useful check on the accuracy of the analysis, since if all major constituents have been determined, the total equivalents of cations should very nearly equal the total equivalents of anions. Any non-ionised species (SiO₂, H₂S) and in some cases Fe is not normally reported as meq/l.

The expression of the analyses in % meq/l is useful in comparing analyses by graphical means, and allow easy evaluation of the major components in the sample.

Regional salinities

The regional salinity of the groundwater varies from about 500 mg/l to 1800 mg/l (an abandoned well near Kelso has a salinity of 6500 mg/l). The poorest quality water occurs at Kelso. The salinities of the Tertiary(?) and Quaternary waters near Greens Beach are roughly comparable.

Groundwater in unconsolidated sediments is derived from infiltrating rain, and as a result the upper levels of the aquifer may contain better quality water than the lower levels. The samples obtained from pumped spears near Greens Beach may therefore represent an average composition of the groundwater removed from the upper levels of the aquifer. Deeper water may in fact be poorer in quality, but the extent of vertical salinity changes is probably insufficient to render the water unacceptable.

Nature of the groundwater

Groundwater from the whole region falls naturally into two main types based on the predominant dissolved species. That from Tertiary(?) sediments may loosely be termed 'sodium chloride water', while 'calcium bicarbonate-sodium chloride water' is characteristic of the Quaternary rocks.

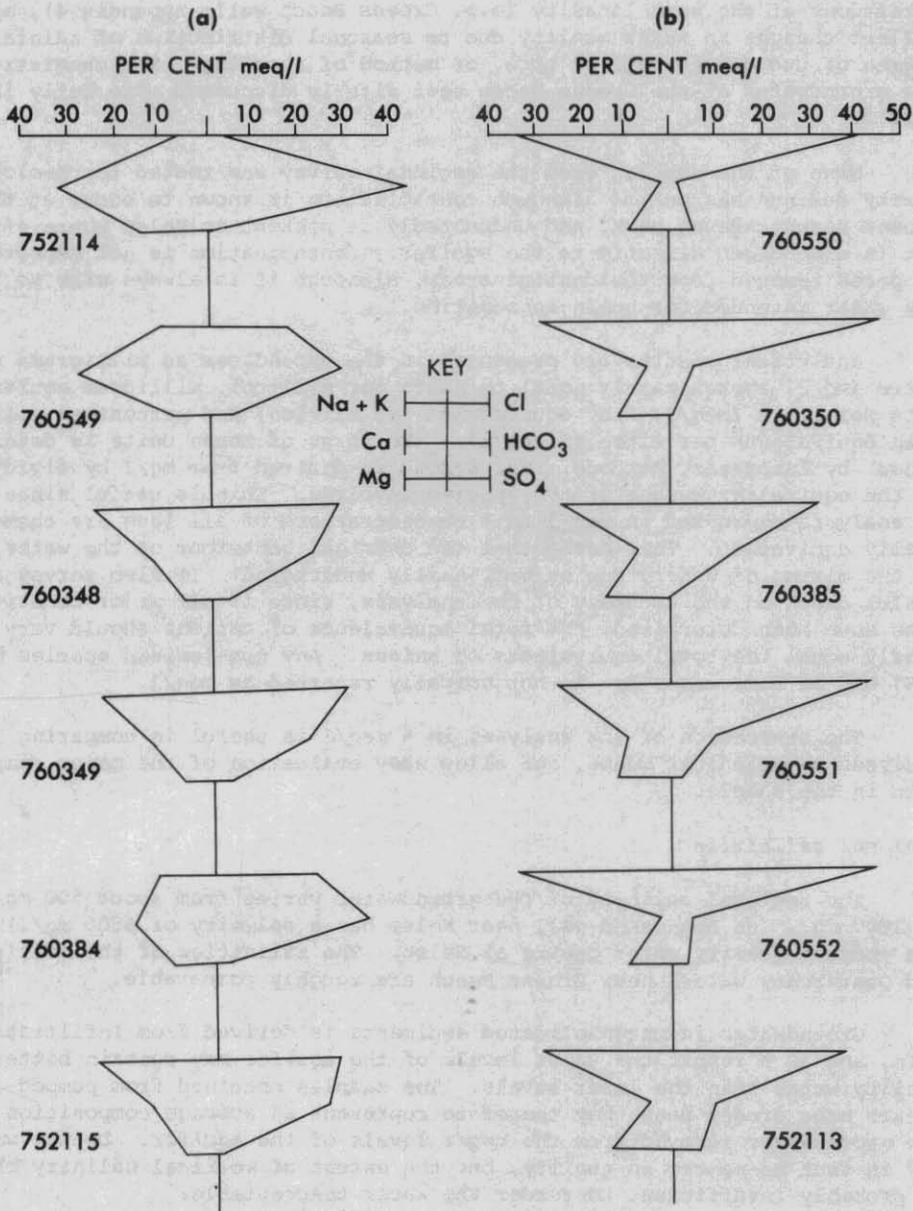
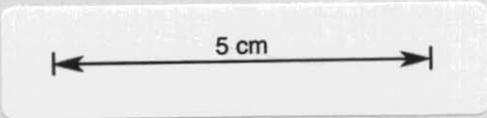


Figure 6. Chemical analyses of water from (a) Quaternary and (b) Tertiary(?) sediments, near Greens Beach, represented as Stiff diagrams.

5 cm

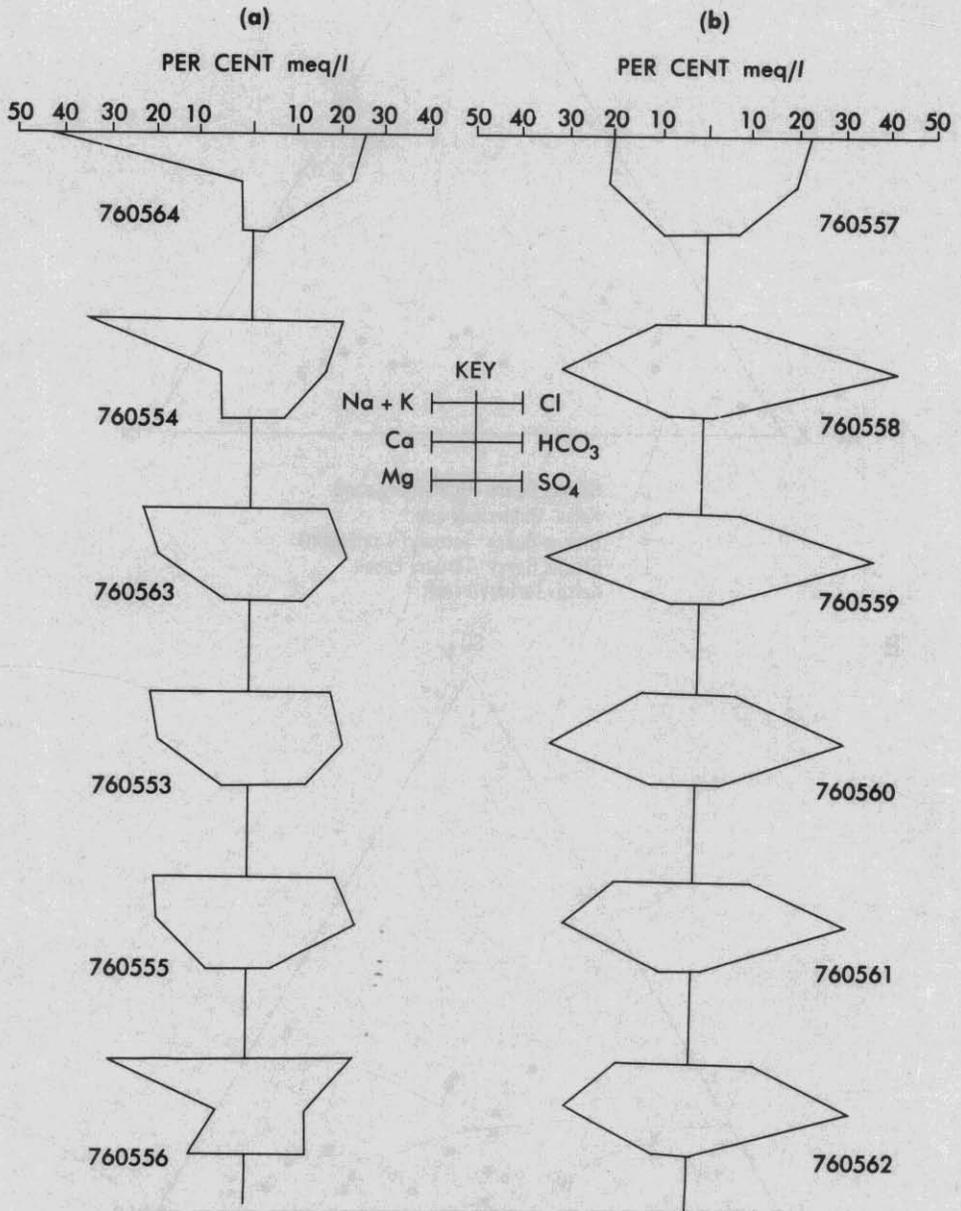
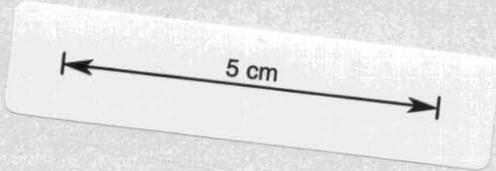
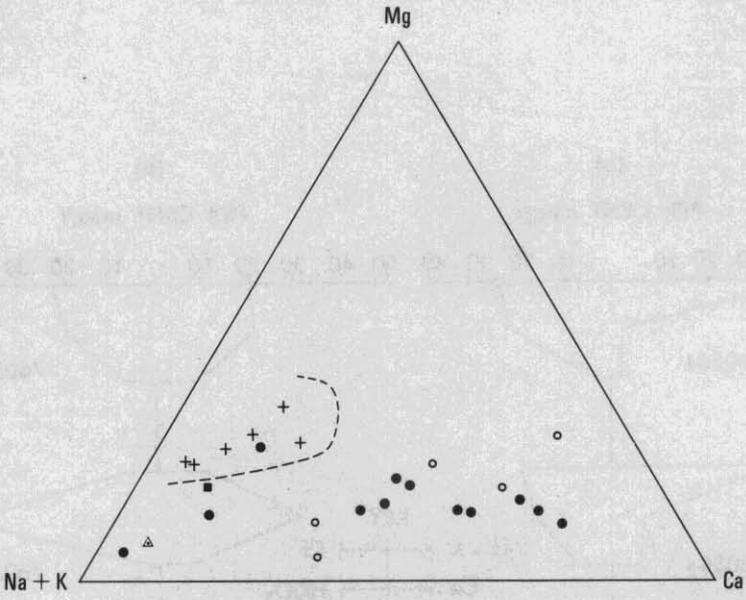


Figure 7. Chemical analyses of water from Quaternary sediments near Kelso, represented as Stiff diagrams.



A



- Greens Beach - Quaternary sand.
- Kelso - Quaternary sand.
- + Greens Beach - Tertiary(?) sediments.
- △ Greens Beach - Tertiary basalt.
- Kelso - Tertiary basalt.

B

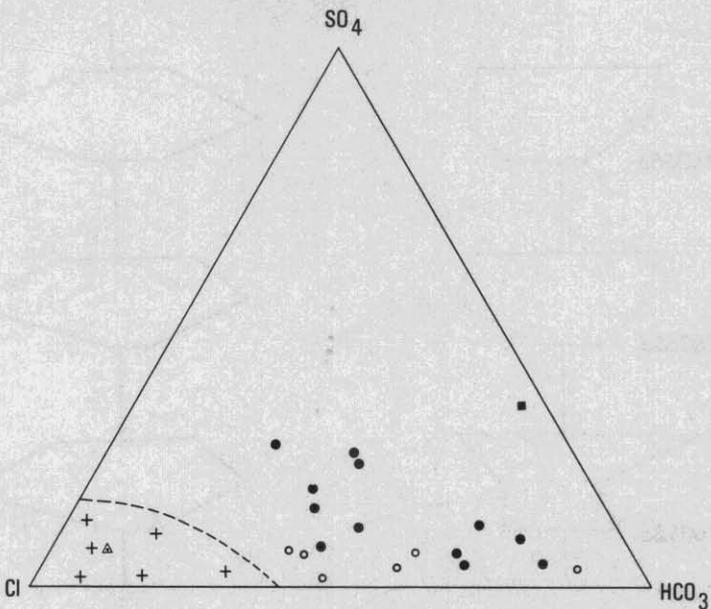


Figure 8. *Triangular diagrams of water analyses from the Greens Beach - Kelso area.*

Most samples also contain significant amounts of magnesium and sulphate.

The water analyses are depicted as a series of comparative variation diagrams (fig. 6, 7, 8). In Figures 6 and 7 the Stiff diagrams are plotted as percentage milligram equivalents per litre (% meq/l). This obscures differences in total dissolved solids and the width of the diagrams is only an approximate indicator of quality, however the shape of each figure is distinctive and readily comparable with others. The difference between the Tertiary (?) and Quaternary waters is obvious.

On triangular diagrams plotted as cation meq/l (fig. 9) and anion meq/l (fig. 10) the analyses again fall into two distinct groups.

Origin of dissolved species

Ca, HCO_3 , and to a lesser extent Mg are derived mainly from dissolution of shelly material in the aquifer. This is especially evident in the water from Kelso where the sediments are rich in shells. Dissolved atmospheric carbon dioxide (as HCO_3) is also incorporated in the groundwater from percolating rainwater.

Na and Cl in coastal groundwater is generally attributed to salt spray contamination as well as from partial dissolution of minerals in the sediments themselves. Salt spray is probably the main source of these constituents in the aeolian and marine sand at Greens Beach, and the aeolian sand at Kelso. Mineral dissolution probably accounts for their presence in groundwater from the Tertiary (?) rocks. The small amount of silica in the water is derived mainly from the breakdown of clay minerals.

High levels of iron and aluminium occur in the low pH groundwater from the Tertiary (?) sediments; these species seem to be partly derived from lateritic material, lag deposits of which occur on the flat plains behind Badger Beach (fig. 2). Iron in groundwater at concentrations greater than 0.3 mg/l causes staining of fixtures and laundry and these waters are therefore unacceptable for domestic use unless treated.

Acceptability of the groundwater for domestic use

Individuals and communities vary in their tolerance of domestic water supplies. That considered acceptable through long use or necessity by one community may be unacceptable and objectionable to another. Thus the general recommended limits of chemical constituents (Hart, 1974) given in Table 4 should be studied with these considerations in mind.

The groundwater in the Quaternary sediments at Greens Beach (fig. 3) is suitable for human consumption despite its hardness and the presence of H_2S . The hardness is mainly temporary and is probably at a level acceptable to most people. The main problem with this water is that it may cause calcium and magnesium carbonate encrustation in hot water cylinders, electric kettles and other domestic equipment unless the hardness-producing constituents are first removed.

Any detectable level of H_2S in water is objectionable, but the gas is easily removed by simple aeration either at the site of pumping, at a reservoir, or at a later stage in the reticulated supply.

The water from the Tertiary (?) sediments is unacceptable on three counts: its corrosively low pH, high iron content, and turbidity. Pumping may reduce turbidity to acceptable levels (e.g. proline hole 16 and table 2).

Table 3. FACTORS AFFECTING THE ACCEPTABILITY OF DOMESTIC WATER SUPPLIES*

Factor	Undesirable effects	Recommended range or upper limit (mg/l)
Alkalinity (as CaCO ₃)	Gastro-intestinal irritation	30-500
Hardness	Encrustations on fittings, utensils. (Physiological effect uncertain).	100 (rarely up to 500)
pH	Sour taste; corrosion of fittings.	6.5-9.0
Sodium (Na)		270
Iron (Fe)	Unpleasant taste; brown staining.	0.3
Magnesium (Mg)	Taste; contributes to hardness; gastro-intestinal irritation.	30-150
Calcium (Ca)	Kidney disease; contributes to hardness.	<200
Chloride (Cl)	Taste; corrosion	200-600
Sulphate (SO ₄)	Gastro-intestinal irritation in presence of Mg and Na.	250

*Adapted from Hart (1974).

Physical and chemical aspects of the groundwater at Kelso and Greens Beach are described in Table 4 as acceptable (✓), doubtful, or unacceptable (X).

Table 4. ACCEPTABILITY OF THE GROUNDWATER AT GREENS BEACH AND KELSO

Factor	GREENS BEACH AREA		KELSO
	Quaternary sediments	Tertiary (?) sediments	
Colour	✓	✓	✓
Turbidity	✓	X	✓
Alkalinity	✓	✓	✓
Hardness	doubtful ¹	✓	X
pH	✓	X	✓
Na	✓	✓	✓
Fe	✓	X ³	✓
Mg	✓	✓	✓
Ca	✓	✓	✓
Cl	✓	✓	✓
SO ₄	✓	✓	✓
H ₂ S	X ²	X ²	✓

¹Mainly temporary.

²Easily removed by aeration.

³Very high.

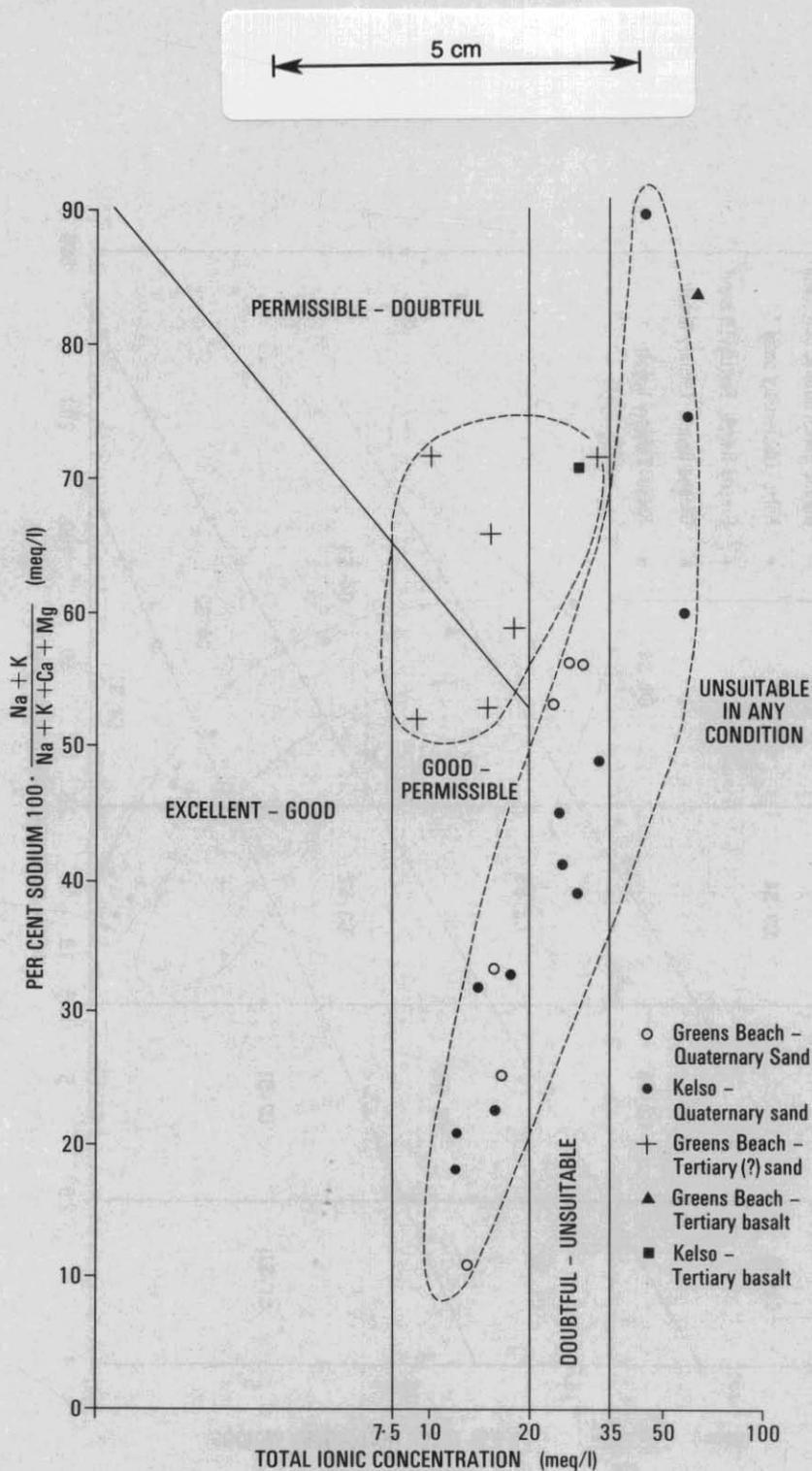


Figure 9. Suitability of groundwater for agricultural use. Per cent sodium criterion.

5 cm

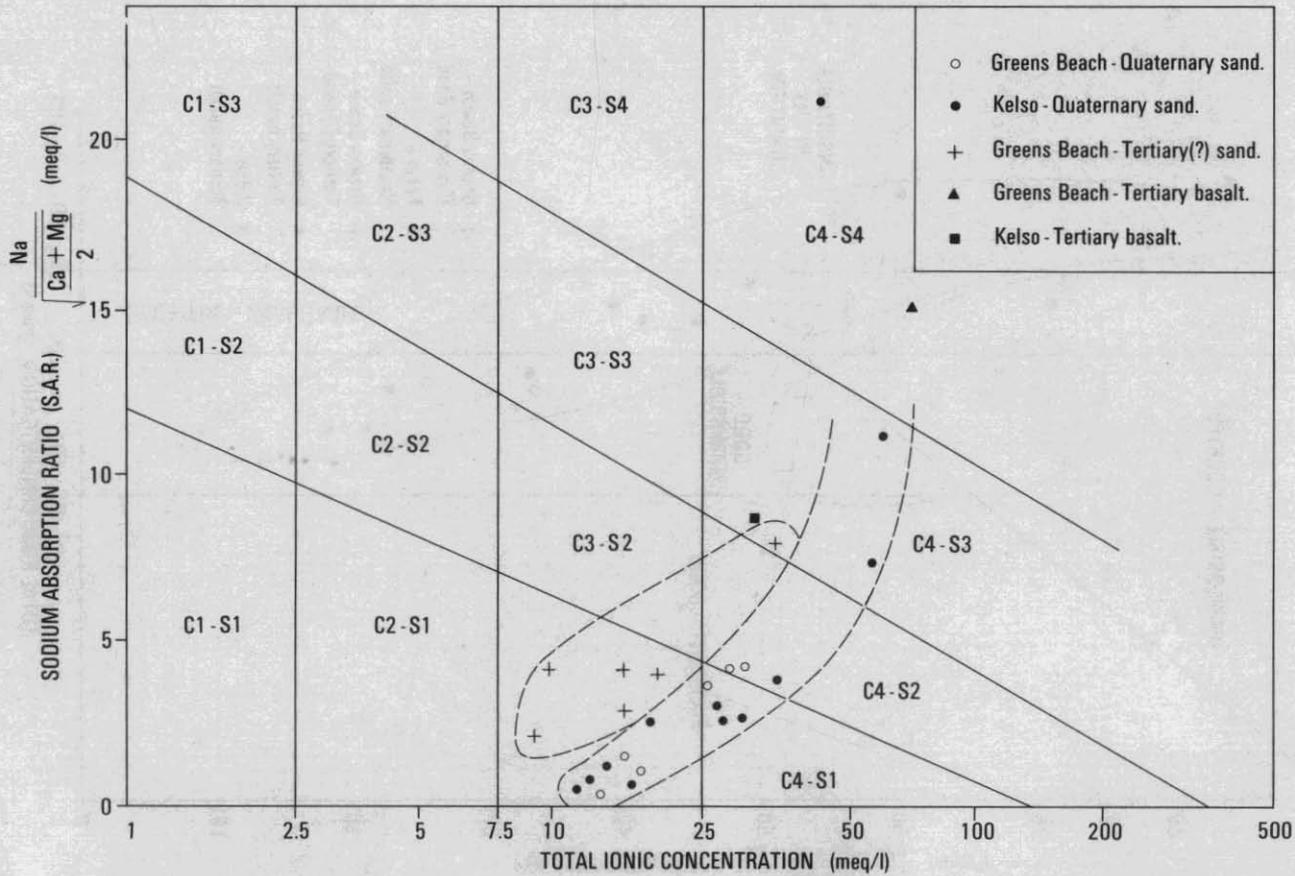


Figure 10. Suitability of groundwater for agricultural use. S.A.R. criterion.

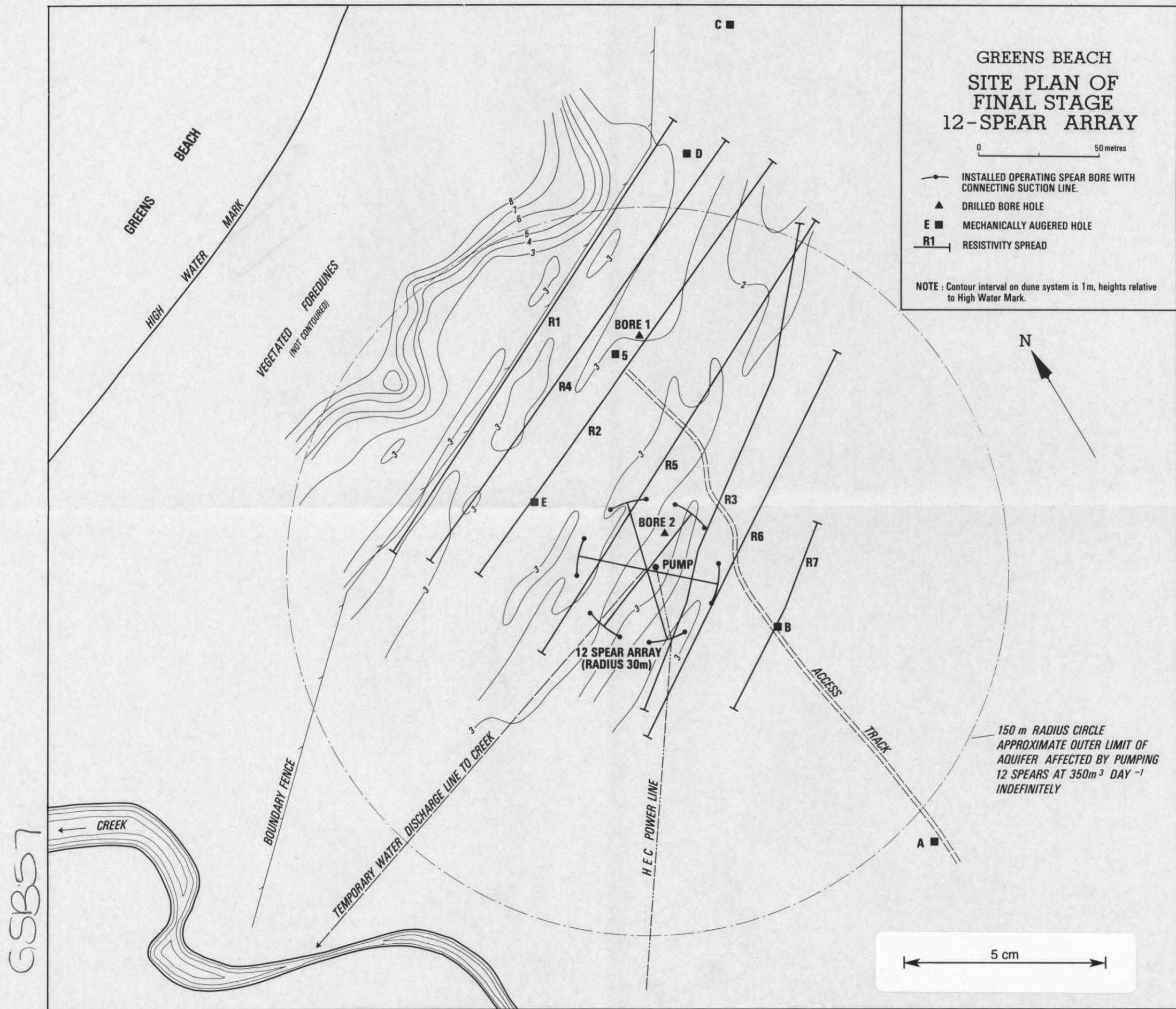


Figure 11.

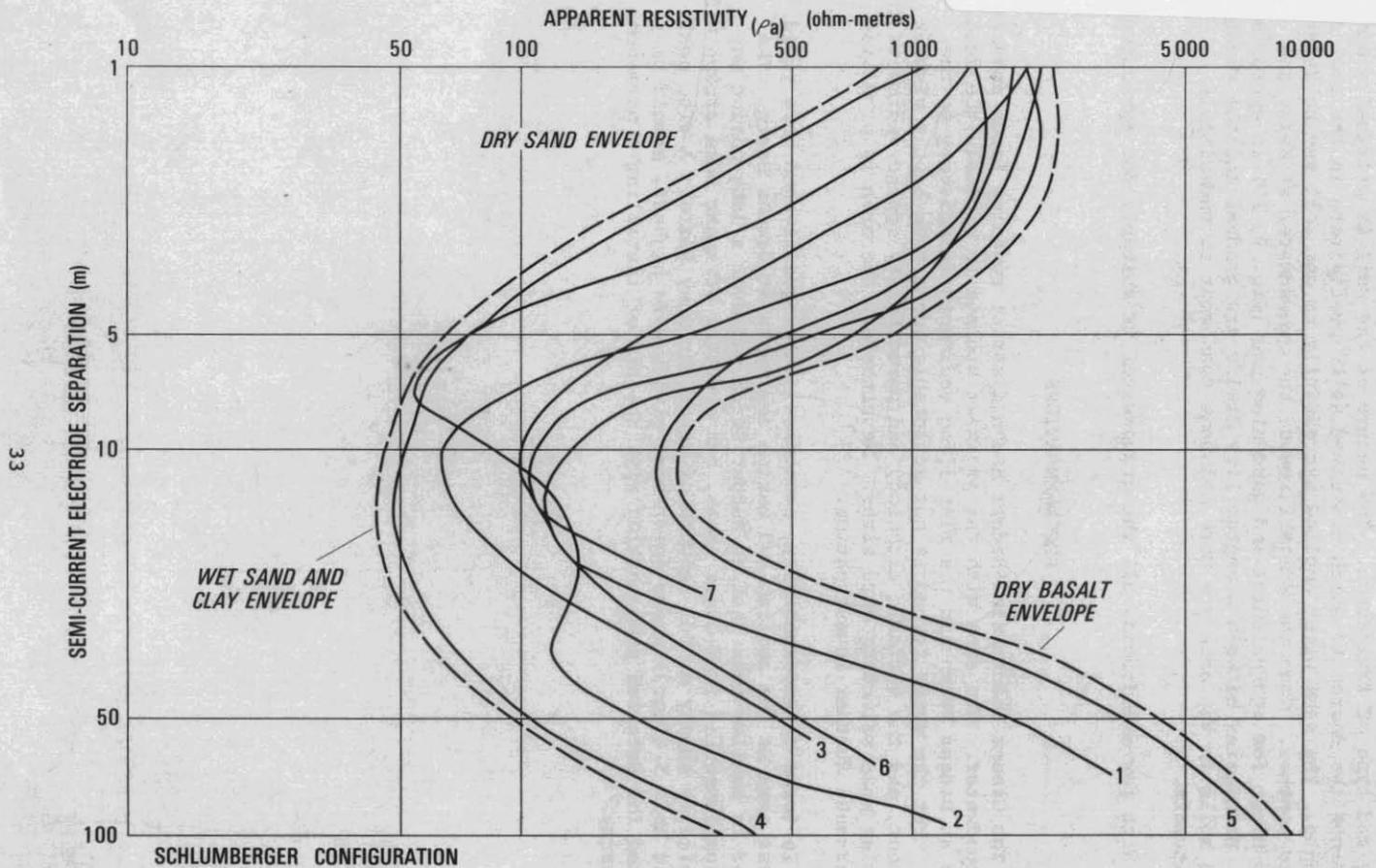


Figure 12. Apparent resistivity curves for the Greens Beach unconfined aquifer.

Water in the Kelso area is too hard for drinking purposes unless it is treated beforehand, and it is almost certainly contaminated by septic tank effluent.

Acceptability of the groundwater for agricultural and garden use

Many factors affect the suitability of irrigation water, including total dissolved solids and their relative proportions, soil type and frequency and type of irrigation. The nature of the soil is critical since it determines the degree to which dissolved salts precipitate in the root zone of plants. The same water applied successfully to one soil may be deleterious to another. Thus the suitability of the groundwater at Kelso and Greens Beach for agricultural and gardening use (fig. 9, 10) is approximate only. Boundaries between acceptability fields are gradual and the sandy porous soils in the area are more tolerant than most to undesirable constituents.

With few exceptions, all the groundwater is suitable for agricultural uses.

RECOMMENDATIONS

The Greens Beach-Kelso-Badger Beach district contains large amounts of groundwater. The area with the greatest storage is probably the dune system at Badger Beach and the flat-lying sediments immediately to the south. But the water tested is not acceptable for a town supply without treatment, and the variable lithology and permeability of the sediments is a problem when selecting bore sites. Nevertheless the area is promising and warrants further investigation.

In terms of accessibility, economics, water quality and bore yield the best area is the aeolian and marine sediments at Greens Beach. The aquifer is smaller than that at Badger Beach and over a long period may need supplementing from other areas, but a system of spear bore arrays will economically supply useful amounts of water for many years. A site near proline hole 5 (fig.3) where spear bore yields were highest, should be selected for detailed pump testing with the aim of installing a permanent bore array.

Part 2: Site Investigations

REFERENCE No.	LAB. SERIAL No.	LOCALITY				SEDIMENT ANALYSIS PARAMETERS								
	771565 - 771571	GREENS BEACH (DQ794518)				M =	V =	Sk =	K =					
COARSE AGGREGATE			FINE AGGREGATE				A77-1957 (concrete)							
COARSE		AGGREGATE		FINE AGGREGATE		BINDER		N.A.A.S.R.A. (road materials)						
COBBLE	PEBBLE		GRANULE	SAND			SILT							
				V. COARSE	COARSE	MEDIUM	FINE	V. FINE						
-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6 ϕ		
75	53	37.5	26.5	19	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	0.038	Aust. Stand. Sieve

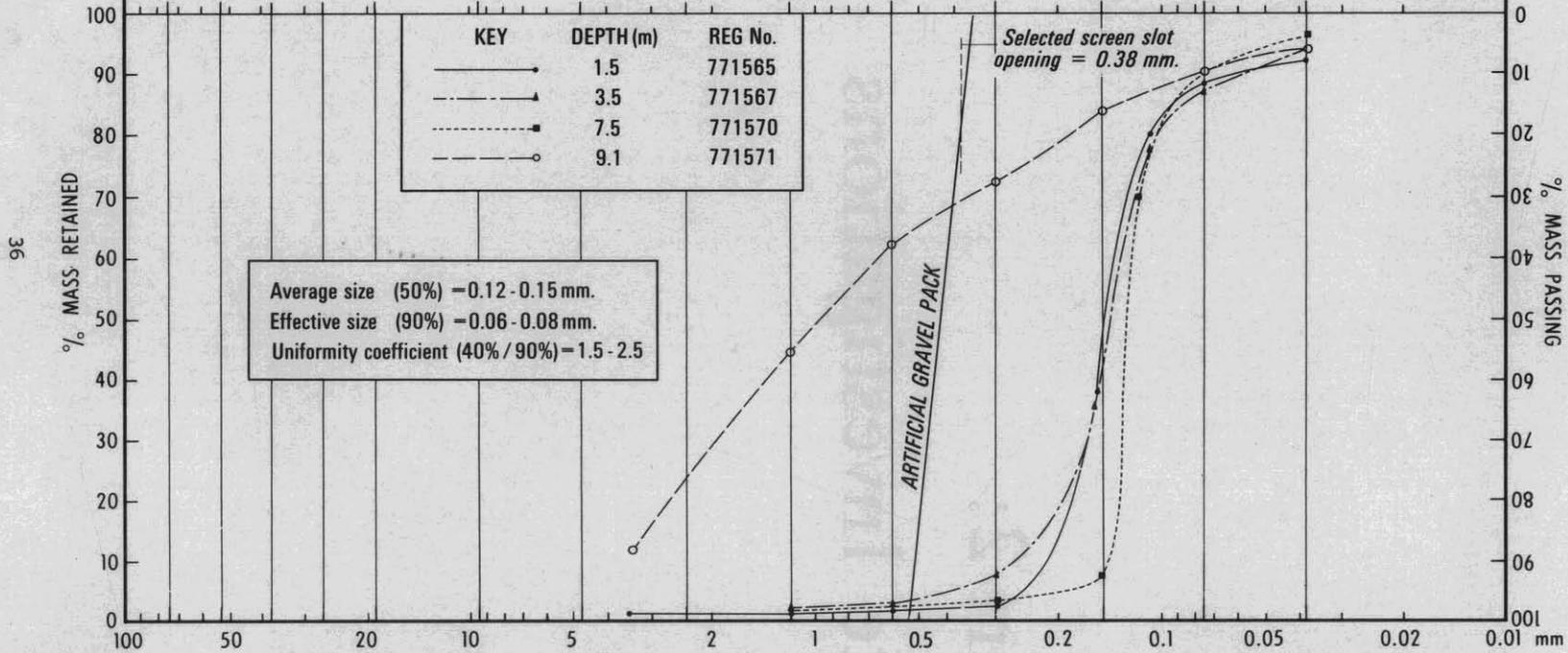
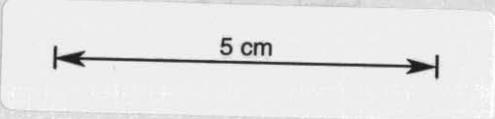


Figure 13. Grain size distribution curves for Greens Beach sand samples, and artificial gravel packs used in production bores.



INTRODUCTION

This section describes the geophysical, geological and hydrological studies made at the recommended pump-test site in the unconfined aquifer at Greens Beach. The investigations ended in November 1977 with a 13-day pump test on a circular 12-spear bore array. The installation is now supplying the Greens Beach caravan park with drinking water, and may eventually contribute to the permanent town supply.

RESISTIVITY SURVEY

Seven resistivity probes were conducted at the test site. Each was aligned roughly parallel with the beach ridge system (fig. 11) in a configuration designed to detect any lateral variation in groundwater quality. The probes also yielded information on the water-bearing potential of the underlying Tertiary basalt.

The results are plotted as apparent resistivity (ρ_a) curves (fig. 12), all of which display the same general shape. The curves are variously displaced along the horizontal axis and there is no apparent relationship between ρ_a and proximity to the coast. It was not practical to continue the survey over the vegetated frontal dunes to the beach, but such an extension would probably reveal a progressive seaward decline in groundwater quality, reflecting the presence of saltwater wedge invading the aquifer near high water mark.

The apparent resistivity envelope which confines the curves displays three general features: (1) an upper high ρ_a zone; (2) an intermediate low ρ_a zone, and (3) a lower high ρ_a zone. These are interpreted respectively as dry sand above the water table; saturated sand and clay below the water table; and dry basalt. Values in the intermediate to low range (50 - 250 ohm-metre) in the saturated zone are broadly consistent with a water quality of a few hundred mg/l T.D.S. Lower values in this range may also reflect the presence of poorer quality water in the saturated clay underlying the unconfined aquifer.

DRILLING

Drilling in unconsolidated sediments

Five mechanically augered holes and two drilled bores were made in addition to the single hole augered during the regional survey. Locations are shown in Figure 11 and geological logs are listed in Appendix 8. The information from this drilling is incorporated in geological sections of the aquifer presented earlier (fig. 4, 5).

Sand samples for grain size analysis were collected from most of the holes. Representative grain size distribution curves (fig. 13) show that the aquifer is lithologically uniform over the test site. It has an average grain size of 0.13 - 0.15 mm, a uniformity coefficient of between 1.5 and 2.5, and is composed of 10% medium to coarse-grained quartz sand, 60% fine-grained quartz sand, 20% very fine-grained sand and 10% silt and clay. The lithological change at a depth of about 8 - 9 m from sand to quartzite gravel and clay is evident from the curves.

Drilling in Tertiary basalt

The basalt underlying the test site was investigated by combined rotary and hammer drilling methods to determine its groundwater potential. The log of the hole (bore 2, Appendix 8) and geological sections (fig. 4, 5) show that

the bore bottomed in basalt at 36.5 m after penetrating 9 m of sand, 3 m of clayey quartzite gravel and 8 m of stiff clay. The upper 4 m of basalt were hard, unfractured and dry which was predicted in the resistivity survey. Artesian water was initially struck at 21 m, and the yield increased with depth as water-bearing vesicular and fractured glassy zones were progressively intersected. Near completion, an estimated 500 l/min of water were being air-lifted from the hole. The bore was finally pump-tested at 230 l/min for 2 hours, during which it sustained a drawdown of 16 m.

Tertiary basalt was also intersected in four bores drilled in the Kelso area (bores 3, 4, 6 and 7 in fig. 3). Two of these were investigation holes and two (6 and 7) were drilled by private interests. All struck artesian water which varies considerably in quality from about 1000 mg/l (Appendix 7) to a reported 7000 mg/l (bore 7). In each case the groundwater in the basalt is hydrologically separated from the overlying unconfined aquifer by a layer of impermeable massive basalt, clay or both. There is no possibility of upward leakage and contamination of the better quality water by the water in the basalt.

PUMP TESTING THE UNCONFINED AQUIFER

Installing and pump testing the initial 5-bore array

In May 1977 a roughly circular array of five spear bores was installed at the test site. Details of installation methods and equipment used are described in Appendix 10 for the final 12-bore array and are also applicable to the 5-bore array.

The system was successfully pump tested for three days in July 1977. Drawdowns were monitored in four observation bores, and the array was pumped at a constant 110 l/min. Water samples were collected and chemically analysed and one sample was tested for bacterial contamination (Table 5).

Results and predictions

Analysis of the pump test results by standard procedures implied that the aquifer had a transmissivity of about 70 m²/day and a specific yield of at least 0.18. Maximum drawdown at the array centre was 0.7 m after 3 days, and the radius of influence of the system (measured from the centre) was about 70 - 80 m.

These figures suggested that adequate water might be recovered from a larger array. It was found feasible to attempt to predict the behaviour of the larger array by estimating the drawdown effect per spear from the 5-bore array and integrating the effect for any desired number of spears in any configuration. This predictive method is empirical and approximate because of the limited number of observation bores available. Despite these drawbacks the approach is useful because in predicting *long-term* drawdowns for a larger circular array* the possibility of equilibrium being attained is not considered, i.e. the predicted drawdowns are conservative and err positively. On this basis it was found that a 12-bore array could safely be pumped for at least 35 days at more than 240 m³/day. Accordingly the installation of the larger array went ahead.

Installing and pump testing the 12-bore array

In September and October 1977, twelve gravel-packed production bores were installed around the circumference of a 30 m radius circle. The

* The circle is hydrologically the most efficient arrangement.

GREENS BEACH GEOMETRY OF 12-SPEAR ARRAY

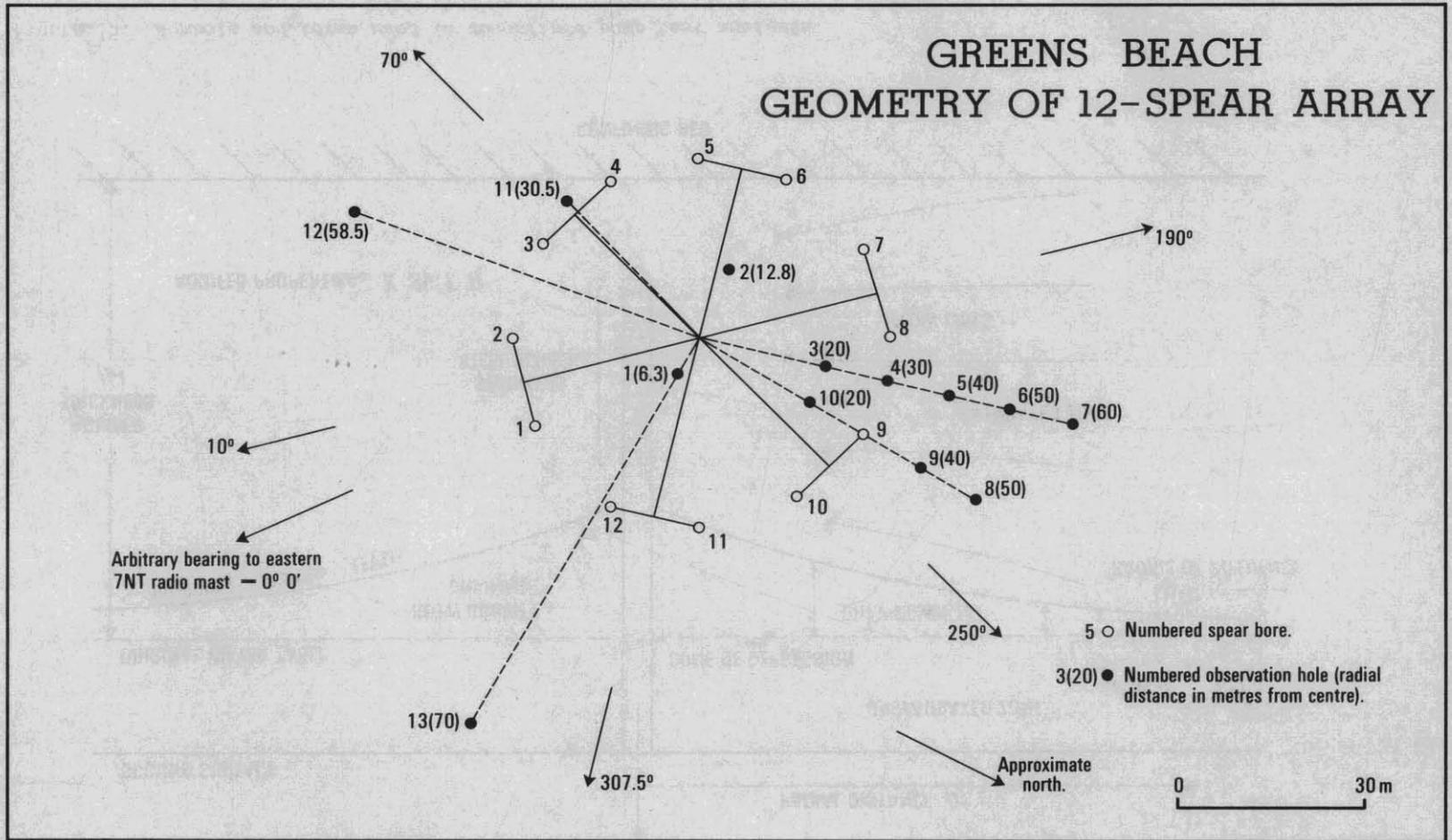


Figure 14.

5 cm

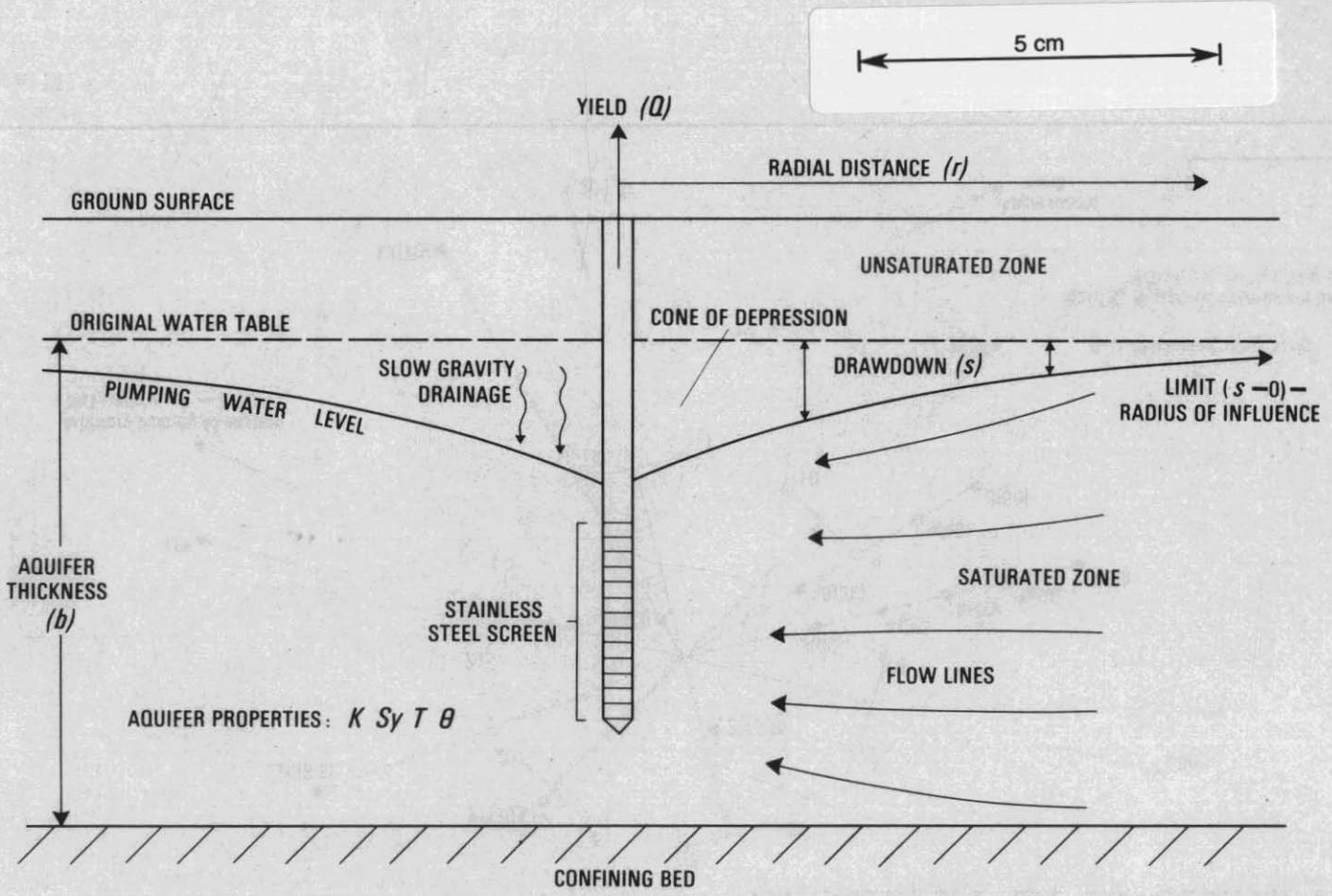


Figure 15. Symbols and terms used in unconfined pump test analysis.

system was monitored by thirteen observation bores. The plan of the site is shown in Figure 11, and the geometry of the array and observation bores is described in Figure 14. Technical details are described in Appendix 10.

During the period 30 October to 12 November 1977 the system was pumped at a constant rate of $350 \text{ m}^3/\text{day}$ ($240 \text{ l}/\text{min}$) for 12.98 days (18700 mins) during which time 4500 m^3 of water were discharged to a creek 200 m west of the site. Drawdowns accurate to the nearest millimetre were measured in each of the thirteen observation bores, and daily water samples collected for chemical analysis.

ANALYSIS OF THE PUMP TEST RESULTS

Symbols, notation and definitions

The following definitions recommended by Lohman et al. (1972) are used throughout this report.

Transmissivity, T [L^2T^{-1}] is the rate at which water is transmitted through a unit width of aquifer under unit hydraulic gradient.

Hydraulic conductivity, K [LT^{-1}] is the volume of water that in unit time will move through a unit area of aquifer measured at right angles to the flow direction, under unit hydraulic gradient.

Specific yield S_y [dimensionless] of an aquifer is the ratio of (1) the volume of water which the saturated aquifer will yield on gravity drainage to (2) the volume of the aquifer. For unconfined aquifers it is virtually equal to the storage coefficient, and is equivalent to porosity minus specific retention.

Specific retention S_r [dimensionless] is the ratio of (1) the volume of water retained by an initially saturated aquifer after drainage, to (2) the volume of the aquifer.

Porosity, θ [dimensionless] is the ratio of the interstices of an aquifer to its total volume.

Other symbols used in the following pump test analysis are listed below, and are schematically described in Figure 15.

Q	yield, pumping rate (m^3/day ; l/min)
b	aquifer thickness (m)
s	drawdown (m)
s'	corrected drawdown (m), where $s' = s - s^2/2b$
r	radial distance (m) from array centre
t	time

The basic aim of pump-test analysis is to establish the fundamental aquifer properties of transmissivity (T) and storage coefficient (S). Methods for determining T and S from pump-test data were developed many years ago for equilibrium and non-equilibrium radial flow conditions in confined and semi-confined aquifers. Techniques and derivations are documented in many publications, e.g. Ferris et al. (1962), Bentall (1963a, 1963b), Jacob (1963), Lohman (1972) and Hazel (1973).

Development of separate equations suitable for analysis of data from unconfined aquifers has been found difficult and is yet to be satisfactorily accomplished. Accordingly, confined aquifer methods are generally applied to unconfined situations. This presents a number of difficulties

and spurious T and S will be obtained if precautions are not taken. The problems arise because confined aquifer analysis involves assumptions which may be invalid in unconfined aquifers. The assumptions are:

- (1) the formation is isotropic, homogeneous, of infinite areal extent and uniform saturated thickness,
- (2) the piezometric surface (the water table in unconfined aquifers) prior to pumping is horizontal,
- (3) the pumped bore fully penetrates the aquifer and receives water from its entire saturated thickness for the duration of pumping,
- (4) water removed from storage during pumping is discharged instantaneously with concomitant head loss,
- (5) storage in the bore itself is negligible,
- (6) vertical flow components are negligible, and
- (7) water flow during pumping is both laminar and radial.

Field experience shows that these assumptions do not seriously affect the usefulness of the analysis in confined aquifer conditions. But often unconfined aquifers depart unacceptably from the ideal model. Assumptions (3), (4) and (6) are most commonly violated; many bores only partially penetrate aquifers, and drawdowns are often a major fraction of the total aquifer thickness, invalidating (3); gravity drainage and associated delayed yield effects result in non-instantaneous discharge, (4); and vertical flow components (6) are often high.

Accordingly, it is necessary to apply a number of corrections to data from an unconfined aquifer before analysis; but often the aquifer will be too complex to allow a clear evaluation of S and T , and dispersion of the data is a measure of how much it departs from the ideal.

Before considering the standard forms of analysis, some semi-quantitative and useful conclusions can be made from log-log and log-linear graphs of drawdown, time and distance.

Drawdown against time (fig. 16)

The relationship between drawdown (s) and time (t) - the basic pump test data - is most conveniently shown in log-log plots of s against t . The resulting curves represent drawdown at various times for each of the thirteen observation holes.

(1) The most obvious and expected feature of the curves is that drawdown *outside* the array (in holes 5, 6, 7, 8, 9, 12 and 13; fig. 14) decreases with increasing distance from the array centre. After 13 days pumping, the observed maximum drawdown at a radius of 70 m is 0.27 m. The corresponding drawdown at the centre is 1.03 m.

(2) The changing shape of the cone of depression *inside* the array is of interest. The effect is best displayed in the relationship between holes 3 and 10 (near the array circumference) and holes 1 and 2 (near the centre). For most of the pumping period, drawdowns in 1 and 2 are less than those in 3 and 10: only near the end of the test do they merge. The maximum drawdown difference is about 40 - 50 mm. The water table inside the array there-

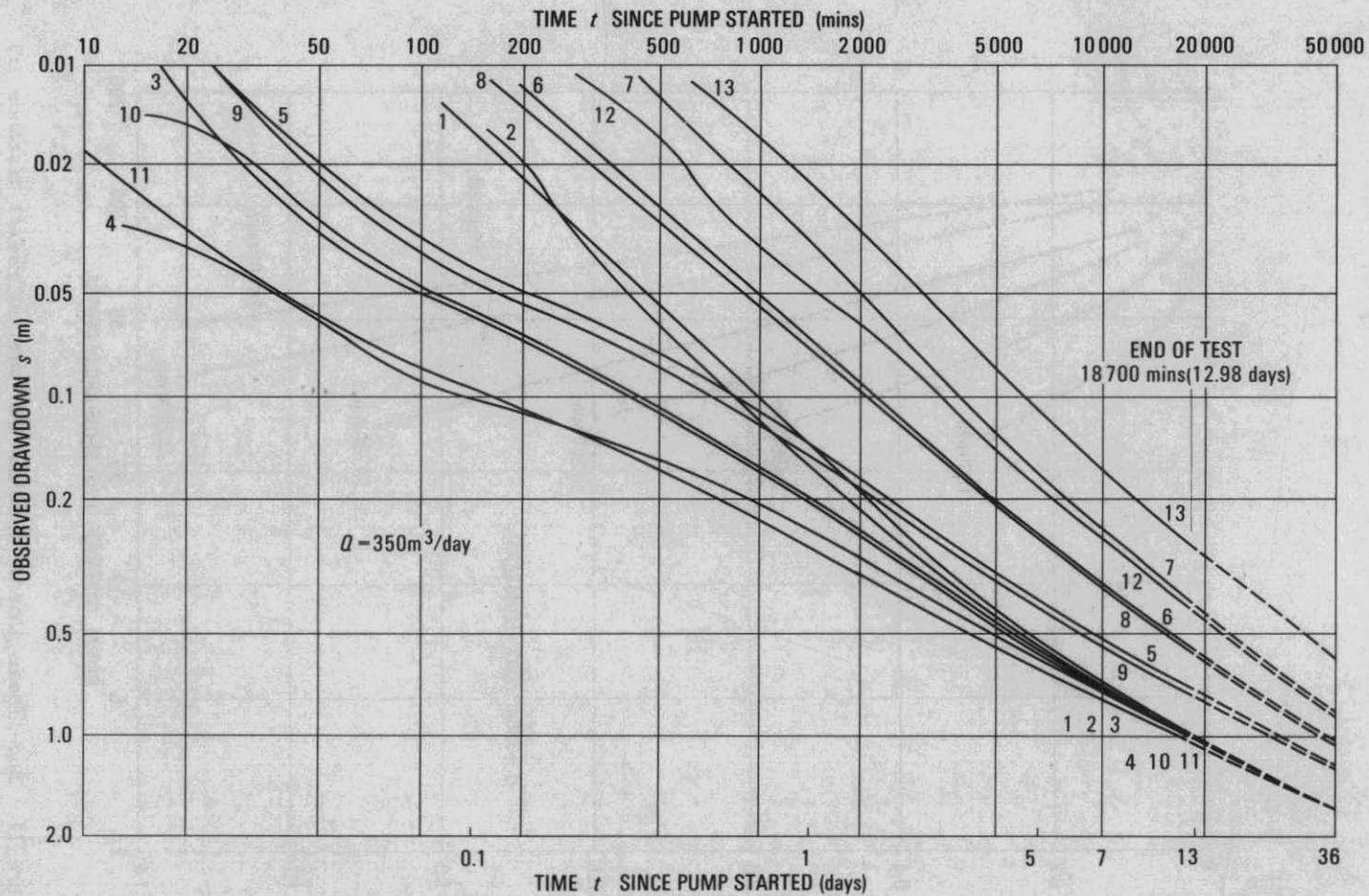


Figure 16. Log-log plot of drawdown (s) against time (t) for each of 13 observation holes for the 12-bore array at Greens Beach.

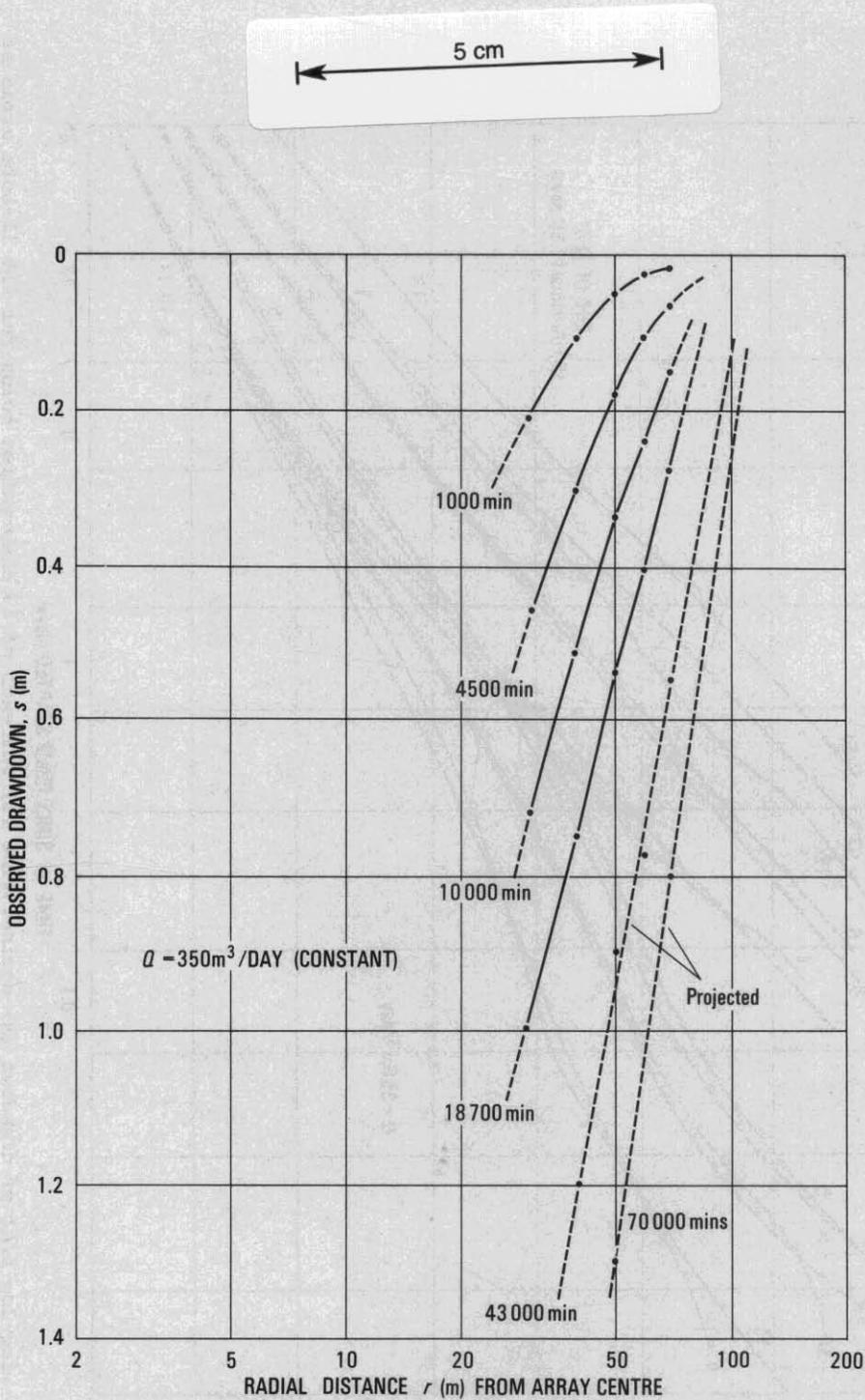


Figure 17. Log-linear plot of drawdown (s) against radial distance (r) from the centre of the Greens Beach array for observation bores 13, 7, 6, 5, 4 and 3 for various times. Q is constant.

fore exhibits an initial low 'residual' hump at the centre. The residue is present throughout the pumping period, never actually disappearing, but gradually flattening as pumping continues to produce an essentially horizontal water-table inside the array at the end of the test.

(3) All the curves in Figure 16 show a gentle flattening out at large t ; most show this effect at $t > 5000$. It is most apparent in holes furthest from the centre (7, 12 and 13). This feature represents a trend towards 'equilibrium', after which pumping will produce no obvious drawdown change. The plots cannot be safely extended to predict when equilibrium is likely to occur, but independent calculations on both the 12-spear and earlier 5-spear arrays suggest a time near $t = 40\ 000 - 45\ 000$ (1 month).

Instead of anticipating equilibrium, the flattening out effect may be neglected (thus over-estimating s and introducing a safety margin into the calculations) and the curves extended to predict drawdowns after long pumping times: for example, near the array centre hole 1 will sustain a drawdown of 1.7 m for $t = 50\ 000$ (36 days) and 2m for $t = 70\ 000$ (50 days). The corresponding drawdowns for hole 13 are 0.6 and 0.8 m. Q is constant at $350\ \text{m}^3/\text{day}$; possible recharge and discharge boundary effects are neglected.

(4) Paired equidistant observation holes such as 3 and 10, 5 and 9, 6 and 8, and to a lesser extent 12 and 7, show very similar drawdowns after long pumping times. This is a useful verification of the assumption that the aquifer is broadly homogeneous, and also shows that after about one week's pumping concentric drawdown contours are produced around the array centre. In plan, then, the cone of depression for $t > \text{one week}$ is essentially circular. The conclusion is not invalidated by the divergence in the graph of individual pairs of lines at low t , since for short pumping periods the cone of depression is then an irregular but symmetrical figure produced by drawdown interference between all twelve spear bores.

Drawdown against radial distance from array centre (Q constant, t variable) (fig. 17)

Log-linear plots of s against r at constant Q for observation holes sited outside the array may be used to show observed and predicted drawdowns at various times (fig. 23). This procedure is normally only applied to single pumped bores, but it seems in this case to be applicable also to circular bore arrays, provided that drawdowns inside the array are omitted because of interference. Usually, too, if t is large enough the resulting curves are straight lines which are extended to $r = 0$ (i.e. the predicted drawdown in the pumped hole*) and $s = 0$ (the outer radial limit of the cone of depression). (In this Greens Beach analysis, it is assumed that the 12-spear circular array can be replaced by an imaginary bore pumped at rate Q at the array centre. This assumption has not been rigorously tested, but the graphical analysis suggests it is justified. Thus, r values in Figures 23 and 24 refer to radial distances from the centre, and not from individual spears).

Accordingly, the curves cannot be meaningfully extrapolated to $r = 0$, because of drawdown interference between neighbouring spears. Extrapolation to $r = 0$ shows instead the predicted drawdown in an imaginary central bore.

* The efficiency of a pumped bore is the ratio of the predicted to the observed drawdown.

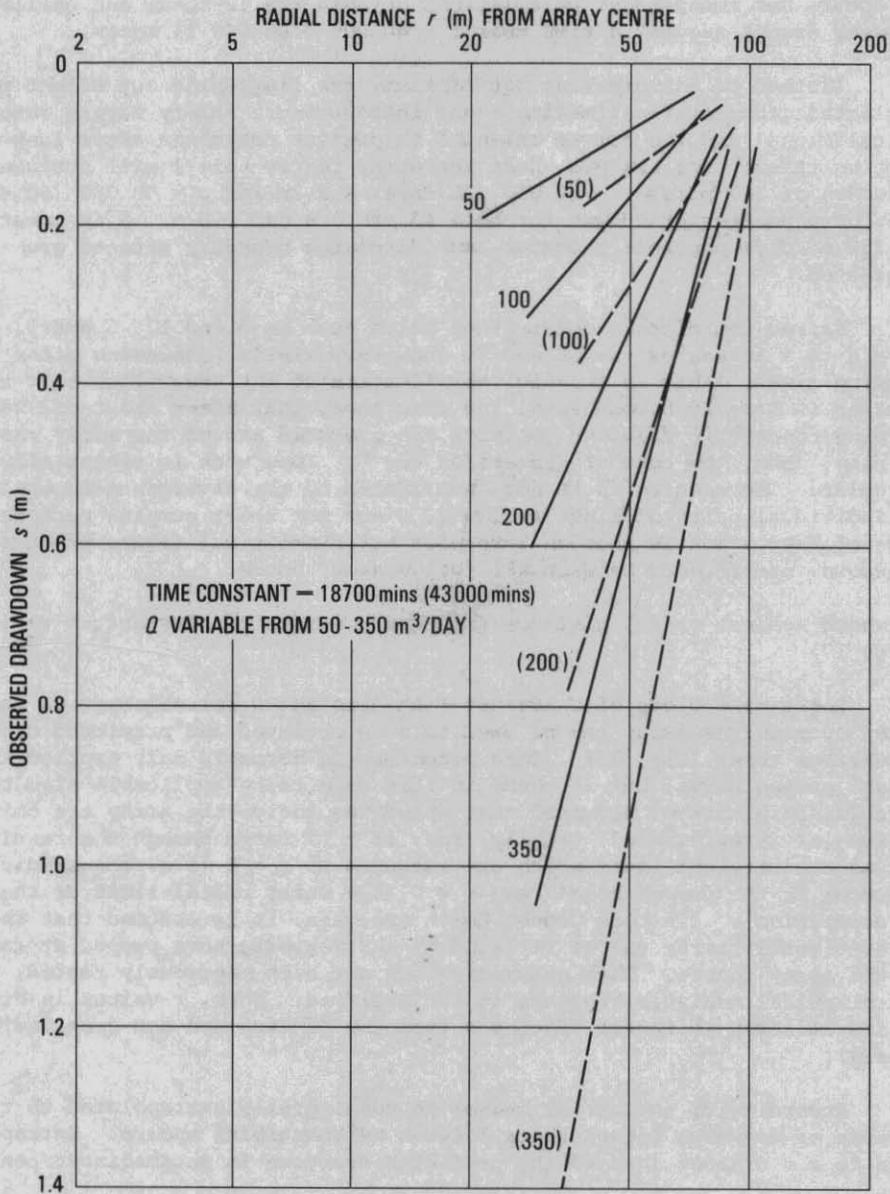
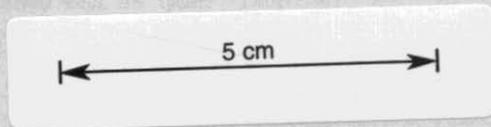


Figure 18. Log-linear plot of drawdown (s) against radial distance (r) from centre of Greens Beach array.

The curves may be extrapolated to $s = 0$, but a precise radius of influence for the array cannot be determined. This is due to the departure from linearity (especially at small t) of most of the curves at small s . In fact these plots clearly demonstrate an important constraint of unconfined aquifer analysis: the straight-line relationship between s and $\log r$ only holds for

$$u = r^2 S_y / 4Tt < 0.05$$

In other words, data from observation bores at distances r cannot be used in analysis until t is large enough to reduce the value of u to at least 0.05, and preferably less than 0.01.

Inspection of Figure 17 shows that extension of the plots to $s = 0$ is only justified for times greater than about 10 000 minutes. Departures from linearity are then negligible, and the long-term radius of influence of the array is about 120 - 130 m.

Drawdown against radial distance from array centre (t constant, Q variable)

Because drawdown is linearly related to yield, curves similar to those in Figure 17 (but plotted at constant t) can be used to predict the drawdowns expected by varying the pumping rate. Thus at 50 m from the array centre, 13 days pumping ($t = 18\ 700$) at $200\ \text{m}^3/\text{day}$ will produce a drawdown of 0.32 m, and 0.58 m at $350\ \text{m}^3/\text{day}$ (fig. 18). The curves should not be extrapolated to $r < 30$ because of drawdown interference within the array.

Main conclusions of the graphical analysis

- (1) The aquifer is showing a tendency towards 'equilibrium' after 13 days, but such a situation will not be reached before one month's pumping at $350\ \text{m}^3/\text{day}$.
- (2) The maximum extent of the cone of depression will be about 130 m after 70 000 minutes pumping at $350\ \text{m}^3/\text{day}$, and is unlikely to greatly exceed this.
- (3) Maximum predicted drawdown at the array centre will be about 2 m after 70 000 minutes pumping at $350\ \text{m}^3/\text{day}$.

Comparative determination of transmissivity and specific yield

It is instructive to calculate T and S using all available standard methods: indeed this approach shows how closely the aquifer conforms to the constraints imposed by each and is a sobering reminder that absolute values are in practise normally unattainable. The following brief notes list the methods used.

Thiem equilibrium equation

If an unconfined aquifer has been pumped for a time sufficient to produce equilibrium conditions, the Thiem formulae may be used to calculate T and S .

$$T = \frac{Q \log_e (r_2/r_1)}{2\pi (s_1 - s_2)}$$

$$s = \frac{Q}{4\pi T} \cdot \log_e \frac{2.25Tt_0}{r^2 S_y}$$

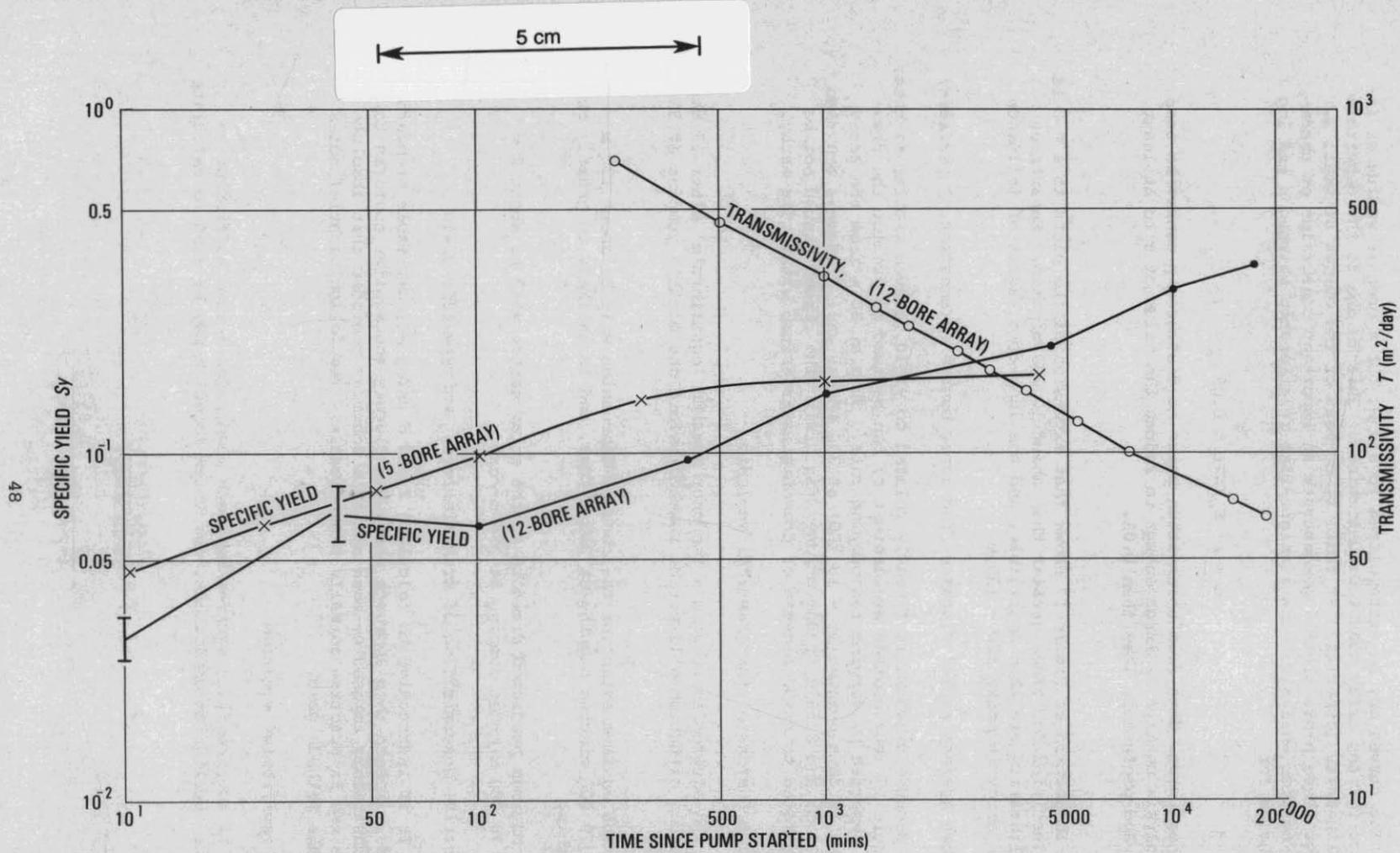


Figure 19. Variation of transmissivity and specific yield during the 13-day pump test at Greens Beach.

5 cm

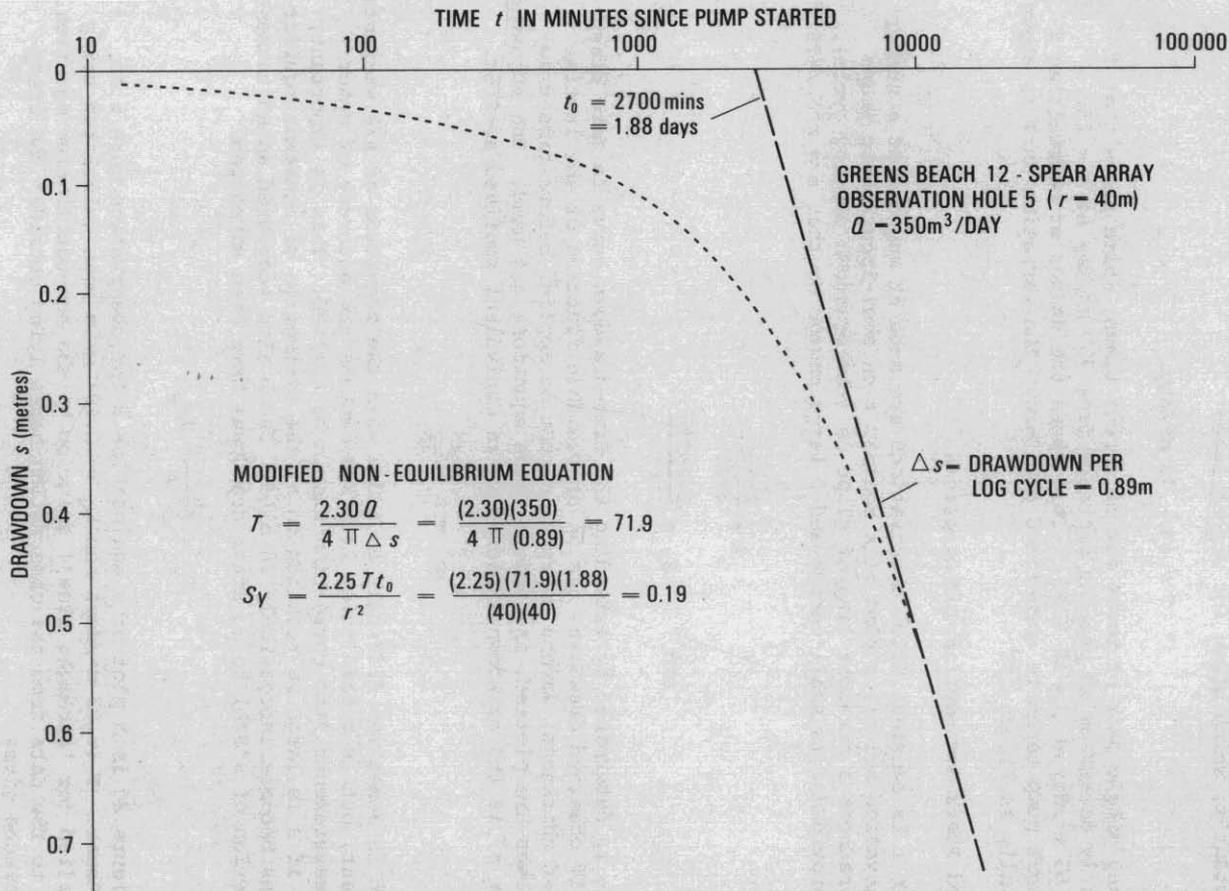


Figure 20. Log-linear plot of drawdown (s) against time (t) for observation bore 5, showing calculation of T and S_y using the modified Theis non-equilibrium equations.

The method is time-independent, and individual drawdown measurements obtained from any two observation holes are sufficient to calculate T and S_y , assuming that the bore discharges at a constant rate. T and S_y may also be solved graphically by plotting s against r on a semi-logarithmic paper.

The equations can validly be applied to pairs of observation holes at constant t , which gives for Greens Beach

$$T = 64 - 73 \text{ m}^2/\text{day}$$

or to any single pair of bores for different times, which shows that T apparently decreases as pumping proceeds from $700 \text{ m}^2/\text{day}$ at $t = 250$ to $T = 65 \text{ m}^2/\text{day}$ at $t = 18\ 700$. This shows the danger of calculating T from short pump tests in unconfined aquifers. The variation in T is shown graphically in Figure 19.

Modified Theis non-equilibrium equations

If r is constant (i.e. observations are made at any one of a number of observation holes), a plot of s against t on semi-logarithmic graph paper produces a straight line of slope Δs (the drawdown per log cycle). Then, provided r is small enough and t large enough so that $u = r^2 S_y / 4Tt \leq 0.05$.

$$T = \frac{2 \cdot 30Q}{4\pi\Delta s}$$

and

$$S_y = \frac{2 \cdot 25Tt_0}{r^2}$$

where t_0 is determined by extending the time-drawdown curve to zero drawdown. If observed drawdowns are an appreciable fraction of the initial saturated thickness, Jacobs correction must be applied before time-drawdown curves are plotted, and before these equations are used. The adjusted drawdown s' is the drawdown expected in an equivalent confined aquifer.

$$s' = s - \frac{s^2}{2b}$$

It is sometimes difficult to judge when the magnitude of s/b warrants adjustment, but as a safe rule, if $s^2/2b$ exceeds the accuracy of water-level measurements, the correction should be applied. This is important, because if s is large in relation to b , the assumption of constant aquifer thickness becomes increasingly invalid. Jacob also suggested an adjustment (a reduction of $s'S/b$) to S_y after drawdowns have been corrected.

$$S_y' = \left(\frac{b - s'}{b} \right) S_y$$

Figure 20 is a plot of s against $\log t$ for observation bore 5 at Greens Beach. T ($= 72 \text{ m}^2/\text{day}$) and S_y ($= 0.19$) have been calculated using the modified (or 'straight line') solution to the non-equilibrium equation. Applied to the data from the observation bores lying outside* the array circumference gives

$$T \text{ in the range } 56 - 99 \text{ m}^2/\text{day}$$

$$S_y \text{ in the range } 0.16 - 0.23$$

* Drawdown data from observation bores *within* the array are subject to excessive interference. None of the usual analytical methods can validly be applied to them.

Boulton's non-equilibrium equations for unconfined aquifers showing delayed yield

Water flows by gravity drainage relatively slowly from the cone of depression in fine-grained unconfined aquifers. Formations exhibiting this *delayed yield* depart from the assumption of instantaneous discharge. This can be demonstrated if *apparent* S_y is plotted against t during an extended pump test (fig. 19). The value of S will progressively increase to a constant or near-constant value.

Generally, delayed yield should be assumed in fine-grained aquifers if data show that equilibrium has not been attained. Boulton (1963) devised a method of analysis for such situations. The technique also partly accounts for the effect of vertical flow components (which often invalidate analysis, especially in the vicinity of a bore during the early stages of pumping).

The method is discussed in detail in many publications (see Hazell, 1973). Applied to data from the Greens Beach test gives

$$T \text{ in the range } 59 - 95 \text{ m}^2/\text{day}$$
$$S_y \text{ in the range } 0.25 - 0.29$$

Stallman's non-equilibrium equations for partially penetrating bores in unconfined aquifers

This method (Lohman, 1972) partially accounts for the many situations when both pumped and observation bores do not extend the full saturated thickness of the aquifer. Applying it to the Greens Beach results gives

and

$$T \text{ in the range } 67 - 79 \text{ m}^2/\text{day}$$
$$S_y \text{ in the range } 0.23 - 0.27$$

The method also calculates K_v/K_h , the ratio of the vertical and horizontal hydraulic conductivities. For Greens Beach this ratio is in the range 0.09 - 0.12 which shows clearly that the aquifer is not homogeneous despite the lithological uniformity implied from bore logs and grain size analysis.

Calculating specific yield from first principles

Specific yield can be independently calculated for any time after pumping starts in various ways. One method* depends on deriving an equation describing the actual (observed) drawdown curve both inside and outside the array, and then integrating to produce the volume of aquifer affected by pumping. This volume is then related to the volume of water pumped to produce an estimate of S_y . The results (fig. 19) show that specific yield varies from about 0.03 after 10 minutes pumping, to a maximum of about 0.33 after 13 days pumping. Clearly, then, there is a danger of underestimating S_y from short pump tests in unconfined aquifers.

Discussion of transmissivity and specific yield values

Results from all methods are listed in Table 6.

* Formulated by D.E. Leaman.

Table 6. SUMMARY OF T AND S_y VALUES CALCULATED FROM VARIOUS METHODS

	Method	$T(m^2/day)$	S_y
1.	Leaman's dewatered volume		0.03 - 0.33
2.	Thiem equilibrium equation	64 - 73	
3.	Modified Theis non-equilibrium equation	56 - 99	0.16 - 0.23
4.	Boulton's delayed yield equations	59 - 95	0.25 - 0.29
5.	Stallman's partial penetration equations	67 - 79	0.23 - 0.27

The main conclusions from these results are:-

(1) T cannot be determined precisely; its value is a function of time. With limitations, its lowest value should probably be considered the most accurate, although there is no reason why T cannot increase rapidly during steady state and steady state conditions. For Greens Beach then, T is in the approximate range 55 - 100 m^2/day .

(2) The maximum value for S_y is near the porosity of the aquifer, which is unknown but probably in the range 0.40 - 0.45. Leaman's maximum value is considered the most accurate. The modified Theis equations not unexpectedly produced values of S_y too low because they considered neither delayed yield nor partial penetration. For Greens Beach, then,

$$S_y \approx 0.33$$

(3) Each of the four standard methods produces overlapping T values, and there is no reason to favour any one method above the others. The accuracy of the results seems to be more a function of the length of the pump test than of the methods themselves.

The problem of array geometry

All the methods described above apply only to single discharging bores. Clearly this situation does not apply at Greens Beach, especially for small t when drawdown interference between neighbouring bores produces a complex cone of depression around the system. As pumping proceeds, the drawdown contours outside the array become increasingly concentric and behave as if they were the result of a single imaginary bore in the array centre. The data are therefore increasingly amenable to standard analysis as t increases, provided drawdowns inside the array are not used.

It is possible that hydrologically the array is behaving in a manner similar to a 60 m diameter bore. This would partly account for the drawdown configuration inside the array, which produces the essentially flat water table expected inside a large diameter well. Such a model would not invalidate the single imaginary bore hypothesis, since the two are mathematically identical and in each case radial distances are measured from the centre.

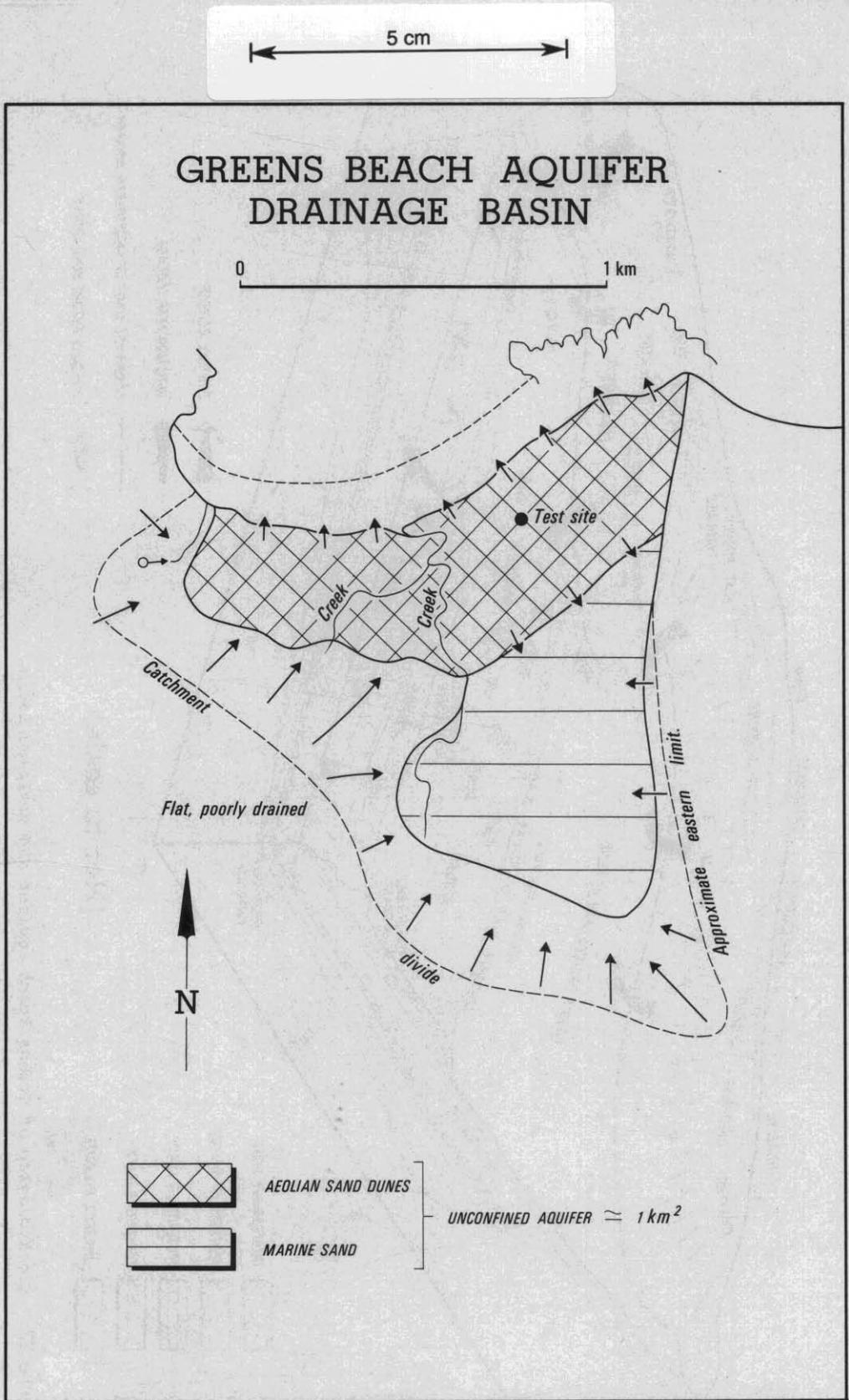


Figure 21.

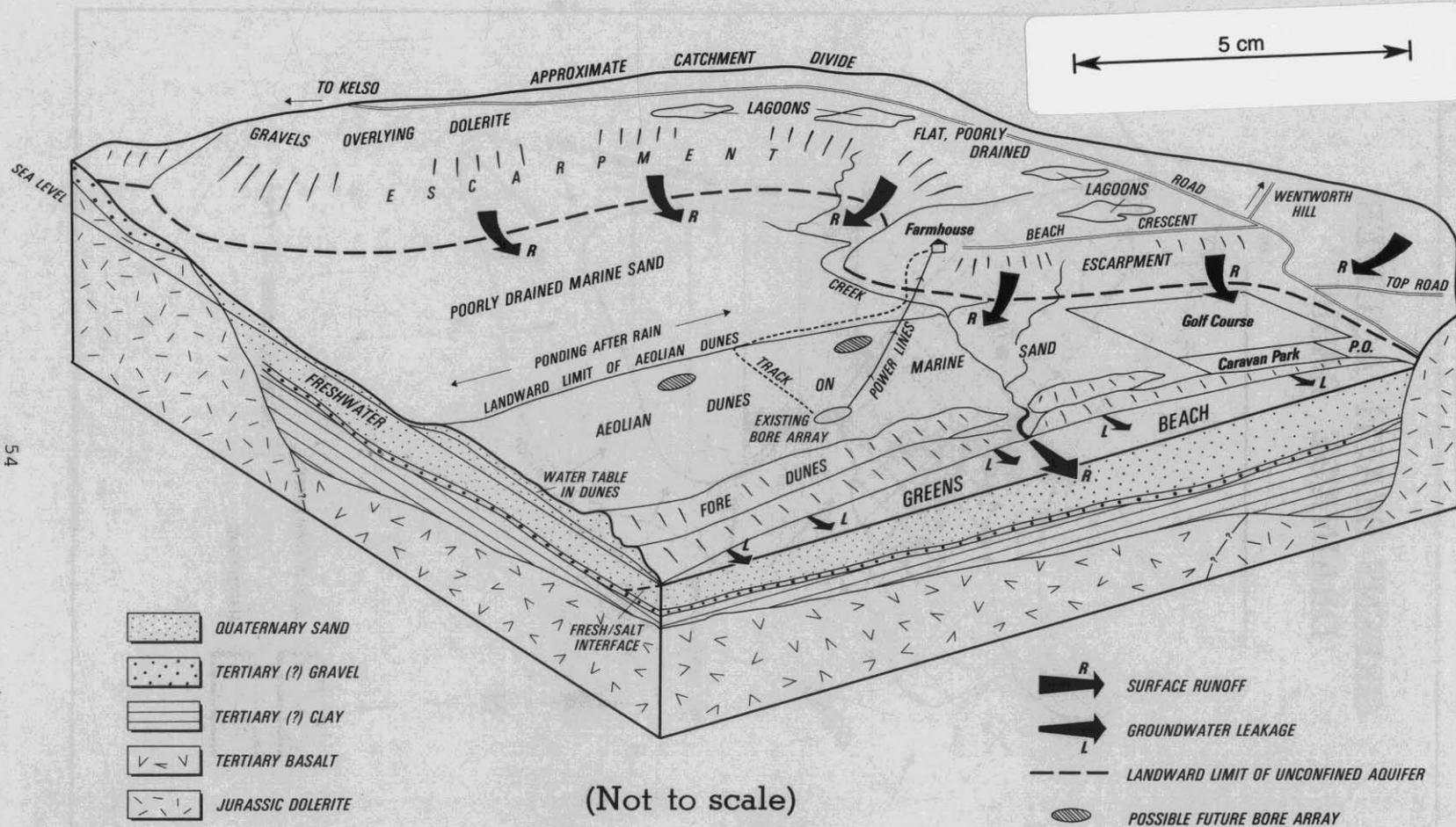


Figure 22. Block diagram of Greens Beach aquifer and drainage basin.

WATER BALANCE IN THE AQUIFER

The unconfined aquifer at Greens Beach is a sub-system of the general hydrological cycle, and one of the main aims of the present study is to attempt to assess the water balance in the aquifer. By defining limits to its surface catchment area (fig. 21) the groundwater body can be considered as a component of a hydrological basin where the principle of hydrological continuity* applies:

$$\text{Recharge} = \text{discharge} \pm \Delta s \quad (1)$$

where Δs is the change in volume of groundwater in storage over a specified period. Recharge is essentially equal to discharge when the period of study is selected to minimise the effect of changes in reservoir storage. The factors involved in balancing (1) vary between basins but at Greens Beach include precipitation, evapo-transpiration, surface run-off and groundwater leakage. Only precipitation - the largest factor - is known with any accuracy. The others can be estimated but this reduces the usefulness of the method. Despite these disadvantages it is instructive to consider first the components of the general water balance equation at Greens Beach and then examine each component in turn. From (1), net recharge to the groundwater reservoir at Greens Beach is defined as

$$\text{Recharge} = P - ET - R \quad (2)$$

and net discharge from the groundwater reservoir at Greens Beach is defined as

$$\text{Discharge} = L + \ell \quad (3)$$

where

- P = precipitation over entire catchment area
- ET = evapo-transpiration from the zone of aeration and the water table
- R = direct surface run-off
- L = groundwater leakage along the coast at sea level
- ℓ = groundwater leakage to streams (base flow)

substituting (2) and (3) in (1),

$$P - ET - R = L + \ell \pm \Delta s \quad (4)$$

The limits of the Greens Beach aquifer and drainage basin are shown in Figures 21 and 22. Both the south-western and eastern boundaries are ill-defined topographically. The former is a broad poorly drained area of lagoons, and the latter, also flat lying and partly inundated after heavy rain, marks the approximate eastern limit to the unconfined aquifer but may not correspond to the catchment divide.

The basin area as stated is 1.5 km², and within it the aquifer extends over about 1 km².

Precipitation (P)

The basin receives an annual average rainfall of 770 mm (Table 7). With the exception of the 1978 figures (collected by the Greens Beach Golf

* For a good example of this application see Pluhowski and Kantrowitz (1964, pp 20-55).

Club) all were recorded by Mr P. Gardner on the eastern side of Wentworth Hill and are considered representative of the basin. The period of record is not known.

Table 7. RAINFALL FIGURES, GREENS BEACH (mm)

	Average to 1973	1974	1975	1976	1977	1978
January	35	54	26	66	37	16
February	51	24	6	21	60	71
March	43	10	122	50	151	40
April	65	95	47	24	24	69
May	78	68	107	53	23	47
June	81	85	85	63	107	68
July	96	213	224	66	28	79
August	87	71	78	87	71	93
September	60	91	93	53	7	58
October	65	65	63	55	55	93
November	57	34	95	55	62	67
December	52	91	60	82	8	44
Total	770	901	1006	675	633	745

Evapo-transpiration (ET)

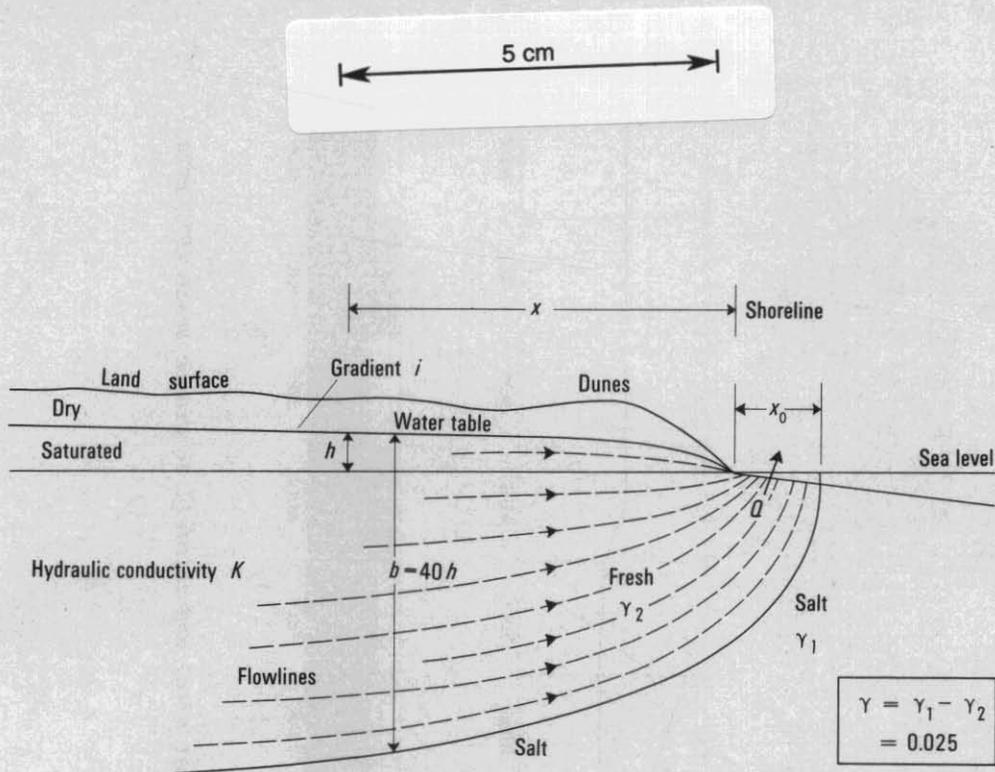
This includes not only evapo-transpiration from the plant root zone, but evaporation of water from the unsaturated zone and from the water table itself. There are no pan evaporation figures for Greens Beach, and the nearest stations for which figures are recorded are Cressy, and Elliott near Burnie. Elliott is considered by the Bureau of Meteorology (Anon, 1973) to be fairly typical of coastal northern Tasmania, and the monthly variation in precipitation (P) and pan evaporation (PE) for the period 1954-64 is (p. 55)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
P:	44	62	57	87	119	134	158	151	114	111	75	72	1185 mm
PE:	139	104	84	51	54	23	22	33	50	73	93	115	840 mm

Pan evaporation figures are usually converted to approximate evapo-transpiration values by multiplying by a correction factor between 0.7 and 0.8. The Bureau of Meteorology recommends 0.75 for Tasmania. As a rough estimate then, evapo-transpiration for Greens Beach is $(0.75)(840) \text{ mm} \approx 600 \text{ mm}$ and its seasonal variation is assumed to be similar to that at Elliott.

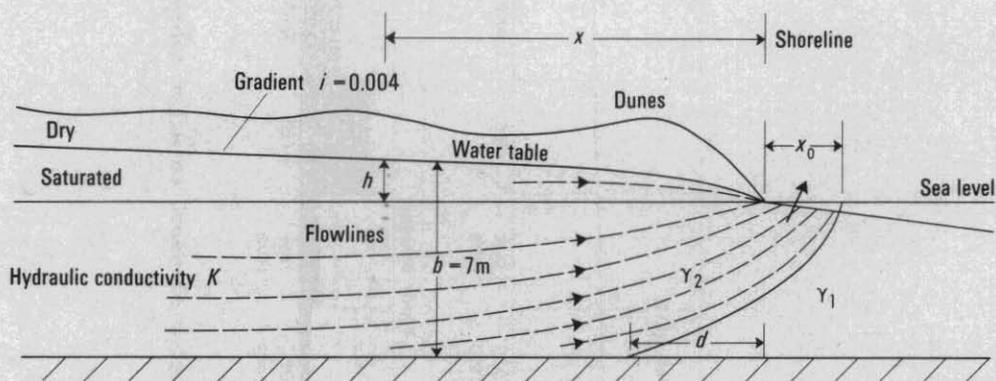
Surface run-off (R)

Surface run-off is an unknown factor in the hydrological equation because there is no gauging station on the only creek draining the basin. The creek is often dry for long periods and therefore receives no baseflow component from the aquifer during this time. Surface run-off is considered negligible in the aeolian dunes (where precipitation either evapo-transpires or infiltrates) and is minor from the marine sand behind the dunes.



(a) FLOW PATTERN NEAR A BEACH IN AN UNCONFINED AQUIFER WHERE $b \geq 40h$ (AFTER GLOVER, 1964)

$$q = \frac{K h^2}{2 \gamma x} \quad \text{and} \quad x_0 = \frac{q}{2 \gamma K}$$



(b) FLOW PATTERN AT GREENS BEACH WHERE $b \ll 40h$

$$\gamma = \gamma_1 - \gamma_2 = 0.025$$

$$d = b/40i$$

Figure 23. Flow patterns near a beach in an unconfined aquifer.

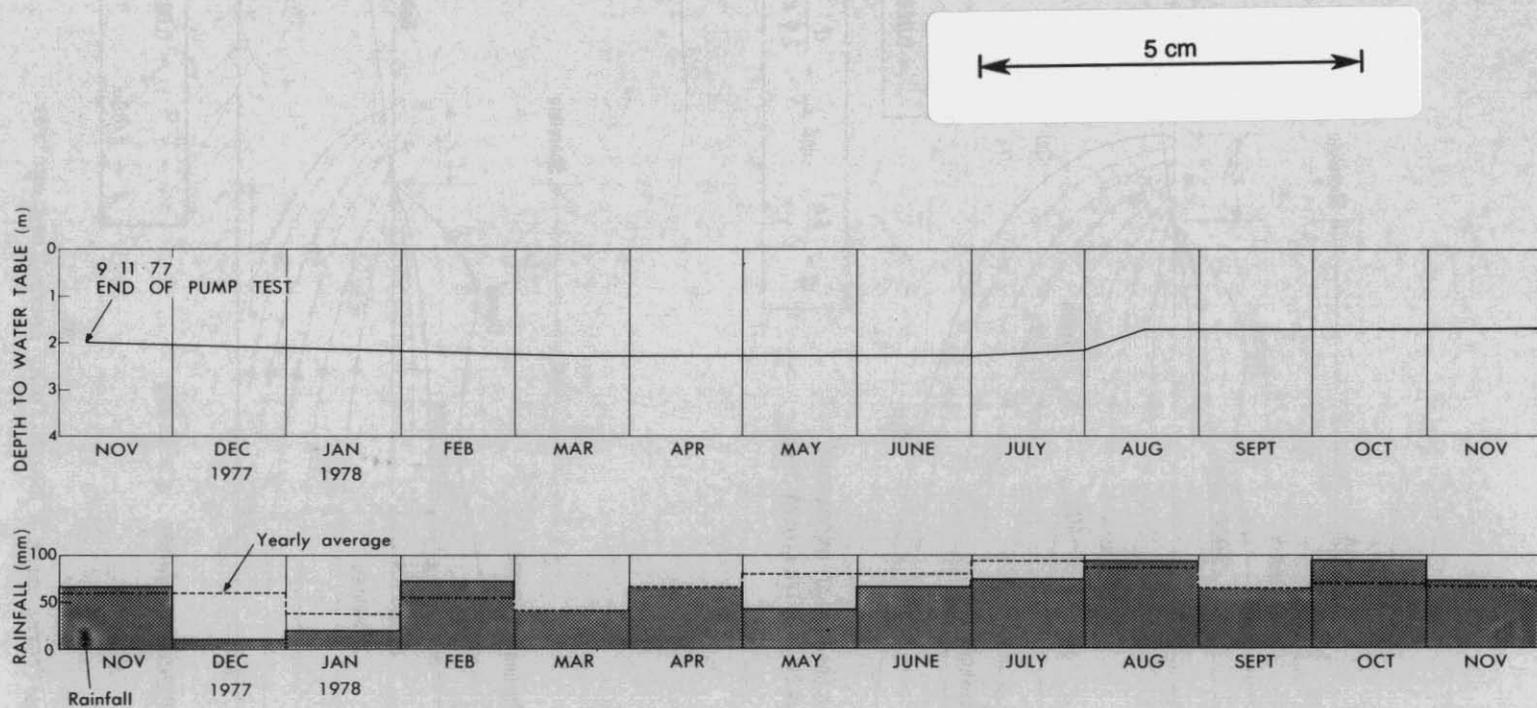


Figure 24. Variation of depth to water table (recorded at pump test site) and rainfall at Greens Beach 1977-1978.

One concept of surface run-off is that in terms of use it is a waste of valuable water. Lowering the water table in the aquifer by continuous pumping reduces evapo-transpiration and induces infiltration which in turn reduces run-off. If the creek were dammed, for instance, much of the surface run-off could be induced to enter the groundwater reservoir by nearby pumping. So, from equation (2)

$$P-ET = R$$

is the *maximum* possible volume of water available for pumping - provided that storage in the aquifer is not affected (*i.e.* the groundwater is not depleted) and discharge from the aquifer along the coast is neglected.

$$i.e. R = 0.77 - 0.6 = 0.17 \text{ m/year}$$

which over the catchment area is

$$0.3 \times 10^6 \text{ m}^3/\text{year}$$

or on average

$$R = 700 \text{ m}^3/\text{day}$$

Discharge from the aquifer

By estimating leakage from the aquifer it is possible to refine the approximate values for surface run-off. In doing so, l in equation (3) is neglected; *i.e.* it is assumed there is no base flow component to stream discharge. Therefore (3) is simply

$$\text{Discharge} = L$$

L can be estimated by considering Figure 23a which depicts an unconfined aquifer sufficiently thick for the head (h) of fresh water above sea level to be hydrostatically compensated by fresh water below sea level. If the fresh-salt boundary is assumed static then the Gyben-Herzberg relationship holds and $b = 40h$. Glover (1964) produced an equation relating the elevation of the water table to the freshwater discharge at the coast. Rearranging his equation 6 (p. C34) gives

$$Q = \frac{Kh}{2\gamma} \left(\frac{h}{x}\right) \quad (5)$$

where Q is the discharge per unit length of shoreline (m^3/day)

K is the hydraulic conductivity (m/day)

h is the height of the water table a distance x inland (so that h/x is the hydraulic gradient) and

γ is the excess of the specific gravity of sea water over that of fresh water (≈ 0.025).

The width of the gap through which Q escapes is

$$x_0 = \frac{Q}{2\gamma K} \quad (6)$$

measured parallel to the groundwater flow lines.

These relationships are shown in Figure 23a. Figure 23b shows the geological situation along the coast for the Greens Beach aquifer, which differs from the previous model in that $b \ll 40h$; *i.e.* the aquifer is relatively thin and therefore filled with fresh water. As a first approx-

imation, the flow at the coastline in the Greens Beach model is directly related to the ratio of the aquifer thicknesses. If in equation (5) x is chosen so that h is unity (i.e. the gradient i is used) then $b = 40$ for Figure 23a. The saturated aquifer thickness at Greens Beach is about 7 m, so the ratio of the flows at the coast is 7/40.

From (5), then, using $i = h/x = 1/250$, and $K = T/b \approx 10$ m/day*

$$Q = \left(\frac{7}{40}\right) \cdot \frac{(10)(1)}{(2)(0.025)} \cdot \left(\frac{1}{250}\right) \text{ m}^3/\text{day/m}$$

$$= 0.14 \text{ m}^3/\text{day/m}$$

and the width of the gap through which this discharge occurs is (from 6)

$$x_0 = \frac{(0.14)}{(2)(0.025)(10)} = 0.28 \text{ m}$$

The total discharge at sea level at Greens Beach, where the coast is about 1.3 km long, is

$$\text{Discharge} = L = (0.14)(1300) \approx 180 \text{ m}^3/\text{day}$$

This value will vary as the hydraulic gradient changes but the effect will not be large. This result enables surface runoff to be estimated if it is assumed that no change in storage occurs in the aquifer. From (4),

$$P - ET - L = R$$

$$\therefore R = 520 \text{ m}^3/\text{day}$$

The value of $L = 180 \text{ m}^3/\text{day}$ is effectively water wasted and should be regarded as the long-term *minimum* volume of water available for pumping each day.

If it is assumed that L is derived only from the aeolian dune sand (an assumption which errs positively and is conservative) then the discharge is equivalent to an actual lowering of water over the dune system of only 0.00045 m/day. Since the aquifer has a specific yield of about 0.35, this represents an apparent drop in water level of about 0.0013 m/day. During the 219 day period, 9 October 1977 - 15 June 1978, readings (fig. 24) from an automatic water level recorder sited in the dunes near the pump test site showed a continuous fall in water levels of 0.53 m (i.e. an actual drop of $(0.53)(0.35) = 0.19$ m) or an average 0.0009 m/day. In other words, over the period studied, natural groundwater leakage accounts for about half the water lost from storage in the dunes. The remainder is removed by evapo-transpiration.

Discussion

All these figures are estimates based on the present knowledge of the aquifer. Their usefulness and predictive value will increase as more data are collected. In particular more water level recorders need to be installed, and reliable figures obtained for evapo-transpiration.

To make the most efficient use of the groundwater in the aquifer requires an understanding of the relationships between all these variables, but in particular precipitation, evapo-transpiration and leakage. All

* $K = 10$ m/day $\Rightarrow T = 70 \text{ m}^2/\text{day}$, which is an average value obtained from pump test analysis.

three change on a regular and usually annual basis.

L is directly related to hydraulic gradient i , so that if the water table falls leakage slowly decreases. L is greatest when water levels are highest, in late spring and early summer, and lowest in late autumn and early winter when water tables are lowest. Since the water level variation is small, the variation in L is small; accordingly it can be considered approximately constant.

On average only a small fraction of the total yearly precipitation reaches the water table and then discharges from the system. The proportion is highest in winter and lowest in summer partly because of the seasonal distribution of rain but also because evapo-transpiration is a function of solar radiation and is also seasonally variable. So an apparent inverse relationship exists between ET and P, and ET may often exceed P.

Precipitation reaching the water table must be of sufficient intensity and duration to maintain a downward moving saturated front which progressively raises the water content of the unsaturated material to field capacity. Only heavy continuous rain and favourable antecedent conditions are effective: light showers and drizzle are usually quickly (evapo-)transpired, especially in summer when P is low and ET high. In the first half of 1978 at Greens Beach, for example, combined evapo-transpiration from all sources exceeded precipitation, causing the removal of water from the water table as well as from the unsaturated zone.

Management of the aquifer

The Greens Beach aquifer contains about two million cubic metres of water in storage and maintains a water table only 1 - 2 metres above sea level. This overall balance is altered by artificial discharge (pumping), and it is clear that if the system is to provide a permanent and reliable water supply most of this water in storage will not be used and the aquifer should be managed on a sustained yield basis where total average pumping does not exceed net recharge. The minimum average volume of water available is that which leaks naturally from the aquifer - about 180 m³/day. The maximum possible - if all could be used - is equal to leakage plus surface run-off from the basin - perhaps 700 m³/day assuming on average groundwater is not removed from storage. Present data are not sufficient to refine these figures. A suitable management plan, then, maintains reserves at a relatively constant level so the resource is not depleted. This is important because the water in storage represents about 10 - 12 years recharge so any large depletion of water in storage produces a long-term water deficit which is not easily made up. Nevertheless, wise planning coupled with careful monitoring of water levels should allow pumping of reserves for brief times when water is badly needed.

Recent water table monitoring has shown that for 1978 at least, water is deficient and unavailable for pumping in late summer and autumn. Conversely, in winter, spring and early summer there is excess water available. Heavy rain at any time of the year is largely wasted through surface run-off. The management plan should then have a two-fold basis: a seasonal, variable pumping regime where for alternative parts of the year daily yield is low and then high, and a capability to interpret this pattern at short notice to take advantage of extra water from unusually continuous and wetting rain whenever it falls. Such a system will be most efficient if it is coupled to a monitoring system of automatic water level recorders, and a storage dam of sufficient capacity to reduce as far as possible the summer demand on the aquifer. Significantly, continuous pumping especially when

water levels are high, creates favourable antecedent conditions which reduce evaporation from the water table and induce recharge to the aquifer.

The following scenario is an attempt to describe the possible seasonal water balance in the aquifer based on existing knowledge. It contains already discussed assumptions and will probably need revision as further data are collected.

3-month period	%P	Average daily precipitation (P) (m ³)	Approximate daily ET (m ³)	Approximate daily leakage (L) (m ³)	Average daily balance (P-ET-L)* (m ³)
Jan.-March	17	2200	3900	180	-1880
April-June	29	3800	1500	180	2120
July-Sept.	31	4100	1250	180	2570
Oct.-Dec.	23	3000	3400	180	-580
Total (average)	100	3275	2500	180	560
Column	1	2	3	4	5

Column 1 lists the percentage of average annual rainfall occurring in each three-month period, based on Table 7. The four-fold division is arbitrary and is limited by the accuracy of ET: more reliable values will permit subdivision on a monthly or even shorter basis. Column 2 lists the average daily volume of water received for each three month period, assuming a total basin area of 1.5 km². The approximate daily evapo-transpiration figures in column 3 are obtained by assuming that ET at Greens Beach varies seasonally in the same manner as it does at Elliott (see p.56), and that it occurs evenly over the total basin area of 1.5 km². Column 4 is the average daily leakage of groundwater at the coast, and is assumed constant. Column 5, the difference P-(ET+L), is the average daily volume of water which from equation (4) represents surface run-off and any change of water in aquifer storage. Negative values indicate a net loss over the three-month period because of evapo-transpiration, and if aquifer storage is to remain essentially constant no groundwater (or very little) is theoretically available for pumping. But lowering the water table in late summer will induce increased infiltration in the following period. Similarly, high pumping rates in late spring will increase aquifer storage for summer pumping. Positive values in column 5 should be regarded as the average daily volume of water wasted by surface run-off, and therefore available for pumping if it can be induced to enter the groundwater system.

It is apparent that since P is known and L is small, the above example is sensitive to small seasonal changes in ET. Obviously more reliable figures are needed for Greens Beach. The figures calculated should be regarded as approximate only, and should not be used for predictive purposes or to define detailed pumping regimes. They are merely intended to show in a general way the seasonal water budget of the basin.

In summary then, a management plan for the aquifer which purports to provide a reliable and permanent town water supply will

- (1) initiate continuous monitoring of the basin by installing more automatic water level recorders, and gauging the creek to determine surface run-off,

* These postulated three-monthly gains and losses may be compared to the automatically recorded water level changes monitored during 1978 near the pump test site and shown here as Figure 24.

- (2) instal more bore arrays inland from the existing array so that extraction of water lowers the water table as uniformly as possible throughout the aquifer, and so the possibility of salt water contamination* is reduced. Likely sites for the arrays are near the inland limit of the aeolian dunes,
- (3) maintain initially an average daily yield in the range 180 to about 600 m³ distributed seasonally to make the most efficient use of waste water (surface run-off) and to conserve water in summer. The limit of 600 m³/day is probably a conservative estimate, but one which should be adhered to until more reliable water balance data are collected,
- (4) construct a dam large enough to store excess water, reduce large fluctuations in pumping rates and provide a back-up capacity when groundwater yields are likely to be lowest i.e. in late summer, autumn.

The main disadvantage of this management plan is that intermittent pumping and the capacity to vary yields at short notice precludes reticulation to consumers from a rising main.

QUALITY OF THE GROUNDWATER

Introduction

Thirty-two samples from the test site have been collected and analysed over a 21-month period. One sample obtained during a pump test in June 1977 was also tested for bacterial contamination. The analyses include thirteen samples collected on successive days from the final pump test.

These analyses are not sufficient to enable predictions to be made of the aquifer's long-term water quality. However, considering the nature of the body and the source of the groundwater, they do suggest that the quality will vary only between narrow limits. Any slight variations that may occur are likely to reflect changes in pumping procedures and seasonal rain patterns, as well as differences in quality between various parts of the aquifer. The water should at all times remain within acceptable limits for domestic, drinking and garden uses. Nevertheless, it will be wise practise to systematically and regularly analyse the groundwater for chemical and bacterial constituents.

The following notes are not an exhaustive treatment of the analytical results, but rather a discussion on various aspects of water quality which may affect its acceptability to consumers.

CHEMICAL QUALITY

Presentation and accuracy of analytical results

Results of selected analyses collected over the 21-month period are listed in Table 8. Analyses of samples collected during the 13-day pump

* In its present un pumped state, the salt-fresh water interface forms the upper surface of a salt water wedge extending inland about 45 m from high water mark (fig. 23). Since the saturated aquifer extends about 7 m below sea level, the *minimum* height of the water table above sea level needed to hydrostatically compensate this depth is $7/40$ m = about 0.2 m. The interface itself is a zone of diffusion whose position fluctuates with the tide and regional changes in the water table.

GREENS BEACH - WATER QUALITY VARIATION DIAGRAM

64

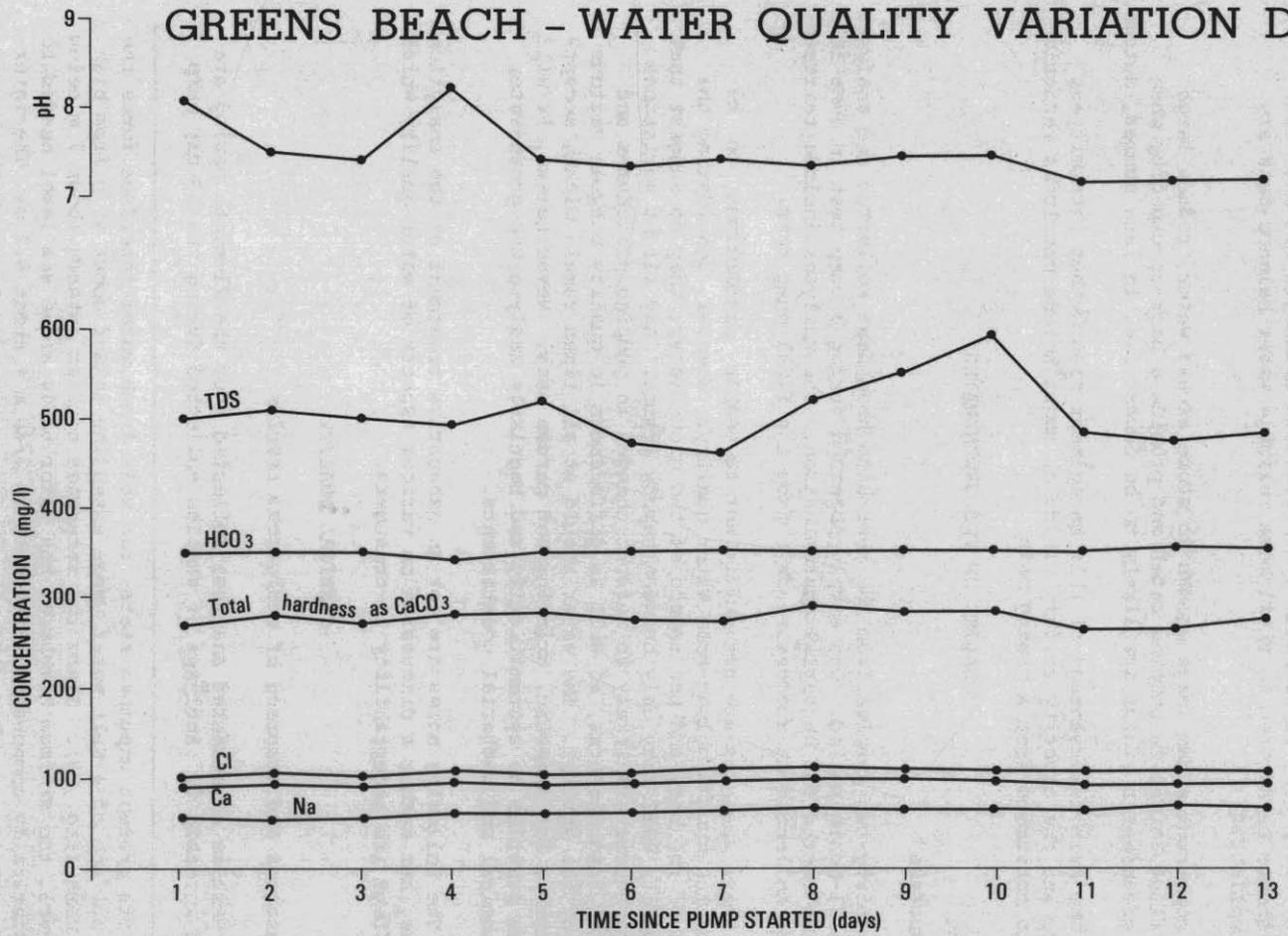
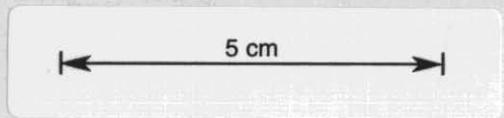


Figure 25. Variation diagram showing changes in concentration of various components of the groundwater at the Greens Beach test site during the 13-day pump test.



test are presented in Appendix 9, and these same results are depicted as variation diagrams in Figure 25. All chemical analyses were made at the Department of Mines Laboratory, Launceston.

The unavoidable scatter of analytical results tends to partly obscure any variations or trends that may be present between similar samples. Duplicate analyses should normally agree within about 5%, but larger variations are sometimes inescapable and the absolute accuracy of the results is often suspect. Some general comments can be made on the Greens Beach analyses:

- the small variations in SO_4 , Cl, HCO_3 , Na, Mg, Ca, Fe, Al, K, SiO_2 , alkalinity and total hardness can probably be explained by analytical variations, and for all practical purposes their concentrations are constant over the 13-day test.

- only the total dissolved solids (T.D.S.) concentration and the pH display variations not accounted for by laboratory error.

- there is no definite trend - seasonal or otherwise - in water quality between any or all of the 32 samples analysed.

Total dissolved solids (T.D.S.)

Over the 21-month period, T.D.S. varied from 470 - 634 mg/l. The highest value occurred in May 1977 (Table 8) and the lowest near the end of the 13-day pump test. There is no apparent pattern to the results, and the variations are more likely to reflect small changes in groundwater quality between different parts of the aquifer (as well as sampling and analytical effects) rather than any long term trend. There are no definite upper recommended limits to the T.D.S. value, because acceptability is a function of necessity and consumer adaptation: communities often accept lower quality water where no other is available. Water with T.D.S. values less than about 500 mg/l generally have little or not taste (although taste depends on the nature of the dissolved constituents as well as T.D.S.).

The average T.D.S value for the test site is about 510 mg/l, which is acceptable for all domestic uses. It is not expected to change markedly either spatially in the aquifer, or over long pumping periods.

pH

pH readings are normally accurate and reproducible to within 0.1 pH units, but differences of up to several tenths of a unit can be introduced into duplicate samples because of variations in field collecting techniques. The time lag between sampling and analysis, the loss of dissolved H_2S and CO_2 , and precipitation of iron hydroxides and oxides during storage, all have an effect on pH. Such factors are likely to have produced the variation which occurred on the first and fourth days of the 13-day pump test, when the value jumped from about 7.4 to over 8. The average pH for the whole test is 7.4, which is within acceptable domestic limits.

Iron

The recommended upper limit for iron in domestic supplies is 0.3 mg/l. Values higher than this are a nuisance rather than a physiological danger, since pipes, fittings and laundered clothing become stained with iron oxides and hydroxides.

Care must be taken when interpreting iron analyses in water. The figure quoted for the Greens Beach groundwater (<0.1 mg/l) represents the

Table 8. CHEMICAL ANALYSES OF GROUNDWATER SAMPLES FROM THE GREENS BEACH TEST SITE OVER A 21-MONTH PERIOD (Concentrations in mg/l).

	1	2	3	4	5	6	7
Date	26.2.76	4.5.77	19.5.77	9.6.77	7.7.77	14.11.77	Average
CO ₃	nil	nil	nil	nil	nil	nil	nil
HCO ₃	305	312	340	330	325	350	327
Cl	120	120	117	110	132	98	116
SO ₄	13	12	5	7	5	8	8
SiO ₂	13	13	-	-	8	8	10
Ca	60	72	95	100	100	93	87
Mg	18	15	14	12	12	10	14
Fe	<0.1	<0.1	<0.1	0.15	<0.1	<0.1	<0.1
Al	<0.2	<0.2	<0.2	<0.2	<0.2	<0.5	<0.2
K	3.1	3.8	3	2.5	2.9	2.6	3
Na	50	83	56	53	63	58	61
H ₂ S	nil	nil	nil	nil	nil	nil	nil
Total hardness as CaCO ₃	220	237	296	300	300	280	272
Alkalinity as CaCO ₃	250	257	280	280	270	284	270
Total dissolved solids	480	498	634	500	540	510	527
Total suspended solids	-	-	5	7	-	-	6
Turbidity	-	-	7.5	<5	-	-	<6
Conductivity (μS/cm)	-	800	690	740	760	695	737
pH	7.4	7.9	8.0	8.0	7.6	7.5	7.7

Notes

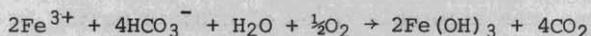
Samples collected by W.C. Cromer, and analysed by the Department of Mines Laboratories, Launceston.

1. One sample from a single spear
2. Average of 4 samples, from a single spear pumped for 20 hours.
3. One sample from five spears.
4. Average of 5 samples, from five spears pumped for 1 day.
5. Average of 8 samples, from five spears pumped for 3 days.
6. Average of 13 samples, from twelve spears pumped for 13 days.
7. Average water quality for total 21-month period.

dissolved iron present in solution at the time of analysis. It does not reflect the total iron content of the groundwater, some of which is removed by oxidation before collection, and during storage when orange-brown iron precipitates often form in sample bottles.

Thus, although the quoted figures represent the amount of iron in the water which reaches the consumers, it hides the fact that the higher total iron will probably have a nuisance effect in pipes and tanks.

The chemistry of iron in groundwater is affected by pH, dissolved oxygen and H₂S, and is complicated by the presence of both ferrous and ferric oxidation states. Ferric iron is highly insoluble: in the pH range 6 - 8 in the absence of CO₂ and oxygen, the theoretical maximum concentration of Fe³⁺ species is <10⁻⁶ mg/l (Hem, 1959), far below detection limits. Almost all the iron in solution in these circumstances is therefore present as Fe²⁺. Where such water comes into contact with atmospheric oxygen, the ferrous iron is rapidly oxidized to insoluble ferric oxides and hydroxides:



Hence the rapid deposition of rust coloured precipitates on pipes, fittings and tanks: the reaction requires only 1 molecule of oxygen for precipitation of 4 molecules of ferric hydroxide.

Deposition of insoluble ferric species had two effects at Greens Beach:

- rust-brown precipitates formed on the P.V.C. discharge pipe.
- the grass beneath the discharge pipe turned brown and died after the 13-day pump test. This is because a film of particulate Fe(OH)₃ and Fe₂O₃ clogged stomatal pores and prevented photosynthesis. This seemingly drastic effect is unlikely to be repeated in domestic gardens or golf course greens because most of the iron will have been deposited in holding tanks and pipes, no lawn will be subjected to 13 days continuous watering, and any Fe(OH)₃ precipitate which does form will be leached by natural rain-water between successive groundwater irrigations.

Obviously, then, the groundwater from the test site contains more iron than is reported in the analyses, and its presence will constitute a nuisance to the water distributors. Advantage should be taken of this ability of the iron to rapidly oxidise and precipitate by aerating the water at the extraction site, or elsewhere in the reticulation system, possibly into temporary tanks. The tanks may then be economically replaced if iron precipitation retards their efficiency. It will take some time before the true nuisance effect of this dissolved constituent can be gauged.

Hardness

Hardness (simply, the soap-wasting effect of the water) is caused by bicarbonates, chlorides, sulphates and nitrates of calcium and magnesium. All are relatively soluble, but boiling or heating the water reduces the bicarbonates to insoluble carbonates, causing the release of CO₂ and the deposition of a calcium and magnesium carbonate encrustation in domestic appliances, including kettles and hot water cylinders.

Temporary hardness is caused by these insoluble carbonates. Permanent hardness is due to the presence of the remaining chlorides, nitrates and sulphates. Although most of the Greens Beach water analyses do not distinguish between the two, some of the earlier results from the test site

show that the hardness is almost entirely temporary (>90%) and will be removed by boiling. This presents a problem to consumers (where the effect will be most noticeable in hot water cylinders), but the overall effect can only be determined by experience.

The Greens Beach water is hard according to recommended standards where 50 - 150 mg/l is not considered objectionable, and values greater than 150 mg/l are 'decidedly noticeable'. If hardness exceeds 200 - 300 mg/l, municipal supplies are often softened to less than 100 mg/l.

Dissolved hydrogen sulphide

Any odour of H₂S in domestic water supplies is objectionable, and concentrations of < 1 mg/l are easily detectable. Fortunately the gas rapidly escapes as soon as the pressure on the groundwater is released during pumping, and no problems are envisaged in this regard.

The gas is a common if minor constituent of many groundwaters, where it forms from two sources: the anaerobic decay of organic matter in the sediments, and the reduction by anaerobic bacteria of sulphates to sulphides. Both these processes probably occur at Greens Beach, but their effect may decrease with time as the aquifer is subjected to successive 'flushings' by long-term pumping.

Domestic water use - experience during the 13-day pump test

Untreated groundwater extracted directly from the pump outlet was used by Mines Department personnel during the 13-day pump test. Some observations on water quality were:

- For drinking, the water had a very slight but unobjectionable taste.
- It was colourless and free from suspended material.
- There was no detectable smell of H₂S.
- The water lathered less easily than most because of its high hardness. In practise, more soap is needed to produce a lather, which only forms after most of the hardness-forming constituents have reacted with the soap and precipitated.
- Water boiled in kettles and pots produced a CaCO₃ - MgCO₃ encrustation on these appliances (especially on the heating element in the kettle). The precipitate was easily removed from pots by washing, but that in kettles and hot water cylinders will cause a problem to consumers.
- No precipitates of ferric hydroxide or oxide were observed; clothes washed in the water were not stained.

EFFECT ON GARDENS AND THE GOLF COURSE

Total dissolved solids

High salinity causes an increase in the osmotic pressure of the soil solution, resulting in a decreased availability of nutrients for the plant roots. The water at Greens Beach is a 'medium-salinity water' (in the T.D.S. range 175 - 500 mg/l; conductivity 280 - 800 µS/cm) and as such can be used if a moderate leaching rate occurs in the soil. This can be expected with most of the sandy soils in the district, and no problems are

envisaged. Sprinkler irrigation may cause leaf-burn on salt-sensitive crops during high daytime temperatures.

Sodium

Accumulation of sodium ions in the soil may have adverse effects on soil structure and permeability. The Greens Beach groundwater is a low-sodium water with a sodium absorption ratio (S.A.R., Appendix 8) of about 1.5. Such a value will cause no problems with gardening and irrigation.

Bicarbonate

Evapotranspiration from soils irrigated with high bicarbonate water often causes precipitation of the insoluble calcium and magnesium carbonates. Such a reduction in Ca and Mg concentration will cause a corresponding rise in the S.A.R. value, and may produce a hazard where none existed before: *i.e.* there is a relationship between bicarbonate hazard and S.A.R. Residual sodium carbonate (R.S.C., Appendix 8) describes the bicarbonate hazard: waters with R.S.C. >2.5 meq/l are not suitable for irrigation, and those between 1.25 - 2.5 meq/l are marginal. Waters with R.S.C. <1.25 are probably safe, and the Greens Beach water (<0.4) will therefore cause no problems in this regard.

Chloride

Excess chloride has an adverse effect on sensitive fruit crops, but the Greens Beach water is acceptable in this regard.

Iron

The effect of precipitated ferric hydroxide and oxide on plants has already been discussed. Most of the iron will have been removed prior to or during reticulation (which itself will be a nuisance) and the remaining dissolved ferrous iron (<0.1 mg/l) will have no adverse effects during irrigation.

BIOLOGICAL QUALITY

A sample of the groundwater collected during a pump test in June 1977 was analysed for deleterious bacterial constituents by the Department of Agriculture in Launceston (Table 9). (The bacterial colony count for a single sample is of little use in itself, and sampling in future should be made on a regular basis). It is difficult to obtain information on commonly accepted bacterial criteria for Tasmania drinking water. Those limits included in Table 9 are derived from Hart (1974) who apparently bases his recommendations on United States health requirements and various other published sources. From the analysis it seems that the water from the test site is suitable for human consumption, but a comparison with other Tasmanian drinking water is lacking.

SUMMARY OF WATER QUALITY

The water from the test site, and presumably all the water in the aquifer, is a medium-salinity, hard, but probably non-corrosive groundwater. The average salinity is 510 mg/l, which is not expected to vary greatly with time. The water is suitable for drinking, general domestic, gardening and irrigation uses, but some of the dissolved constituents will have an adverse effect on consumer acceptability. The hardness of the water is high and will cause encrustations in kettles and hot water cylinders. It may therefore be necessary to soften the supply to reduce this factor to acceptable levels (<100 mg/l). The total iron content will cause problems

Table 9 BACTERIAL ANALYSIS OF GREENS BEACH GROUNDWATER

Collected: 1200 hours, 8.6.1977, 22 hours after pumping started.
 Analysed: 1520 hours, 8.6.1977, Lab. No. 77/276.

	Greens Beach	Recommended maximum levels for untreated water (Hart, 1974).
Colony count per ml		
37°C	<1	0
20-22°C	160	500 ²
Coliform count/100 ml (MF) ¹	<2	3
<i>E.coli</i> count/100 ml (MF)	<2	0
Faecal streptococcus count/100 ml (MF)	<1	0

1. Membrane filter method
2. Recommended United State drinking water standard for treated water.

in the reticulation system unless the water is aerated before hand. The resulting dissolved iron content of <0.1 mg/l will be acceptable to consumers.

Biologically, the groundwater is apparently acceptable for human consumption, although it would be wise to periodically sample the supply to ensure the absence of deleterious constituents. Unconsolidated sand is an excellent filter of bacterial organisms, and no contamination is expected near the test site.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The existing 12-bore array at Greens Beach is capable of yielding 350 m³/day for long periods. Additional arrays will be able to produce similar yields but such a pumping regime mines the groundwater, lowers water-tables and causes long-term deficits. Water balance estimates suggest instead that if the resource is to be a permanent supply then groundwater reserves should remain virtually untouched, and that if properly monitored and wisely managed the aquifer is able to supply an average yield of at least 180 m³/day, but at the most 600 m³/day. These figures cannot be considered precise: they will almost certainly require revision as pumping and further studies continue. Nevertheless it is clear that the aquifer will not be able to sustain future maximum peak demands of 2500 m³/day and that supplementary sources of groundwater should be considered. In this regard the area to the south of Badger Beach may be a promising aquifer, but studies show the water may be of poorer quality, and the sediments of lower permeability.

Despite its disadvantages of small size and yield, the Greens Beach aquifer should not be abandoned. The water it contains is of relatively good quality, it lies at shallow depth and is cheaply and easily extracted by simple methods, the site is readily accessible and the existing

array is capable of supplying the present needs of Greens Beach and Kelso. If an extra array is sited near the rear of the dunes to more evenly load the water table, then the two arrays pumping together at perhaps 500 - 600 m³/day and coupled to a surface storage dam would supply the two towns for many years.

ACKNOWLEDGEMENTS

Many people helped in the field investigations and spear installations during the two year period up to and including the final 13-day pump test on the existing bore array. In particular I acknowledge the field assistance of geologist D.J. Sloane. My colleague D.E. Leaman analysed in detail some aspects of the pump test results. The help given by D. Partridge and G. Murray (Rivers and Water Supply Commission) at all stages of the investigations was greatly appreciated. G. Spaulding (Monopumps Pty Ltd, Devonport) loaned an electric pump for the 13-day pump test.

REFERENCES

- AUSTRALIA: BUREAU OF METEOROLOGY. 1973. Climatic Survey, Northwest, Region 1, Tasmania. AGPS : Canberra.
- BENTALL, R. (comp.). 1963a. Methods of determining permeability, transmissivity and drawdown. *Wat.Supply Pap.U.S.geol.Surv.* 1536-I.
- BENTALL, R. (comp.). 1963b. Shortcuts and special problems in aquifer tests. *Wat.Supply Pap.U.S.geol.Surv.* 1545-C.
- BOULTON, N.S. 1963. Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage. *Proc.Instn Civ.Engrs* 26: 469-482.
- BOWDEN, A.R. 1978. Geomorphic perspective on shallow groundwater potential, coastal north-eastern Tasmania. *Tech.Pap.Aust.wat.Resour.Counc.* 36.
- CROMER, W.C. 1974. Groundwater prospects, Greens Beach. *Unpubl.Rep.Dep. Mines Tasm.* 1974/32.
- CROMER, W.C. 1977. Groundwater investigations, Chinamans Bay, Maria Island. *Unpubl.Rep.Dep.Mines Tasm.* 1977/52.
- CROMER, W.C.; SLOANE, D.J. 1976. Geology and hydrology of the Tertiary and Quaternary sediments near Greens Beach, northern Tasmania. *Unpubl.Rep. Dep.Mines Tasm.* 1976/24.
- FERRIS, J.G.; KNOWLES, D.B.; BROWN, R.H.; STALLMAN, R.W. 1962. Theory of aquifer tests - groundwater hydraulics. *Wat.Supply Pap.U.S.geol.Surv.* 1536-E:69-174.
- GEE, R.D.; LEGGE, P.J. 1971. Geological atlas 1 mile series. Zone 7 sheet 30 (8215N). Beaconsfield. *Department of Mines, Tasmania.* [2 ed. 1979].
- GLOVER, H.H. 1964. The pattern of fresh water flow in a coastal aquifer. *Wat.Supply Pap.U.S.geol.Surv.* 1613-C:32-35.
- HART, B.T. 1974. A compilation of Australian water quality criteria. *Tech.pap.Aust.wat.Resour.Counc.* 7.
- HAZEL, C.P. 1973. *Lecture notes on groundwater hydraulics, Australian Water Resources Council 1973 Groundwater School.* Irrigation & Water Supply Commission, Queensland.
- HEM, J.D. 1959. Study and interpretation of the chemical characteristics of natural water. *Wat.Supply Pap.U.S.geol.Surv.* 1473. [2 ed., 1970].

- JACOB, C.E. 1963. Correction of drawdowns caused by a pumped well tapping less than the full saturated thickness of an aquifer. *Wat. Supply Pap.U.S.geol.Surv.* 1536-I:272-282.
- LANGFORD, R.H. 1964. The chemical quality of the groundwater, in WHITCOMB, H.A.; MORRIS, D.A. Ground-water resources and geology of northern and western Crook County, Wyoming. *Wat.Supply Pap.U.S.geol.Surv.* 1698:52-78.
- LOHMAN, S.W. 1972. Ground-water hydraulics. *Prof.Pap.U.S.geol.Surv.* 708.
- LOHMAN, S.W. and others. 1972. Definitions of selected ground-water terms - Revisions and conceptual refinements. *Wat.Supply Pap.U.S.geol.Surv.* 1988.
- PLUHOWSKI, E.J.; KANTROWITZ, I.H. 1964. Hydrology of the Babylon - Islip area, Suffolk County, Long Island, New York. *Wat.Supply Pap.U.S.geol.Surv.* 1768.
- SUTHERLAND, F.L. 1971. The geology and petrology of the Tertiary volcanic rocks of the Tamar Trough, northern Tasmania. *Rec.On Vict.Mus.* 36.

Appendices 1-10

APPENDIX 1

Geological logs of augered holes and drilled bores in the Greens Beach-Kelso area.

Locations are shown in Figure 3. All depths are in metres. Unless otherwise indicated all holes were logged by W.C. Cromer and D.J. Sloane.

Hole 1. [789516]

- 0-2.0 Buff medium- to fine-grained Holocene aeolian quartz sand. Contains small fragmented shell particles, including sponge spicules and gastropods.
- 2.0-3.7 Buff-brown medium-grained marine quartz sand. Increased shell content.
- 3.7-9.0 Grey medium-grained marine quartz sand. Small gastropods and bivalves present. Grain size and shell content decreases after 7 m.
- 9.0-9.2 Sticky green-brown clay containing rounded quartzite pebbles (up to 50mm) and wood fragments.
- 9.2-10.0 Brown carbonaceous clays. Wood and charcoal fragments common.
- 10.0-11.0 Coarse-grained shelly quartz sand containing rounded quartzite pebbles (up to 30 mm).

Hole 2. [789514]

- 0-9.6 Thin (less than 0.7 m) veneer of medium- to fine-grained buff Holocene aeolian quartz sand overlying fawn-buff medium-grained shelly marine quartz sand. After 4 m, a colour change to grey-yellow quartz sand. Shell content increases.
- 9.6-14.6 Interbedded green-blue clay, and rounded quartzite gravels (containing pebbles up to 60 mm in diameter).

Hole 3. [785510]

- 0-1.0 Medium-grained grey-brown slightly clayey Tertiary(?) quartz sand.
- 1.0-2.0 Sandy blue-yellow clay.
- 2.0-9.0 Clayey medium-grained brown quartz sand.
- 9.0-15.0 Medium-grained grey-brown quartz sand; slightly clayey; some partly cemented dark brown sandy fragments.

Hole 4. [797514]

- 0-14.6 Slightly clayey medium- to fine-grained brown quartz sand. Colour becomes greyer and clay content increases near 2 m. Shell fragments absent above 4 m. Rare rounded quartzite pebbles present near 4-5 m, becoming more common with depth; sand approaches a fine quartzite grit between 12 and 14.6 m.

Hole 5. [794518]

- 0-3.7 Yellow-buff medium- to fine-grained Holocene aeolian quartz sand; small gastropod, bivalve and sponge spicule fragments present. CaCO₃ concretions at water table. Grain size increases slightly near 2.7 m.

Hole 5. (continued)

- 3.7-11.0 Grey medium-grained shelly marine quartz sand, containing occasional rounded quartzite pebbles and increased shell content near 10 m.
11.0-14.6 Clean fine angular quartzite and quartz grit; fragments up to 10 mm in diameter. Shells absent.

Hole 6. [799522]

- 0-3.0 Yellow-buff medium- to fine-grained Holocene aeolian quartz sand. Grain size and shell content increases slightly after one metre.
3.0-5.0 Grey medium-grained shelly marine quartz sand, becoming greyer, more shelly and coarser below 4.3 m. Small amounts of well-rounded yellow-white quartzite pebbles up to 10 mm across. Grades into grey sandy grit near 5 m.
5.0-5.2 Sticky blue-green clay.
5.2- Drilling hard. Probably Tertiary basalt or boulders

Hole 7. [803518]

- 0-1.0 Medium- to fine-grained dark yellow-brown Holocene aeolian quartz sand.
1.0-4.0 Coarser grained shelly quartz sand.
4.0- Solid bottom. Probably Tertiary basalt or boulders.

Hole 8. [807516]

- 0-1.3 Fine-grained buff Holocene aeolian quartz sand. Hard shelly and quartz pebble band at 1.3 m.
1.3-2.3 Green shelly clay.
2.3- Solid bottom. Probably Tertiary basalt or boulders.

Hole 9. [808514]

- 0-0.3 Buff quartz-pebble sand.
0.3-1.0 Mottled yellow-brown clay containing basalt pebbles.
1.0- Tertiary basalt or boulders

Hole 10. [810511]

- 0-1.1 Very fine silt overlying clay containing basalt fragments.
1.1- Tertiary basalt or boulders.

Hole 11. [812508]

- 0-1.1 Mottled grey-brown sandy clay.
1.1- Tertiary basalt or boulders.

Hole 12. [808506]

- 0-0.3 Medium to fine buff-grey organic quartz sand.
0.3-1.0 Mottled yellow, brown and grey sandy clay.
1.0-1.3 Grey-brown clayey sand.
1.3-2.0 Mottled clay containing rounded quartzite and weathered basalt pebbles. Some relict textures present.
2.0-2.5 Very sandy yellow-brown clay containing rounded quartzite and basalt pebbles.
2.5- Tertiary basalt or boulders.

Hole 13. [809501]

- 0-0.3 Grey sandy A₁ soil horizon.
- 0.3-2.0 Yellow-brown sandy clay.
- 2.0-3.0 Medium-grained slightly clayey quartz sand containing rounded quartzite pebbles (up to 50 mm). Clay content increases with depth.
- 3.0-11.0 Clayey yellow quartz-pebble sand becoming coarser with depth, and containing angular coarse sand-size quartzite fragments.
- 11.0-12.2 Grey-green clay containing quartz and basalt gravel horizons and wood fragments.
- 12.2-14.0 Grey clayey sand with quartzite pebbles (up to 50 mm).
- 14.0- Vesicular Tertiary basalt.

Hole 14. [764508]

- 0-4.6 Dark brown-grey clayey quartz sand, becoming sandier near 4.6 m.
- 4.6-6.4 Grey-green stiff clay containing relict textures of Jurassic dolerite.

Hole 15. [770504]

- 0-0.2 Dark yellow-brown sandy and organic A₁ horizon
- 0.2-1.0 Dark yellow-brown sandy clay.
- 1.0-2.0 Bright yellow-brown sticky sandy clay grading at 2 m into very sticky clayey quartz sand.
- 2.0-2.3 Sticky pale grey clayey quartz sand.
- 2.3-6.4 Pale yellow-brown clayey quartz sand containing grit-sized angular quartzite and dolerite fragments. Distinct colour change at about 4 m, together with decrease in clay content, to produce grey-brown medium-grained slightly clayey quartz sand. Small shell and charcoal fragments present; as well as small amounts of quartzite grit. Sand poorly sorted, moderately rounded.
- 6.4-10.4 Sticky dark green clayey quartz sand with rare rounded quartzite pebbles (up to 10 mm).
- 10.4-11.0 Relatively consolidated pale grey clayey quartz sand; high percentage of rock fragments. Probably weathered Precambrian (?) basement.

Hole 16. [778504]

- 0-0.2 Dark brown partly calcareous and sandy A₁ horizon
- 0.2-1.0 Yellow-brown clayey soil profile.
- 1.0-3.0 Dark yellow-brown sticky sandy clay.
- 3.0-12.8 Grey medium- to fine-grained slightly clayey sand.
- 12.8-14.6 Stiff grey-brown-orange sandy clay.

Hole 17. [805502]

- 0-1.3 Pale grey-brown medium-grained gritty Tertiary quartz sand.
- 1.3-2.3 Dark brown medium-grained slightly clayey quartz sand; becoming more orange in colour near 2.3 m.
- 2.3-3.1 Clayey grey-pale green quartz sand. Possibly contains quartzite pebbles.
- 3.1-3.2 Sticky dark green mottled and textured clay with angular fragments of fine-grained dark grey and unweathered Tertiary basalt. Clay may be weathered basalt. Drilling hard; stopped at 3.2 m by dolerite(?)

Hole 18. [798512]

- 0-0.5 Brown-black sandy A₁ horizon.
- 0.5-1.0 Dull yellow-brown sandy A₂ horizon.
- 1.0-1.5 Iron-stained clayey quartz sand.
- 1.5-2.5 Coarse quartz gravel; well rounded pebbles up to 50 mm.
- 2.5-3.0 Dark brown-black coarse angular quartz sand and fine gravel.
- 3.0-4.0 No recovery.
- 4.0-5.0 Coarse-grained quartz sand.
- 5.0-5.5 Drilling hard. Clay?
- 5.5-6.5 Coarse-grained and gritty angular quartz sand.
- 6.5-7.3 Quartzite gravel.
- 7.3-10.7 Angular quartz sand.
- 10.7-11.6 Quartzite gravel.
- 11.6- Hard drilling. Green, blue and grey clay containing rounded quartzite and dolerite(?) pebbles. Relict textures present in clay. Weathered basement?

Hole 19. [801508]

- 0-6.1 Brown and yellow quartz sand; well-rounded quartzite pebbles at 6 m.
- 6.1-7.3 Weathered Tertiary basalt (?) boulders.
- 7.3- Dolerite (?)

Hole 20. [791506]

- 0-0.2 Brown-black organic and sandy A₁ horizon.
- 0.2-6.0 Brown-greyish yellow, in places clayey, quartz sand.
- 6.0-6.3 Green-grey very sandy clay.
- 6.3-14.6 Quartz sand.

Hole 21. [777507]

- 0-1.7 Dull yellow-brown quartz sand.
- 1.7-10.7 Olive green-grey sandy clay and clays.

Hole 22. [772509]

- 0.1-0.6 Fine-grained light grey quartz sand.
- 0.6-11.0 Dull yellow-brown quartz sand.
- 11.0- Brown clayey sand; coarse in places; well cemented, with rare dolerite pebbles.

Hole 23. [778498]

- 0-3.0 Dark brown quartz sand.
- 3.0-11.0 Dull yellow-orange medium-grained quartz sand.
- 11.0- Sandy grey and blue and green clay.

Hole 24. [760500]

- 0-1.0 Dark black-brown silty A₁ horizon
- 1.0-2.4 Clayey sand.
- 2.4-3.7 Mottled grey and white plastic clay.
- 3.7-8.3 Mottled brown, yellow and white sandy clay; well rounded quartzite pebbles struck at 5.5 m.

Hole 25. [770497]

- 0-4.0 Medium-grained quartz sand.
- 4.0-5.5 Grey clayey sand.
- 5.5-9.2 Grey quartz sand.

Hole 26. [774496]

- 0-6.4 Grey clayey quartz sand; clay content increases near 6 m.
- 6.4-10.1 Clay at 7.5 m; predominantly medium-coarse grained clayey sand containing grit-sized angular quartzite fragments.

Hole 27. [782492]

- 0-0.5 Dark grey-brown silty A₁ horizon.
- 0.5-3.7 Yellow-brown clay.
- 3.7-12.0 Grey medium-coarse grained quartz sand, becoming brown/yellow after 7 m. Grey sandy clay present at 9.5 m.

Hole 28. [775525]

- 0-1.5 Grey, yellow and brown fine-grained quartz sand.
- 1.5-2.0 Yellow-brown and in places mottled, sandy clay.
- 2.0- Hard drilling. Probably dolerite.

Hole 29. [771525]

- 0-3.7 Brown mottled sandy clay.
- 3.7- Jurassic dolerite.

Hole 30. [768529]

- 0-1.0 Brownish-grey quartz sand.
- 1.0-2.0 Yellow-brown mottled clayey sand.
- 2.0-5.5 Bright yellow-brown aeolian quartz sand.
- 5.5- Solid bottom.

Drilled bore 1. [794518] See Appendix 8

Drilled bore 2. [793517] See Appendix 8

Drilled bore 3. [811499]

- 0-1.52 Sand.
- 1.52-9.14 Clay.
- 9.14-12.0 Stiff-textured green clay.
- 12.0-35 Hard Tertiary basalt; vesicular in places.

Drilled bore 4. [809500]

- 0-14 Sand and clay.
- 14-50 Tertiary basalt.

Drilled bore 5. [789516] Logged by D. J. Sloane

- 0-1.5 Aeolian sand.
- 1.5-9 Shelly marine sand.
- 9-14.8 Brown-black to grey-brown micaceous clayey silt, rich in plant fragments. Zone of rounded quartzite pebbles at 9 m.

Drilled bore 5. (continued)

- 14.8-17.6 Brown-grey muddy siltstone. Minor plant fragments and pyrite nodules.
- 17.6-23.2 Brown-grey fine silty sand. Minor plant fragments; some quartz sand particles up to 0.4 mm.
- 23.2-23.9 Fine clayey sand with up to 50% organic matter.
- 23.9-25.1 Dark brown sandy clay and fine sand with minor organic matter (<2%).
- 25.1-31.9 Moderately to deeply weathered coarse-grained Jurassic dolerite.

Drilled bore 6. [813508] (Drilled and logged by Monopumps Pty Ltd (Devonport); June 1978)

- 0-0.3 Loam.
- 0.3-4 Clay.
- 4-5.5 Boulders.
- 5.5-11 Clay.
- 11-36 Basalt with cavities.

Water was struck at 11, 16, 31 and 36 m. yield about 65 l/min. Salinity about 1500 mg/l. Bore operating; cased 0-14 m.

Drilled bore 7. [812510] (Drilled and logged by Monopumps Pty Ltd (Devonport); June 1978)

- 0-0.3 Loam.
- 0.3-4.5 Clay.
- 4.5-6.5 Boulders.
- 6.5-16 Basalt.

Yield about 15 l/min; salinity about 7000 mg/l. Abandoned.

Drilled bore 8. [816509] (Drilled and logged by Monopumps Pty Ltd (Devonport); June 1978)

- 0-3 Sand.
- 3-10 Basalt.

Yield about 4 l/min; salinity about 250 mg/l.

APPENDIX 2

Wells in the Kelso area.

	Owner	Grid reference	Date dug	Depth (m)	Standing water level ¹ (m)	Quality (mg/l TDS ²)
1	J.S. Beams	827493	1970	4.3	3.1	1000
2	H.B. Roberts	824498	n.d.	2.1	1.5	1150
3	A. Milner	824498	n.d.	1.8	1.1	800
4	T. Mason	823498	n.d.	1.4	0.8	450
5	J. Gimpl	823499	n.d.	2.4	1.4	550
6	T.E. Parkinson	823499	n.d.	2.3	n.d.	n.d.
7	R. Smith	823500	n.d.	2.6	1.3	1500
8	G. Bealey	823501	pre 1900	2.7	2.1	600
9	H. Schell	822502	1968	2.4	1.8	250
10	B. Moy	822502	n.d.	3.1	2.1	n.d.
11	K.C. Herbett	822502	n.d.	2.4	2.0	75
12	J.A. Dunn	822502	n.d.	2.1	1.5	300
13	G. Stewart	822502	n.d.	n.d.	n.d.	n.d.
14	R.L. Eadie	822503	n.d.	2.6	2.0	360
15	B. Malvern	822503	n.d.	2.6	2.0	250
16	K. Banfield	822503	1975	2.9	2.2	250
17	J. Whybrow	822505	c.1956	3.1	2.1	400
18	A. Black	822505	1976	2.0	n.d.	n.d.
19	B. Butler	822505	1976	2.4	2.1	n.d.

Approximate safe yield (l/min)	Status	Geology	Remarks
10	Operating	0.1 m: sand, 1-1.5 m clay. 1.5-4.3 m: weathered basalt.	Concrete liners, 1.3 m in diameter; domestic and gardening purposes, excluding drinking.
3	Operating	0-2.1 m: sand, 2.1 m basalt.	General gardening purposes; concrete liners 1.3 m dia.
<5	Disused	0-1.8 m: sand, 1.8 m, weathered basalt.	General gardening purposes.
10	Operating	0-1.4 m shelly sand.	General gardening purposes.
10	Operating	0-2.4 m: shelly sand, green shelly clay, 2.4 m basalt.	General gardening purposes. Concrete lined, 1.3 m diameter; drawdown 0.3 m after 10 minutes at 35 l/min.
n.d.	Abandoned	0-2.3 m: brown sand, shelly clay.	Hole collapsed during excavation.
n.d.	Operating	n.d.	General gardening purposes; high TSS ³ : steel lined 0.6 m diameter.
n.d.	Disused	n.d.	Concrete lined 2 m diameter, high TSS. Probably bottomed in basalt.
5	Operating	0-2.4 m: brown-yellow sand.	General gardening purposes.
n.d.	Operating	n.d.	Concrete lined, 1.5 m dia; sandy bottom. General gardening and domestic uses, excluding drinking.
n.d.	Operating	0-2.4 m: sand.	General gardening purposes; concrete lined 1.4 m diameter. Probably diluted by rainwater.
n.d.	Operating	0-2.1 m: sand.	Concrete lined, 1.3 m dia.
n.d.	Operating	n.d.	Well secured.
<5	Operating	0-2.6 m: sand	Concrete lined, 1.3 m dia. Gardening purposes.
n.d.	Operating	0-2.6 m: sand	Concrete lined, 1.3 m dia. Gardening purposes.
n.d.	Operating	0-2.9 m: sand	Concrete lined tank 2 m ² with well at base.
n.d.	Operating	0-3.1 m: sand	
n.d.	Operating	0-2.0 m: sand; shells at base.	
n.d.	Operating	0-2.4 m: sand; shells at base.	

	Owner	Grid reference	Date dug	Depth (m)	Standing water level ¹ (m)	Quality (mg/l TDS ²)
20	G. O'Brien	822506	1976	3.1	2.4	420
21	W. Goer	821506	c.1960	2.2	2.0	420
22	E. Cornish	821506	1970	2.6	2.4	450
23	n.d.	819509	n.d.	n.d.	n.d.	n.d.
24	J. Squires	816498	c.1900	4.6	3.4	200
25	Comm. of Aust.	817494	c.1940	7.0	1.7	6500
26	J. Squires	825493	c.1870	6.1	3.1	300
27	L. Reid	823488	1968	3.1	1.5	150
28	V. Saboonskas	823488	1966	3.4	2.3	100

Approximate safe yield (l/min)	Status	Geology	Remarks
n.d.	Operating	0-3.1 m: sand; 3.1 m wood fragments.	Concrete lined 1.3 m dia- meter; gardening purposes.
n.d.	Operating	n.d.	Gardening purposes.
n.d.	Disused	0-2.6 m: sand	
n.d.	n.d.	n.d.	Well secured
5-10	Disused	0-4.6 m: basalt boulders.	Occasionally used for gard- ening purposes; unlined 3 m diameter.
n.d.	Disused	n.d.	Timber lined, 1.3 m dia- meter; occasionally used for cattle.
n.d.	Abandoned	0-6.1 m: basalt boulder beds	Unlined, 2.4 m diameter; solid basalt at base.
n.d.	Operating	0-3.2 m: sand	
n.d.	Abandoned	0-3.4 m: sand.	

Notes:

¹As of April 1976. Owners of wells generally state that water levels rise to ground level during winter.

²Measured by portable conductivity meter in the field.

³TSS = Total suspended solids.

n.d. = Not determined.

APPENDIX 3

Wells in the Greens Beach area.

	Owner	Grid reference	Date dug	Depth (m)	Standing water level ¹ (m)	Quality (mg/l TDS ²)
1	Beaconsfield Council	786515	1974	3	2	440
2	Edwards	783514	n.d.	1.3	0.6	n.d.
3	McGee	788512	n.d.	4.3	2.9	n.d.
4	Thorn	783514	c.1956	2.5	0.5	6000
5	Shaw	782514	n.d.	n.d.	n.d.	n.d.
6	n.d.	780523	n.d.	n.d.	n.d.	n.d.

Approximate safe yield (l/min)	Status	Geology	Remarks
12-15	Operating	0-3 m Quaternary aeolian and marine sand.	Concrete lined, 1.3 m dia. Supplies toilets in caravan park. TDS = 370 mg/l in April 1974. Water apparently contains small amounts of faecal coliforms.
n.d.	Operating		Apparently supplements council supply to caravan park.
n.d.	Operating	0-1 m sand; 1-4.3 m dolerite boulders and clay.	Concrete, 1.3 m diameter; gardening purposes. Water table rises to surface during wet months.
n.d.	Operating	0-2.5 m white sand.	Also supplements council supply to caravan park. General gardening uses.
n.d.	n.d.	n.d.	Owner absent; well not located.
n.d.	n.d.	n.d.	Well secured; owner absent.

Notes:

¹As of April 1976. Water levels fluctuate annually.

²Measured by portable conductivity meter in the field.

n.d. = not determined.

APPENDIX 4

Chemical analyses¹ of water in Quaternary sediments at Greens Beach

Constituent	752114 ² 15/12/75 ³			760549 6/4/76			760348 24/2/76		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
Silica (SiO ₂)	5	-	-	<5	-	-	8	-	-
Iron (Fe)	0.4	0.01	0.07	0.2	0.00	0.0	<0.1	0.0	0.0
Calcium (Ca)	84	4.19	32.4	95	4.74	29.1	76	3.79	14.8
Magnesium (Mg)	22	1.81	14.0	17	1.40	8.6	22	1.81	7.1
Sodium (Na)	16	0.70	5.41	45	1.96	12.0	160	6.96	27.1
Potassium (K)	2.0	0.05	0.39	2.4	0.06	0.37	8	0.20	0.78
Bicarbonate (HCO ₃)	340	5.57	43.1	290	4.76	29.2	330	5.41	21.1
Sulphate (SO ₄)	<5	<0.1	<0.8	29	0.61	3.7	35	0.73	2.84
Chloride (Cl)	21	0.59	4.56	95	2.66	16.3	240	6.77	26.4
Total dissolved solids	360	12.9		540	16.3		730	25.7	
Permanent hardness (as CaCO ₃)	20			67			10		
Temporary hardness (as CaCO ₃)	280			240			270		
Alkalinity (as CaCO ₃)	280			240			270		
pH	8.0			7.5			7.5		
% difference of anion and cation equivalents ⁴	5			1			0.6		
Per cent sodium ⁵	11			25			56		
Sodium adsorption ratio ⁶	0.4			1.1			4.2		

752114. Well, Greens Beach caravan park, [787517]

760549. Well, Greens Beach caravan park, [787517]

760348. Pump test, proline Hole 1 [789516], 50 minutes after pump started.

1. Analyses by Department of Mines Laboratory, Launceston.

2. Department of Mines registered number.

3. Sample collection date.

4. An indication of the accuracy of the analysis. Should approach zero if all major species have been determined.

Calculated: $100 \times (\text{difference of cation and anion meq/l}) / \text{total meq/l}$.5. $\text{Per cent Sodium} = \frac{100 \times (\text{Na} + \text{K})}{\text{Na} + \text{K} + \text{Ca} + \text{Mg}}$ (meq/l).6. $\text{S.A.R.} = \frac{\text{Na}}{\sqrt{\text{Ca} + \text{Mg}}}$ (meq/l).

Constituent	760349 24/2/76			760384 26/2/76			752115 17/12/75		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
Silica (SiO ₂)	10	-	-	13	-	-	3	-	-
Iron (Fe)	<0.1	0.0	0.0	<0.1	0.00	0.0	0.1	0.00	0.0
Calcium (Ca)	82	4.09	14.6	60	2.99	19.4	70	3.49	15.1
Magnesium (Mg)	24	1.97	7.04	18	1.48	9.6	24	1.97	8.53
Sodium (Na)	170	7.39	26.4	50	2.18	14.2	140	6.09	26.4
Potassium (K)	8	0.20	0.71	3.1	0.08	0.52	3.5	0.09	0.4
Bicarbonate (HCO ₃)	340	5.57	19.9	305	5.00	32.5	330	5.41	23.4
Sulphate (SO ₄)	42	0.87	3.11	13	0.27	1.8	5	0.11	0.5
Chloride (Cl)	280	7.90	28.2	120	3.36	21.8	210	5.88	25.5
Total dissolved solids	800	28.0		480	15.4		670	23.1	
Permanent hardness (as CaCO ₃)	24			} 220			5		
Temporary hardness (as CaCO ₃)	280				270				
Alkalinity (as CaCO ₃)	280			250			270		
pH	7.6			7.4			8.2		
% difference of anion and cation equivalents	2.5			12			1		
Per cent sodium	56			33			53		
Sodium adsorption ratio	4.2			1.5			3.7		

67
760349. Pump test, proline Hole 1, 400 minutes after pump started.

760384. Pump test, proline Hole 5 [794518], 60 minutes after pump started. Al <0.2 mg/l.

752115. Lagoon in sand dunes, [795520].

APPENDIX 5

Chemical analyses of water in Tertiary(?) sediments near Greens Beach

Constituent	760550 7/4/76			760350 25/2/76			760385 25/2/76		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
Silica (SiO ₂)	30	-	-	29	-	-	76	-	-
Iron (Fe)	3.5	0.13	0.38	0.9	0.03	0.32	8.6	0.31	4.90
Calcium (Ca)	18	0.90	2.67	15	0.75	4.86	13	0.65	6.93
Magnesium (Mg)	44	3.61	10.7	21	1.73	11.2	17	1.40	14.9
Sodium (Na)	270	11.8	34.9	110	4.79	31.1	50	2.18	23.2
Potassium (K)	4.3	0.11	0.29	4	0.10	0.65	2	0.05	0.53
Bicarbonate (HCO ₃)	42	0.69	2.0	41	0.67	4.35	94	1.54	16.4
Sulphate (SO ₄)	95	2.00	5.9	<5	<0.1	<0.65	<5	<0.1	<0.1
Chloride (Cl)	520	14.6	43.2	260	7.33	47.6	110	3.10	33.0
Total dissolved solids	1210	33.8		520	15.4		350	9.23	
Permanent hardness (as CaCO ₃)	190			90					
Temporary hardness (as CaCO ₃)	34			33					
Alkalinity (as CaCO ₃)	34			33					
pH	6.6			6.0			6.2		
% difference of anion and cation equivalents	2			4			0.5		
Per cent sodium	72			66			52		
S.A.R.	7.8			4.3			2.1		

760550. Pump test, proline Hole 3 [785510], 5 minutes after pump started. Al = 9 mg/l.
760350. Pump test, proline Hole 15 [770504], 10 minutes after pump started. Al = 1.3 mg/l.
760385. Pump test, proline Hole 16 [778504], 35 minutes after pump started. Al = 1.5 mg/l.

Constituent	760551 7/4/76			760552 6/4/76			752113 15/12/76		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
Silica (SiO ₂)	15	-	-	14	-	-	10	-	-
Iron (Fe)	3.7	0.13	0.87	6.9	0.25	2.40	1	0.05	0.27
Calcium (Ca)	30	1.50	10.1	6.2	0.31	2.98	24	1.20	6.58
Magnesium (Mg)	23	1.89	12.7	13	1.07	10.3	30	2.47	13.6
Sodium (Na)	85	3.70	24.8	80	3.48	33.5	120	5.22	28.6
Potassium (K)	2.2	0.06	0.4	2.5	0.06	0.58	6.9	0.18	0.99
Bicarbonate (HCO ₃)	83	1.36	9.1	23	0.38	3.65	91	1.49	8.17
Sulphate (SO ₄)	<5	<0.11	0.7	16	0.34	3.27	41	0.85	4.66
Chloride (Cl)	220	6.16	41.3	160	4.48	43.1	240	6.77	37.4
Total dissolved solids	580	14.9			10.4		660	18.23	
Permanent hardness (as CaCO ₃)	100						110		
Temporary hardness (as CaCO ₃)	68						75		
Alkalinity (as CaCO ₃)	68						75		
pH	6.4			5.6			6.8		
% difference of anion and cation equivalents	2			1			1		
Per cent sodium	53			72			59		
S.A.R.	2.8			4.2			3.9		
760551.	Pump test, proline Hole 19 [801508], 60 minutes after pump started.					Al = 7.1 mg/l.			
760552.	Pump test, proline Hole 20 [792506], 25 minutes after pump started.					Al = 13 mg/l.			
752113.	Spring in Tertiary sediments, Greens Beach [783514]. Al <0.2 mg/l.								

APPENDIX 6

Chemical analyses of water in Quaternary sediments at Kelso

Constituent	760564 (1)* 5/4/76			760554 (2) 5/4/76			760563 (3) 5/4/76		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l	mg/l	meq/l	meq/l
Silica (SiO ₂)	25	-	-	18	-	-	8.0	-	-
Iron (Fe)	<0.1	0.0	0.0	<0.1	0.0	0.0	<0.1	0.0	0.0
Calcium (Ca)	18	0.90	2.0	83	4.14	6.90	130	6.49	19.7
Magnesium (Mg)	12	0.99	2.2	43	3.53	5.88	27	2.22	6.73
Sodium (Na)	460	20.0	44.7	480	20.9	34.8	180	7.83	23.7
Potassium (K)	11	0.28	0.63	30	0.77	1.28	16	0.41	1.24
Bicarbonate (HCO ₃)	610	10.0	22.4	610	10.0	16.7	420	6.89	20.9
Sulphate (SO ₄)	77	1.62	3.6	230	4.83	8.05	170	3.57	10.8
Chloride (Cl)	390	10.9	24.4	420	11.8	19.7	200	5.6	17.0
06 Total dissolved solids	1320	44.7		1770	60.0		1050	33.0	
Permanent hardness (as CaCO ₃)	nil			nil			95		
Temporary hardness (as CaCO ₃)	94			380			340		
Alkalinity (as CaCO ₃)	500			500			340		
pH	8.0			7.9			7.5		
% difference of anion and cation equivalents	0.8			4.5			2.7		
Per cent sodium	91			74			49		
S.A.R.	21			11			3.8		

* Numbers in parentheses correspond to those in Appendix 2.

760564. Well at Kelso [827495].. J.S. Beams, owner Al <0.2 mg/l.
 760554. Well at Kelso [823498]. H. B. Roberts, owner Al <0.2 mg/l.
 760563. Well at Kelso [823498]. A. Milner, owner Al <0.2 mg/l.

T6

Constituent	760553 (4) 5/4/76			760555 (5) 6/4/76			760556 (7) 6/4/76		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
Silica (Si ₂)	<5	-	-	10	-	-	6.0	-	-
Iron (Fe)	<0.1	0.0	0.0	<0.1	0.0	0.0	0.5	0.02	0.03
Calcium (Ca)	100	4.99	19.7	105	5.24	20.4	88	4.39	7.43
Magnesium (Mg)	22	1.81	7.15	30	2.47	9.61	93	7.64	12.9
Sodium (Na)	120	5.22	20.6	120	5.22	20.3	400	17.4	29.4
Potassium (K)	10	0.26	1.03	5.7	0.15	0.58	30	0.77	1.3
Bicarbonate (HCO ₃)	330	5.41	21.4	380	6.23	24.2	480	7.87	13.3
Sulphate (SO ₄)	150	3.15	12.5	62	1.30	5.06	360	7.56	12.8
Chloride (Cl)	160	4.48	17.7	180	5.04	19.6	480	13.4	22.7
Total dissolved solids	750	25.3		770	25.7		1790	59.1	
Permanent hardness (as CaCO ₃)	70			75			210		
Temporary hardness (as CaCO ₃)	270			310			390		
Alkalinity (as CaCO ₃)	270			310			390		
pH		7.5			7.7			7.7	
% difference of anion and cation equivalents		3.0			2.0			2.3	
Per cent sodium		45			41			60	
S.A.R.		2.8			2.7			7.1	

760553.	Well at Kelso [823498]	T. Mason, owner	Al <0.2 mg/l
760555.	Well at Kelso [823499]	J. Gimpl, owner	Al <0.2 mg/l
760556.	Well at Kelso [823500]	R. Smith, owner	Al <0.2 mg/l

Constituents	760557 (8) 6/4/76			760558 (9) 6/4/76			760559 (16) 6/4/76		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
Silica (SiO ₂)	16	-	-	7.2	-	-	9.0	-	-
Iron (Fe)	0.2	0.01	0.0	<0.1	0.0	0.0	<0.1	0.0	0.0
Calcium (Ca)	120	5.99	21.3	76	3.79	31.2	83	4.14	33.8
Magnesium (Mg)	31	2.55	9.1	9.3	0.76	6.25	7.8	0.64	5.22
Sodium (Na)	120	5.32	18.9	25	1.11	9.13	23	1.02	8.33
Potassium (K)	6.8	0.17	0.6	3.3	0.08	0.66	1.2	0.03	0.25
Bicarbonate (HCO ₃)	340	5.58	19.8	320	5.25	43.2	300	4.92	40.2
Sulphate (SO ₄)	100	2.10	7.46	13	0.27	2.22	22	0.46	3.76
Chloride (Cl)	230	6.44	22.9	32	0.90	7.4	37	1.04	8.49
Total dissolved solids	940	28.2		360	12.2		390	12.3	
Permanent hardness (as CaCO ₃)	150			nil			nil		
Temporary hardness (as CaCO ₃)	280			230			240		
Alkalinity (as CaCO ₃)	280			260			250		
pH		7.9			7.9			7.7	
% difference of anion and cation equivalents		0.3			5.6			4.8	
Per cent sodium		39			21			18	
S.A.R.		2.6			0.74			0.66	

760557. Well at Kelso [823501]. G. Bealey, owner Al <0.2 mg/l.
 760558. Well at Kelso [822502]. H. Schell, owner Al <0.2 mg/l.
 760559. Well at Kelso [822502]. K. Banfield, owner Al <0.2 mg/l.

Constituents	760560 (17) 6/4/76			760561 (21) 7/4/76			760562 (22) 7/4/76		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
Silica (SiO ₂)	11	-	-	11	-	-	14	-	-
Iron (Fe)	<0.1	0.0	0.0	0.2	0.01	0.0	<0.1	0.0	0.0
Calcium (Ca)	100	4.99	32.1	78	3.89	27.6	93	4.64	26.7
Magnesium (Mg)	15	1.23	7.91	11	0.90	6.39	14	1.15	6.62
Sodium (Na)	35	1.55	9.97	48	2.13	15.1	61	2.71	15.6
Potassium (K)	13	0.33	2.12	4.1	0.10	0.71	3.4	0.09	0.52
Bicarbonate (HCO ₃)	310	5.08	32.7	290	4.76	33.8	370	6.07	34.9
Sulphate (SO ₄)	38	0.80	5.14	20	0.42	2.98	17	0.36	2.07
Chloride (Cl)	56	1.57	10.1	67	1.88	13.4	84	2.35	13.5
Total dissolved solids	620	15.6		420	14.1		490	17.4	
Permanent hardness (as CaCO ₃)	61			nil			nil		
Temporary hardness (as CaCO ₃)	250			240			290		
Alkalinity (as CaCO ₃)	250			240			300		
pH		7.3			7.9			7.9	
% difference of anion and cation equivalents		4.2			0.2			1.1	
Per cent sodium		23			32			33	
S.A.R.		0.88			1.4			2.5	

760560. Well at Kelso [822505]. J. Whybrow, owner Al <0.2 mg/l.
760561. Well at Kelso [821506]. W. Goer, owner Al <0.2 mg/l.
760562. Well at Kelso [821506]. E. Cornish, owner Al <0.2 mg/l.

APPENDIX 7

Water analyses of groundwater from Tertiary basalt near Greens Beach

Constituent	771604 17/5/77			772982 6/11/77		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
CO ₃	15	0.5	0.7	nil	0.0	0.0
HCO ₃	245	4.0	5.8	330	5.4	17.4
Cl	1060	29.9	43.3	340	9.6	31.0
SO ₄	77.5	1.6	2.3	9.1	0.2	0.6
SiO ₂	n.d.	-	-	42	-	-
Ca	38.3	1.9	2.7	29	1.4	4.5
Mg	43.1	3.5	5.1	34	2.8	9.0
Fe	<0.1	-	-	<0.1	-	-
Al	<0.2	0.0	0.0	<0.5	0.0	0.0
K	29	0.7	1.0	10	0.3	1.0
Na	621	27.0	39.1	260	11.3	36.5
H ₂ S	nil	-	-	nil	-	-
Hardness -						
permanent	33			} 210		
temporary	240					
Alkalinity	240			270		
Total dissolved solids	2120	69.1		960	31.0	
Conductivity (μS/cm)	2800			1310		
pH	8.6			7.0		
Analytical error (%)	4.2			1.9		
% Na	84			73		
S.A.R.	16			8		

771604: Bore 2, Greens Beach (fig. 3).

772982: Bore 3, Kelso (fig. 3).

APPENDIX 8

Geological logs of augered and drilled holes, Greens Beach pump test site.

Locations of holes are shown in Figure 11.

Augered hole A: On access track. Approximate collar elevation: 2m AHWM.

<i>Depth (m)</i>	<i>Description</i>
0-0.2	Grey sandy loam.
0.2-3.4	Buff, medium- to fine-grained well-sorted aeolian quartz sand with occasional shell fragments.
3.4-5.5	Grey-blue slightly shelly medium- to fine-grained moderately sorted saturated marine quartz sand.
5.5-6.1	Grey-blue moderate to poorly sorted fine-grained marine quartz sand. No apparent clay content. Shells range in size from fragmented sand-size particles to intact specimens up to 10 mm.
6.1-7.3	Grey-blue very poorly sorted marine(?) quartz sand containing occasional well rounded quartzite pebbles up to 25 mm, and intact shell valves up to 25 mm. Sorting becomes poorer near 7.3 m, and in places is gravelly and gritty, with minor clay and silt fractions.
7.3-10.0	Generally as above; sorting becomes increasingly poorer; below 8.2 m, compact, richly organic clay nodules and lumps are common, as are well rounded basalt cobbles (up to 80 mm) and intact shells.

Augered hole B: On access track. Approximate collar elevation: 1m AHWM.

<i>Depth (m)</i>	<i>Description</i>
0-0.2	Grey sandy loam.
0.2-3.4	Buff, medium- to fine-grained well sorted aeolian quartz sand. Occasional shell fragments present.
3.4-4.6	Pale grey medium- to fine-grained well sorted aeolian(?) quartz sand.
4.6-6.1	Slightly clayey dark brown (organic ?) medium-grained moderately sorted quartz sand.
6.1-7.0	Pale grey medium- to fine-grained moderately sorted marine(?) quartz sand. Similar to interval 3.4-4.6 m, but containing relatively abundant well rounded quartzite pebbles up to 10 mm.

Augered hole B: (continued)

Depth (m)	Description
7.0-7.3	Dark grey-brown slightly clayey and sandy well rounded quartz grit, with well rounded and polished quartzite pebbles up to 20 mm.
>7.3	Richly organic pale grey-white mottled clay containing abundant leaf impressions and wood fragments.

Augered hole C: 150 m north-east of bore hole 1. Approximate collar elevation: 2 m AHWM.

This hole was not logged. Samples were collected for grain size analysis; gravelly clay was struck at 5.5 m.

Augered hole D: 75 m north-east of bore hole 1. Approximate collar elevation: 2 m AHWM.

This hole was not fully logged. The general sequence is grey, medium-grained marine(?) quartz sand from 0-6.4 m, underlain to a depth of 8.2 m by stiff mottled grey-buff clay, gritty in places, and containing carbonaceous patches with occasional brown wood fragments. Samples were collected for grain size analysis.

Augered hole 5: Approximate collar elevation: 2 m AHWM.

This hole was augered during the 1976 survey. The log is quoted from Cromer and Sloane (1976; Appendix 1). No samples were collected for grain size analysis.

Depth (m)	Description
0-3.7	Yellow-buff medium- to fine-grained Holocene aeolian quartz sand; small gastropod, bivalve and sponge spicule fragments present. CaCO ₃ concretions at water table. Grain size increases slightly near 2.7 m.
3.7-11.0	Grey medium-grained shelly marine quartz sand, containing occasional rounded quartzite pebbles and increased shell content near 10 m.
11.0-14.6	Clean fine angular quartzite and quartz grit; fragments up to 10 mm in diameter. Shells absent.

Augered hole E: 75 m south-west of bore 1. Approximate collar elevation: 2.5 m.

No log was made of this hole, although samples were collected for grain size analysis.

Drilled hole (bore 1): Approximate collar elevation: 2 m AHWM.

This hole was drilled with a Keystone percussion rig. Samples for grain size analysis were collected at 1-1.5 m intervals.

Depth (m)	Description
0-1.5	Yellow-buff medium- to fine-grained aeolian quartz sand.
1.5-2.1	Dark grey-brown organically stained moderately rounded to angular well-sorted medium- to fine-grained quartz sand. Shell fragments present.
2.1-3.7	Buff medium-grained sand. Similar to interval 0-1.5 m.
3.7-6.1	Grey-blue slightly shelly and clayey moderately sorted medium- to fine-grained marine(?) quartz sand. Rare angular quartzite fragments (up to 15 mm) present.
6.1-7.6	Grey, well sorted fine-grained slightly clayey quartz sand. Intact shells common; occasional hard, well-rounded to angular basalt cobbles (up to 50 mm) present.
7.6-9.1	Predominantly grey, clayey poorly sorted quartzite grit, composed of angular to partly rounded quartzite fragments (up to 3-4 mm) and smaller dark grey fine-grained basalt fragments. Well rounded to spherical water worn cobbles and pebbles of quartzite (up to 50-60 mm) and basalt (up to 100 mm) occur. Slightly coarser near 9 m.
9.1-9.7	Stiff, dark brown organic clay containing wood fragments.

Drilled hole (bore 2): Sited within the present 12-spear array. Approximate collar elevation: 3 m AHWM.

The hole was drilled with the Failing WW1 rotary rig, using both rotary and hammer methods. The general log is:

Depth (m)	Description
0-9	Buff-grey medium-grained aeolian and marine quartz sand.
9-12	Clayey quartzite grit, containing quartzite and basalt gravel and cobbles.
12-17	Grey-green textured clay. Possibly highly weathered and partly transported basalt.
17-36.5	Hard, fresh Tertiary basalt; contains some glassy fractured zones (especially near 21 m) and vesicular horizons.

APPENDIX 9

Chemical analyses¹ of groundwater samples collected during the 13-day pump test at the Greens Beach test site.

Constituent	1 (772991) ² + 27 hours ³ 30/10/1977 ⁴			2 (772989) + 50 hours 1/11/1977		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
CO ₃	nil	0.0	0.0	nil	0.0	0.0
HCO ₃	350	5.7	34.5	350	5.7	34.1
Cl	95	2.7	16.4	100	2.8	16.8
SO ₄	7.6	0.16	0.96	7.1	0.15	0.90
SiO ₂	7.9	-	-	7.9	-	-
Ca	93	4.6	27.9	94	4.7	28.1
Mg	10	0.8	4.8	10	0.8	4.8
Fe	<0.1	0.0	0.0	<0.1	0.0	0.0
Al	<0.5	<0.05	<0.3	<0.5	<0.05	<0.3
K	2.4	0.06	0.4	2.5	0.06	0.4
Na	55	2.4	14.5	56	2.4	14.4
H ₂ S	nil	-	-	nil	-	-
Total hardness (as CaCO ₃)	270			280		
Alkalinity (as CaCO ₃)	290			280		
Total dissolved solids	500	16.5		510	16.7	
Conductivity (µS/cm)	690			690		
pH	8.1			7.5		
Analytical error (%) ⁵	3.9			3.8		
% Na ⁶	31			31		
S.A.R. ⁷	1.5			1.5		
R.S.C. ⁸	0.3			0.2		

1. Collected by W. C. Cromer and D. J. Sloane. Analyses by Department of Mines Laboratories, Launceston.
2. Department of Mines registered number.
3. Time after pump test started.
4. Collection date.
5. An indication of the accuracy of the analysis. Error should be zero only if all major constituents have been determined. Error = $100 \times \frac{|\text{difference of cation and anion meq/l}|}{\text{total meq/l}}$.
6. % Na = $100 \times \frac{(\text{Na} + \text{K})}{(\text{Na} + \text{K} + \text{Mg} + \text{Ca})}$, in meq/l. Undesirable soil leaching effects may occur in irrigated areas if the value rises considerably above 50%.
7. S.A.R. = $\text{Na} / \sqrt{(\text{Ca} + \text{Mg})/2}$, in meq/l. Undesirable soil effects may occur in areas irrigated with medium salinity water (250-750 mg/l.) if the S.A.R. value exceeds 10-20.
8. R.S.C. = residual sodium carbonate = $(\text{HCO}_3^- + \text{CO}_3^{--}) - (\text{Ca}^{2+} + \text{Mg}^{2+})$ in meq/l. Undesirable soil effects may occur in irrigated areas if the R.S.C. exceeds about 1.5 meq/l.

Appendix 9 (continued)

Constituent	3 (772990) + 70 hours 2/11/1977			4 (772987) + 94 hours 3/11/1977		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
CO ₃	nil	0.0	0.0	nil	0.0	0.0
HCO ₃	350	5.7	34.5	340	5.6	33.5
Cl	95	2.7	16.4	100	2.8	16.8
SO ₄	7.6	0.16	0.97	10	0.20	1.2
SiO ₂	8.5	-	-	8.5	-	-
Ca	93	4.6	27.9	94	4.7	28.1
Mg	10	0.8	4.8	10	0.8	4.8
Fe	<0.1	0.0	0.0	<0.1	0.0	0.0
Al	<0.5	<0.05	<0.3	<0.5	<0.05	<0.3
K	2.6	0.07	0.4	2.5	0.06	0.4
Na	56	2.4	14.5	58	2.5	15.0
H ₂ S	nil	-	-	nil	-	-
Total hardness (as CaCO ₃)	270			280		
Alkalinity (as CaCO ₃)	280			280		
Total dissolved solids	500	16.5		490	16.7	
Conductivity (μS/cm)	690			680		
pH	7.4			8.2		
Analytical error (%)	3.9			2.9		
% Na	31			32		
S.A.R.	1.5			1.5		
R.S.C.	0.3			0.1		

Appendix 9 (continued)

Constituent	5 (772988) + 120 hours 4/11/1977			6 (772986) + 144 hours 5/11/1977		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
CO ₃	nil	0.0	0.0	nil	0.0	0.0
HCO ₃	350	5.7	34.3	350	5.7	34.3
Cl	95	2.7	16.3	95	2.7	16.3
SO ₄	8.9	0.19	1.1	8.2	0.17	1.0
SiO ₂	8.5	-	-	7.9	-	-
Ca	94	4.7	28.3	93	4.6	27.7
Mg	10	0.8	4.8	10	0.8	4.8
Fe	<0.1	0.0	0.0	<0.1	0.0	0.0
Al	<0.5	<0.05	<0.3	<0.5	<0.05	<0.3
K	2.8	0.07	0.4	2.7	0.07	0.4
Na	56	2.4	14.5	58	2.5	15.1
H ₂ S	nil	-	-	nil	-	-
Total hardness (as CaCO ₃)	280			270		
Alkalinity (as CaCO ₃)	280			280		
Total dissolved solids	520	16.6		470	16.6	
Conductivity (μS/cm)	700			700		
pH	7.4			7.3		
Analytical error (%)	3.4			2.9		
% Na	31			32		
S.A.R.	1.4			1.5		
R.S.C.	0.2			0.3		

Appendix 9 (continued)

Constituent	7 (772984 + 169 hours 6/11/1977			8 (772985) + 192 hours 7/11/1977		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
CO ₃	nil	0.0	0.0	nil	0.0	0.0
HCO ₃	350	5.7	33.7	350	5.7	33.2
Cl	100	2.8	16.6	100	2.8	16.3
SO ₄	8.2	0.17	1.0	9.9	0.21	1.2
SiO ₂	7.9	-	-	9.1	-	-
Ca	94	4.7	27.8	97	4.8	28.0
Mg	10	0.8	4.7	11	0.9	5.3
Fe	<0.1	0.0	0.0	<0.1	-	-
Al	<0.5	<0.05	<0.3	<0.5	<0.05	<0.3
K	2.7	0.07	0.4	2.7	0.07	0.4
Na	60	2.6	15.4	60	2.6	15.2
H ₂ S	nil	-	-	nil	-	-
Total hardness (as CaCO ₃)	278			290		
Alkalinity (as CaCO ₃)	290			290		
Total dissolved solids	460	16.9		520	17.1	
Conductivity (μS/cm)	700			710		
pH	7.4			7.3		
Analytical error (%)	1.4			1.7		
% Na	33			32		
S.A.R.	1.6			1.5		
R.S.C.	0.2			0		

Appendix 9 (continued)

Constituent	9 (772983) + 216 hours 8/11/1977			10 (772981) + 240 hours 9/11/1977		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
CO ₃	nil	0.0	0.0	nil	0.0	0.0
HCO ₃	350	5.7	33.4	350	5.7	33.8
Cl	100	2.8	16.4	100	2.8	16.6
SO ₄	8.4	0.17	1.0	7.9	0.16	0.9
SiO ₂	7.9	-	-	8.5	-	-
Ca	96	4.8	28.1	94	4.7	27.8
Mg	11	0.9	5.3	10	0.8	4.7
Fe	<0.1	-	-	<0.1	-	-
Al	<0.5	<0.05	<0.3	<0.5	<0.05	<0.3
K	2.7	0.07	0.4	2.7	0.07	0.4
Na	60	2.6	15.2	60	2.6	15.4
H ₂ S	nil	-	-	nil	-	-
Total hardness (as CaCO ₃)	280			280		
Alkalinity (as CaCO ₃)	290			280		
Total dissolved solids	550	17.1		590		
Conductivity (μS/cm)	700			700		
pH	7.4			7.4		
Analytical error (%)	1.5			2.6		
% Na	32			33		
S.A.R.	1.6			1.6		
R.S.C.	0			0.2		

Appendix 9 (continued)

Constituent	11 (773111) + 274 hours 10/11/1977			12 (773112) + 295 hours 11/11/1977		
	mg/l	meq/l	% meq/l	mg/l	meq/l	% meq/l
CO ₃	nil	0.0	0.0	nil	0.0	0.0
HCO ₃	350	5.7	34.3	350	5.7	33.9
Cl	100	2.8	16.9	100	2.8	16.6
SO ₄	9.4	0.20	1.2	6.9	0.14	0.8
SiO ₂	9.9	-	-	10	-	-
Ca	87	4.3	25.9	88	4.4	26.0
Mg	11	0.9	5.4	11	0.9	5.3
Fe	<0.1	-	-	<0.1	-	-
Al	<0.2	<0.02	<0.1	<0.2	<0.02	<0.1
K	2.9	0.07	0.4	2.8	0.07	0.4
Na	60	2.6	15.7	64	2.8	16.6
H ₂ S	nil	-	-	tr.	-	-
Total hardness (as CaCO ₃)	260			260		
Alkalinity (as CaCO ₃)	280			280		
Total dissolved solids	480	16.6		470	16.8	
Conductivity (μS/cm)	730			730		
pH	7.1			7.1		
Analytical error (%)	4.8			2.7		
% Na	34			35		
S.A.R.	1.6			1.7		
R.S.C.	0.5			0.4		

Appendix 9 (continued)

Constituent	13 (773113) + 312 hours 12/11/1977		
	mg/l	meq/l	% meq/l
CO ₃	nil	0.0	0.0
HCO ₃	350	5.7	33.6
Cl	100	2.8	16.5
SO ₄	8.4	0.17	1.0
SiO ₂	10	-	-
Ca	92	4.6	27.1
Mg	11	0.9	5.3
Fe	<0.1	-	-
Al	<0.2	<0.02	<0.1
K	2.8	0.07	0.4
Na	61	2.7	15.9
H ₂ S	nil	-	-
Total hardness (as CaCO ₃)	270		
Alkalinity (as CaCO ₃)	290		
Total dissolved solids	480	17.0	
Conductivity (μS/cm)	740		
pH	7.1		
Analytical error (%)	2.2		
% Na	33		
S.A.R.	1.6		
R.S.C.	0.2		

APPENDIX 10

Technical and installation details of the 12-spear array at Greens Beach

Spear specifications

The screens were manufactured to specifications by *Surescreen* of Brisbane, Queensland, and obtained through their agents *Monopumps (Aust.) Pty Ltd* in Devonport. Each production screen is 1800 mm in length and 50 mm in diameter, with a slot opening of 0.38 mm (0.015", #15). The bottom of each is sealed with a screwed cast iron conical point, and the top is a welded 50 mm female coupling. All observation screens are 600 mm long and 40 mm in diameter, with a slot opening of 0.25 mm (0.010", #10).

Only the production screens were gravel packed.

Gravel packing and selection of screen slot sizes

In moderately to poorly sorted unconsolidated aquifers, pumping from screened spears or bores removes some of the finer grained particles from the immediate vicinity of the screen, creating a *natural* gravel pack of the coarser fraction of the aquifer. This thin zone of more permeable material increases the efficiency of the bore and reduces drawdown for any given pumping rate.

In well sorted aquifers (such as at Greens Beach) where finer material forms only a small fraction of the aquifer, it is wise to install an *artificial* gravel pack to achieve increased efficiency. (This is not absolutely necessary if the bore or spear is for household uses, or will only be used for short term pumping). Theoretically, the gravel-packed zone need only be a few grain diameters thick, but this presents practical difficulties of ensuring a uniform veneer around the screen, and generally a layer a few centimetres thick is installed.

At Greens Beach, the screens were packed with 25 mm of clean, well-rounded medium-grained quartz sand. The selection of a suitable gravel pack has the advantage that larger slot openings can be used - openings that would otherwise allow the passage of large amounts of aquifer material. Larger slot openings also mean that the spear has a higher percentage of open area. (e.g. 0.25 mm slots = 14.5% open area; 0.38 mm slots = 20.2% open area).

The slot opening and gravel pack design at Greens Beach was selected as follows (fig. 13):

- multiply the 70% size of the aquifer sand (0.125 mm) by a factor of 4 or thereabouts. This figure (0.50 mm) represents the 70% size of the gravel pack grain size curve.
- draw a curve through this point with a uniformity co-efficient < 2.5. The co-efficient is the ratio of the 40% size to the 90% size.
- on the basis of this curve, prepare grain size specifications for the gravel pack.
- select a screen slot opening which will retain \geq 90% of the gravel pack material.

For convenience, a slot opening of 0.38 mm was selected, since these spears are readily available commercially as *Surescreen #15* (0.015"). Fortunately, screened material suitable for a gravel pack is readily available from *Industrial Sands Pty Ltd* of Bakers Beach. The material is a medium-grained well rounded quartz sand from Flinders Island, and its grain size analysis curve (fig. 13) is almost exactly that required at Greens Beach.

Spear installation

Manufacturers recommend various methods for installing shallow spear bores, including ramming, bailing and jetting. Not all are equally successful in any given area, and much depends on the nature of the aquifer, its degree of compaction and the presence of hard-pan layers, and grain size variations with depth. Ramming is generally not recommended, since specially strengthened spears are required, and much physical labour often only produces a penetration of less than a metre into the saturated material. Jetting has been successfully used in many areas of Tasmania, especially where the sand is well-sorted, clay free and contains no harder horizons. It was unsuitable at Greens Beach. Bailing is a slower method, especially where harder layers occur in the aquifer, but it was successfully used for installation of all of the spears at Greens Beach. Installation was made easier by augering with a portable diesel drilling rig to 7 m prior to bailing, since the more compacted layers in the aquifer were disturbed.

One hundred millimetre Class 12 PVC casing was bailed to depths up to seven metres (plate 1). Individual spears were lowered into the casing and kept centrally positioned by 3-point devices screwed at the top and bottom of each. Selected gravel was added to the hole, as the casing was gradually removed. In this way, each spear is surrounded by a gravel annulus 25 mm thick extending from the base of the spear to a height about 1 metre above the screen.

Pipes and fittings

Each production spear consists of the 1800 mm length of 50 mm screen coupled to a 5-6 m length of Class 12 50mm PVC pipe (plate 2). All spears were installed at the ends of trenches (plate 3), the bases of which slope gently up towards the centre of the array to remove any air which may collect in the system.

Water is pumped from each spear via a 25 mm class 12 riser pipe, which extends down through the screen to within 150 mm of the bottom. At the top of each spear, the annulus between the two pipes is sealed with a loose-fitting PVC cap (plate 4) to prevent outside sand from blocking the screen, and the riser pipe is fitted with a brass 25 mm non-return valve (plate 5) to retain water in the pipes leading to the pump. This facilitates priming and reduces air pumping, but the valves are not completely water-tight and water slowly drains back down the spears and into the aquifer.

Riser pipes are connected on the pump-side of the spear to near-horizontal 25 mm class 12 PVC pipes. Opposite pairs of these from neighbouring spears are connected at trench junctions by class 12 PVC T-adaptors to 40 mm class 12 PVC radial pipes (plates 6 and 7).

5 cm



Plate 1. Bailing 100 mm PVC casing to 7 m.

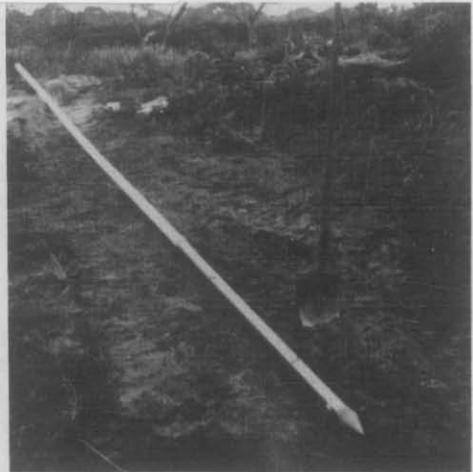


Plate 2. Complete spear: 1800 mm production screen, 50 mm in diameter, coupled to 6m x 50mm Class 12 PVC pipe.



Plate 3. View of test site, showing parts of radial trenches and central manifold position.

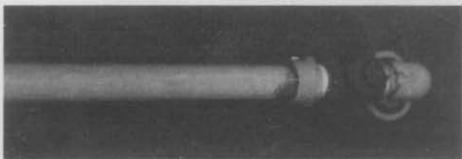


Plate 4. Spear installed in trench prior to back-filling, showing brass non-return valve, elbow at top of 25 mm riser pipe, and near horizontal 25 mm pipe to T-junction.



Plate 5. Valve assembly prior to fitting to screen: 25 mm elbow is glued to vertical riser pipe which extends almost to bottom of screen.

Manifold

The manifold (plate 8) consists of a circular steel cylinder 200 mm in diameter and 400 mm in height, welded to a circular 9 mm steel plate 600 mm in diameter. Six equally spaced 40 mm brass valves are welded near its base and each is connected to 40 mm class 12 PVC radial pipes. A 75 mm G.I. elbow outlet (with inspection opening for priming the system) is welded to its top.

The assembly is bolted through its base plate to a concrete slab, laid in a shallow pit so that the valves are level with the six radial PVC pipes. The pump is connected to the outlet side of the manifold (plate 9).

The design is a prototype, and any one of a number of methods of assembly would be equally suitable.

Potential problems with the array

(1) *Air in the system.* Even small amounts of air entering the inlet side of the pump will impair its efficiency, but it is virtually impossible to maintain an air tight system. For example, it is suspected that dissolved oxygen may be released from the groundwater because of the pressure changes during pumping. This is unavoidable. What is avoidable is air intake from faulty joints in the pipes. This may not be noticeable at first, but will eventually reduce yield. A key factor here is the life expectancy of the glued PVC joints - all were cleaned with fluid prior to fitting, but failures should be expected. Any such fault can be isolated to individual radial lines, or individual *pairs* of spears, by progressively closing the valves on the manifold.

A related problem is the potential failure of the glued joint holding the riser pipe vertically in the spear. During pumping, this joint is the one most strained in the system, for it supports a column of water about 6 m high. Correction is a simple matter, involving the detection of the faulty spear (one of two) and reglueing or replacing the riser pipe.

(2) *Corrosion of the spears.* Certain dissolved constituents of groundwater, notably dissolved CO_2 , O_2 and H_2S , as well as high T.D.S., and pH, attack screens, and their effects may vary from complete blockage of slot openings, to partial or complete removal of corroded screen material. Iron and steel screens are most affected, and special stainless screens least affected.

The screens at Greens Beach are constructed from type 304 stainless steel, containing 18% chromium, 8% nickel, 72% iron and <0.08% carbon. The chromium and nickel contents give it excellent resistance to corrosion - especially against dissolved H_2S - and the steel has been found to be the most suitable for well screens, giving long and trouble-free operation.

At Greens Beach, the spears have a life expectancy of at least 25 and probably 35 years. Their usefulness can be further increased by ensuring that as far as practicable, the lowest possible *continuous* pumping rate should be maintained. This produces a lower water velocity

through the slot openings, and reduces water level fluctuations which enhance bacterial growth and associated corrosion by producing alternating oxidising and reducing conditions.

(3) *Iron precipitation.* Precipitation of iron from the water may be a problem in the PVC pipes, and in time it will certainly become a nuisance in the steel manifold.

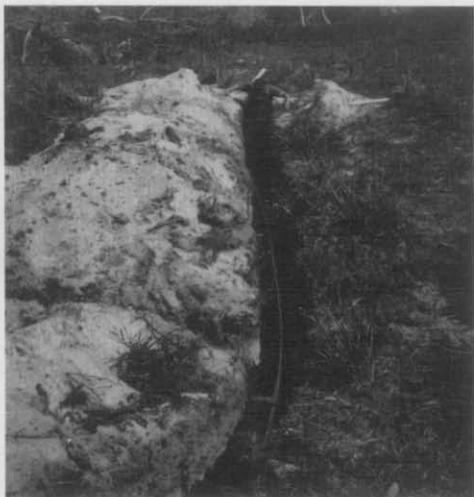


Plate 6. View of trench showing T-junction, horizontal 25 mm pipe and spear positions.

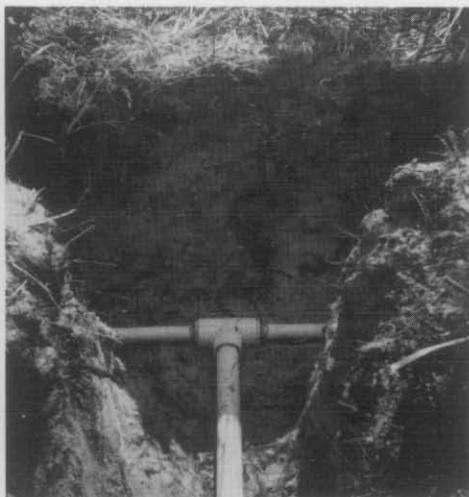


Plate 7. T-junction, showing 40mm radial pipe connected to two spears by 25mm pipe.



Plate 8. Manifold, showing radial 40 mm pipes, valves and outlets.



Plate 9. Manifold - pump assembly. Larger 100 mm pipe is outlet from pump.

