121

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
RECORD 1979/9

GEOLOGY AND GROUNDWATER RESOURCES OF THE SOUTHWESTERN CANNING BASIN WESTERN AUSTRALIA

by

R.E.J. LEECH

1979

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

RECORD 1979/9

GEOLOGY AND GROUNDWATER RESOURCES OF THE SOUTHWESTERN CANNING BASIN WESTERN AUSTRALIA

by

R.E.J. LEECH

PERTH 1979

National Library of Australia Card Number and ISBN No.
0 7244 8034 X

Map Reference

SF/50-4

CONTENTS

FIGURES

TABLES

APPENDIX

GEOLOGY AND GROUNDWATER RESOURCES OF THE SOUTHWESTERN CANNING BASIN, WESTERN AUSTRALIA

by

R.E.J. LEECH

SUMMARY

A hydrogeological study was conducted to asses the stratigraphy and groundwater potential of 3 500 km^2 of the western part of the Canning Basin. Forty-seven bores were constructed with an aggregate depth of 6 790 m. Two major aquifers have been defined; the shallowest is the Broome Sandstone which supports an unconfined groundwater system, and the other is the Wallal Sandstone which contains a largely confined system separated from the Broome Sandstone by the almost impermeable Jarlemai Siltstone.

The Broome Sandstone has an areal extent of about 1 575 km^2 and a saturated thickness up to 57 m. This aquifer is estimated to contain about 3.2×10^9 m^3 of groundwater in storage. Yields of up to 1 000 m^3/day of potable water have been obtained from suitably constructed bores. The groundwater salinity (T.D.S.) in this formation ranges from 380 mg/L in the east to more than 3 000 mg/L in the west. Nitrate concentrations are locally higher than the accepted limit for human consumption. Recharge to the Broome Sandstone is by direct percolation from rainfall. Groundwater movement is towards the north where it is discharged into the Indian Ocean. The throughflow has been estimated to be 20×10^6 m^3/year of which about a third is of domestic quality.

The Wallal Sandstone has an areal extent of about 2 100 km^2 and a saturated thickness of between 14 and 218 m. The

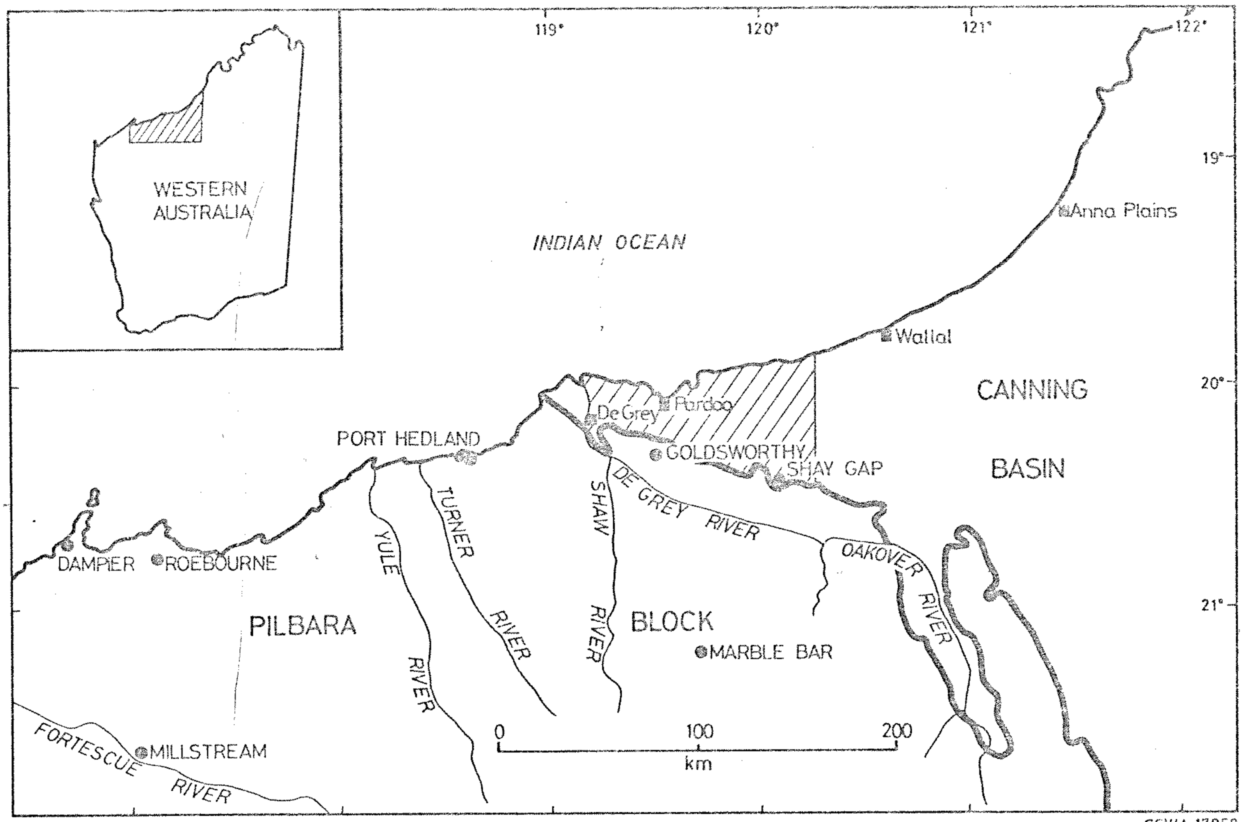
estimated groundwater storage in this aquifer is 55 x 10^9 m^3. Close to the coast hydraulic heads may exceed 30 m above ground level, and artesian flows from individual bores range up to 3 000 m^3/day. The salinity of groundwater in the Wallal Sandstone ranges from 240 to 13 000 mg/L, and groundwater temperatures range between 27 and 37°C. Recharge to this aquifer takes place outside the area investigated, towards the east and southeast, and is by direct percolation from rainfall in areas where the Jarlemai Siltstone is absent. Groundwater movement is towards the northwest where it discharges into the Indian Ocean. The estimated throughflow at the eastern margin of the area is 21 x 10^6 m^3/year. The salinity here is less than 350 mg/L (T.D.S.); over part of the flow section the nitrate concentration is known to be slightly high but still suitable for human consumption.

INTRODUCTION

The investigation area is located in the southwestern Canning Basin of Western Australia about 100 km east of Port Hedland (Fig. 1). The area is approximately 3 500 km^2 in extent and is bounded by the Pilbara Block to the south, by drill line 1 to the west, by the Indian Ocean to the north, and by drill line 5 to the east.

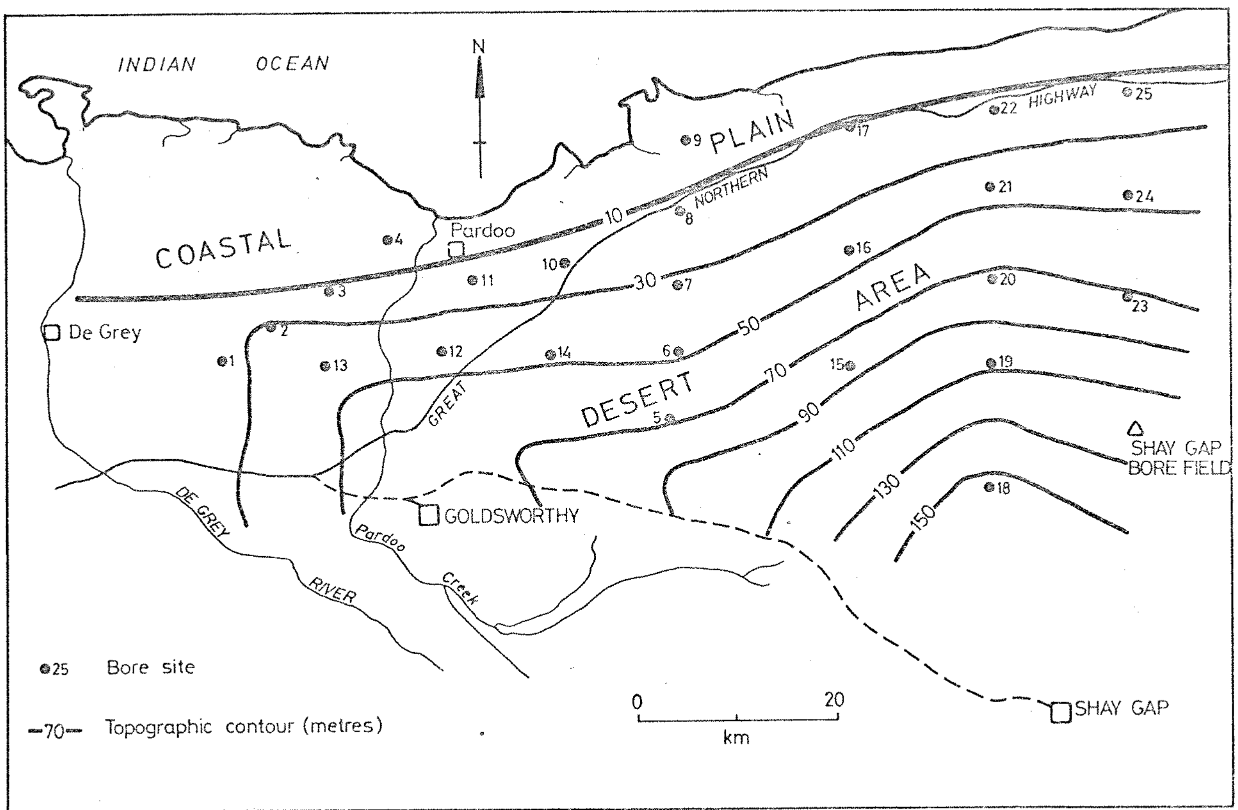
Industry in the Pilbara Region is at present dominated by iron-ore mining. However, in the future it is likely that with the advent of offshore gas production, new industries will be established in the region. These will require increased supplies of domestic and industrial-quality water. As most of the prospective aquifers close to existing townships have already been investigated and mostly developed, the current study has been directed to the next most accessible area likely to meet the anticipated water-supply needs.

The work was undertaken in three stages: a reconnaissance



GSWA 17958

Figure 1: Location plan



GSWA 17959

Figure 2: Generalized topographic contours and physiographic subdivisions

survey to map the surface geology and obtain data from existing bores and wells; a drilling and testing program to define the stratigraphy and derive aquifer characteristics; and finally, an assessment of all the data obtained.

This study was funded jointly by the Commonwealth and State Governments under the States Grants Water Resources Act.

PREVIOUS WORK

The first geologist to work in the area was Maitland (1904) in 1903, and, except for several reports by mining companies on mineral prospects in the adjacent Pilbara Block, no further work was done until 1954, when Wells and others mapped the Yarrie 4-mile geological sheet (Wells, 1959). Low and Noldart (Low, 1965) mapped the Port Hedland geological sheet during 1960-61.

Veevers and Wells (1961) described the geology of the Canning Basin as it was then known. Completion of the geological mapping of the Canning Basin at 1:250 000 scale in recent years by the Geological Survey of Western Australia and the Bureau of Mineral Resources, has provided new information, which at present is being published as geological maps with explanatory notes. An outline of the geology of the whole basin has been published in "The geology of Western Australia" by the Geological Survey of Western Australia (1975).

The current work is the first systematic investigation into the groundwater resources of the western part of the Canning Basin. Local studies have been made for Derby town water supply, (O'Driscoll, 1964; Leech, 1972), and of the groundwater resources in the alluvium along the De Grey River for Port Hedland town water supply (Davidson, 1973).

Rowston (1973, 1974 and 1976) described methods and the results of refraction seismic surveys used to assist the present investigation by delineating the basin basement topography.

PHYSIOGRAPHY

The physiography of the area contrasts with that of the Pilbara region to the southwest in that it is a low-lying, rather flat plain, lacking dissection by rivers. The generalized topographic contours given on Figure 2 show the land rises gently southward to an elevation of no more than 200 m. A strip of land north of the 10 m contour constitutes the coastal plain, which is a flat area of grass plains, tidal salt flats and Recent sand dunes, which developed after a high Pleistocene sea level. The inland desert area (above the 10 m contour) is covered by residual soils and sands, with occasional mesas and fixed seif dunes.

The De Grey River and Pardoo Creek are the only two major water courses. The De Grey River crosses the Canning Basin between De Grey Station and the coast. Several small tidal creeks occur along the coast. Elsewhere, a few internal drainage channels which rise on mesas dissipate into surrounding Recent sands. Flows in the De Grey River, Pardoo Creek and the internal drainages are ephemeral, flowing for a short time only after intense cyclonic rainfall.

CLIMATE

Rainfall is almost entirely cyclonic and occurs mainly during the period December to March; monthly rainfall may exceed 350 mm (e.g., March, 1969, see Fig. 3). Histograms of monthly rainfall for Port Hedland from 1968 to 1977 are shown

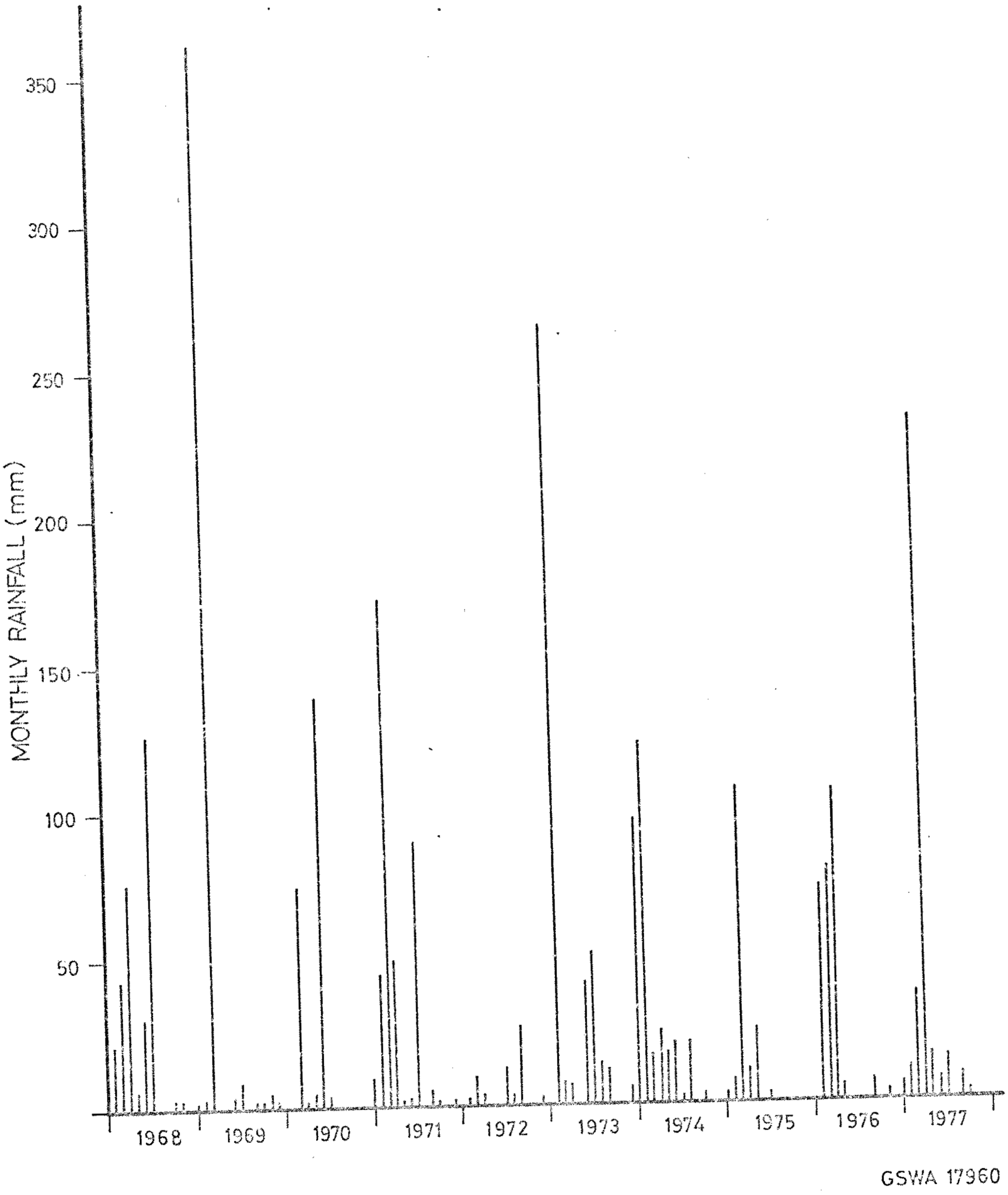


Figure 3: Monthly rainfall for Port Hedland Aerodrome, 1968 - 1977

in Figure 3, and illustrate the variability of cyclonic rainfall, and also that small winter rainfalls occur, usually during June and July. Table 1 gives the average annual rainfall figures together with the extremes over the periods of record at recording stations in and around the investigation area.

TABLE 1. AVERAGE, MINIMUM, AND MAXIMUM ANNUAL RAINFALLS AT STATIONS IN AND AROUND THE INVESTIGATION AREA.

Recording station	Average annual rainfall (mm)	Annual rainfall range (mm) Minimum	Maximum	Years of record
Port Hedland	299	47(1944)	627(1956)	35
Goldsworthy	271	141(1972)	448(1974)	8
Shay Gap*	376	-	-	4
De Grey Station	294	1(1924)	722(1942)	85
Pardoo Station	287	18(1924)	816(1942)	73
Wallal Station	314	15(1924)	647(1899)	80

* Poor Records

Evaporation is very high throughout the area; at Port Hedland the mean annual evaporation is 3 494 mm. Evaporation exceeds rainfall each month of the year unless there is exceptional cyclonic rain. Mean monthly evaporation, rainfall and rainfall deficit are given in Table 2, and it can be clearly seen that rainfall deficit is greater than 175 mm for each month. The large annual rainfall deficit has important implications when considering groundwater recharge. Evaporation close to the coast in the southwestern Canning Basin area would be similar to that recorded at Port Hedland; however, evaporation would be higher inland due to lower humidity away from the coast.

TABLE 2. MEAN MONTHLY EVAPORATION, RAINFALL, AND RAINFALL DEFICIT FOR PORT HEDLAND.

MONTH	Mean evaporation (mm)	Mean rainfall (mm)	Mean rainfall deficit (mm)
January	343	61	282
February	296	91	205
March	305	36	269
April	278	24	254
May	240	31	209
June	195	20	175
July	224	9	215
August	229	4	225
September	284	1	283
October	360	1	359
November	360	5	355
December	380	16	364
Annual Total	3494	299	3195

Temperatures recorded at Port Hedland and Goldsworthy show that December and January are the hottest months, and June and July the coolest. Temperatures of 40°C and above are common from November through to March. During winter, daily minimum and maximum temperatures may vary by as much as 25°C, with overnight frosts fairly common in inland areas.

VEGETATION

On the coastal plain grasses are the main ground cover; with river gums occurring along river or creek beds. Dense mangrove stands occur in most tidal creeks. Halophytes (samphires) grow on the coastal salt flats.

The inland area has a thick ground cover of spinifex. Low scrub is common throughout the area, the most common species being *Grevillea*, *Acacia* and *Melaleuca*.

LAND USE

The De Grey, Pardoo and Wallal Downs pastoral stations occupy the northern and western parts of the investigations area. These properties take up most of the land west of drill line 2, and then a 10 km wide strip of land running northeast adjacent to the coast. The inland desert area has remained crown land and is not used for grazing. All stations graze sheep for wool production, and cattle for beef.

The rocky headlands and sandy beaches are popular recreational areas for residents of Port Hedland, Goldsworthy and Shay Gap. The chief activity is fishing and some shell collecting.

Goldsworthy and Shay Gap townsites, situated to the south of the area, were established by Goldsworthy Mining Limited to service their iron-ore mines which abstract high-grade ore from the Archaean Gorge Creek Group rocks.

DRILLING AND BORE CONSTRUCTION

All drilling was completed by the Mines Department Drilling Section, using Jacro 1500 and Mayhew 2000 rotary drilling rigs. Forty-seven bores with an aggregate depth of 6 790 m were drilled. Their locations are shown on Figure 4.

Drilling difficulties were encountered when aquifers with large positive heads were intersected at sites 4, 9, 17, 22 and 25. These were overcome by the addition of barytes or a salt/sugar mixture to the drilling mud. This increased its density sufficiently to raise the pressure exerted by the mud column to that of the water in the formation. The control of mud density and viscosity became critical in areas where large positive heads occur at shallow depth. Such is the case at bore 9A which was drilled early in the investigation and

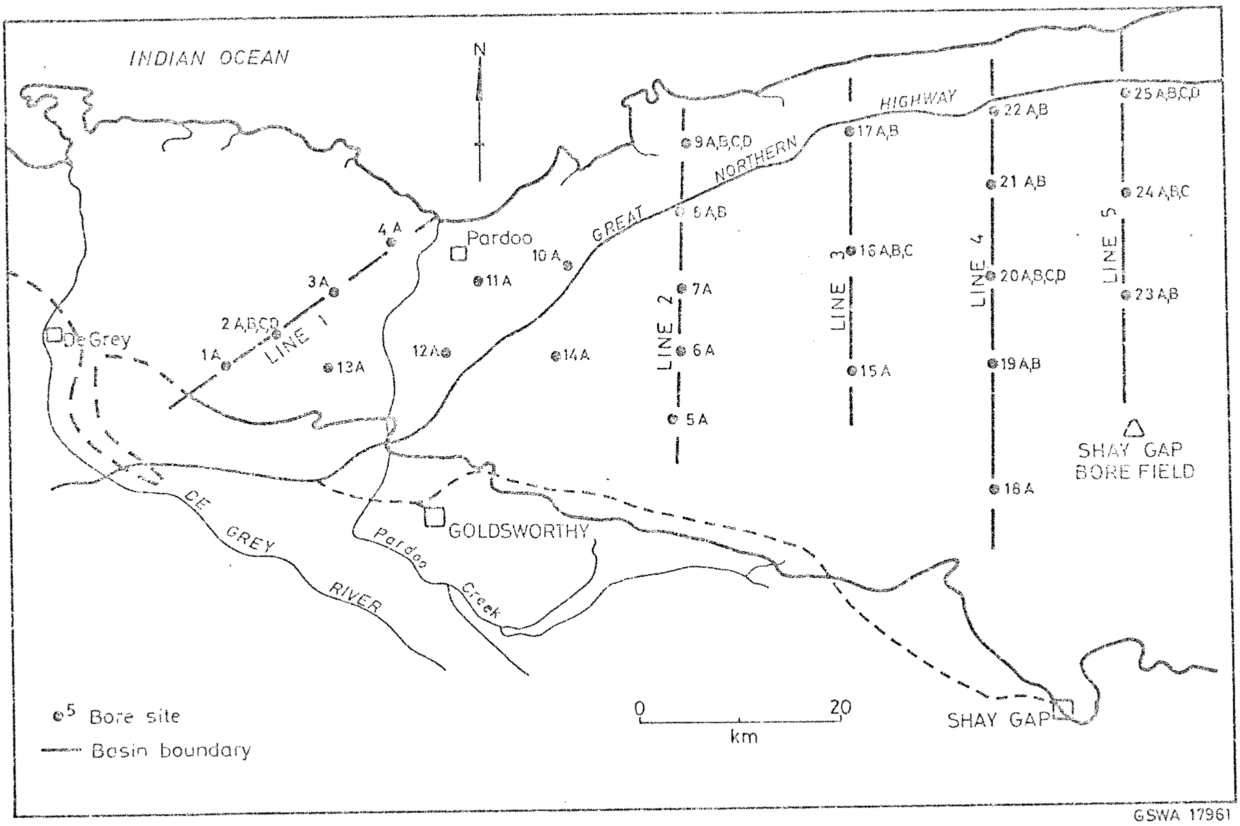


Figure 4: Bore sites

flowed out of control for three years before being successfully cemented off.

The method of bore construction adopted for those bores tapping the Wallal Sandstone (confined aquifer) was firstly to cement in a 6 to 30 m length of conductor pipe at the surface, and secondly to run pressure-cemented casing into the Jarlemai Siltstone (aquiclude) above the aquifer, and finally a third casing string was run with a suitable length of stainless steel screen on the bottom to span the selected aquifer interval. Details of the bore construction and test data are given in Appendix 1. Also included are the abandoned bores resulting from drilling and construction difficulties.

The second run of casing, as described above, was omitted from those bores completed in the unconfined aquifer (Broome Sandstone) on drill lines 3, 4 and 5. All bores have been left with head works and locked caps, for sampling and observation purposes.

No bores were completed in the Broome Sandstone west of and including drill line 2, as sufficient hydrological data was available from station bores and wells.

Bore nomenclature

Up to 4 bores were drilled on each of the 25 drilling sites (Fig. 4). Each bore is identified by the site number and followed by a letter A, B, C or D depending upon it being the first, second, third, or fourth bore drilled on that site. The nomenclature includes abandoned bores, and reference should be made to Appendix 1 to determine the aquifer in which a particular bore has been left screened.

Levelling

All project bores have been levelled to Australian Height Datum (A.H.D.) by consultant surveyors. Reference points on the bore heads and the natural surface were levelled to an a accuracy of 0.001 m using third-order levelling. Bench marks were constructed at each bore site.

Station broes and wells of interest were levelled using Thommen altimeters; Trig point R135, 1.6 km north of Pardoo Homestead, was used as the base.

SAMPLING

Lithological samples

Drill cutting samples were collected at the bore head for every 3 m interval drilled. On completion of the deepest bore at each site and after geophysical logging, selected intervals in the bore were sidewall cored for palynological analyses and petrological examination. All lithological samples were reduced and are stored at the Geological Survey's core library.

Water samples

Water samples were collected from each bore on completion, either by bailing in the case of a non-artesian bore, or as a flow sample from an artesian bore, and the salinity was determined in the field by a portable resistivity meter. Other samples for full laboratory analysis were taken at the end of flow-testing or pump-testing. The results of these are given in Tables 7 and 12.

GEOPHYSICS

Methods and results of surface geophysical techniques conducted for this study have been documented by Rowston (1973, 1974 and 1976). Seismic refraction spreads proved most useful for interpreting depths to bedrock, but bedrock velocities could not be used with confidence to predict bedrock type. Electrical resistivity sounding techniques were used to obtain depths to bedrock and, where possible, to provide qualitative indication of groundwater salinity. Generally, this technique gave less accurate depths to bedrock than the seismic refraction technique. Inherent ambiguities in the interpretation of the electrical soundings precluded accurate predictions of groundwater quality.

The deepest bore on each site was geophysically logged to supply data for stratigraphic correlation between bore sites, and also to supplement data obtained from lithological and groundwater samples. Several different types of geophysical logs were run; they were gamma ray, long and short normals resistivity, and caliper logs.

PALYNOLOGY

Sidewall-core or sludge samples from most bores were submitted for palynological examination. The results are given by Backhouse (1972; 1973; 1974a,b; 1975a,b; 1976a,b,c, d,e,f; and 1978).

PETROLOGY

Core samples from some bores were submitted for petrological examination and rock identification. These results as well as heavy mineral analyses from bores 4A, 6A, 7A, 8A and 9B are available on file at the Geological Survey.

POROSITY STUDY

Geophysical tools for the determination of aquifer porosity were not available; therefore, an attempt was made to estimate this parameter by laboratory testing. Samples of sand from the Wallal Sandstone were combined, washed to remove salt, and dried, before being introduced into a burette whose dimensions were 1 m long by 25 mm diameter. Small amounts of the sand were introduced into the burette and compacted with the aid of a wooden ram; further amounts of sand were progressively added and compacted until the sand column was complete.

After completion of the sand column it was saturated with a known volume of water. Water was then drained slowly from the column until no further discharge was observed. This volume was then measured. From these two volumes and the known volume of the soil column the specific retention and the specific yield can be derived. These werefound to be 10.2% and 28.4% respectively. The sum of these two parameters yields the porosity (38.6%).

AQUIFER TESTING

The test program was designed to obtain values of transmissivity and storage coefficient for use in estimating the regional groundwater resources. Those bores in which unconfined or sub-artesian conditions occur were test pumped, and others tapping artesian flows were flow tested.

In 1973 several constant discharge and constant drawdown flow tests were conducted. Analyses of data from these tests showed the Wallal Sandstone appeared to respond as a leaky artesian aquifer. Observed drawdowns during the tests reached a maximum within several minutes from the start of each test, indicating that the aquifer very quickly reached equilibrium conditions. Conventional procedures of recording drawdown measurements at one-minute intervals from the start of testing gave inadequate early-time data for type curve matching. To overcome this the Geological Survey developed electronic equipment capable of sensing and continuously recording drawdown in the pumping bore and in up to three observation bores simultaneously, as well as continuously recording pump or flow discharge and barometric pressure.

Equipment

A twenty-stage Metcalf electric submersible pump was used for most pump tests. This pump gave a maximum discharge up to 950 m^3/day, depending upon the operating head of water. In bores which had small supplies (less than 125 m^3/day) a small Onga electric submersible pump was used. During flow tests the discharge was controlled by a valve fitted to the bore head.

For all tests discharge was measured using a piezometer connected to a calibrated horizontal discharge pipe, with an orifice plate of known diameter at the outlet. This discharge was checked by measuring the time taken to fill a 500 L container.

Tyco AB strain gauge pressure transducers with operating ranges of 0-689 kPa (0-100 psi) or 0-1378 kPa (0-200 psi) were used to measure pressure head changes in pumping or flowing bores (i.e. drawdown) and also barometric pressure. The transducers operated on a constant 5V DC input, which was supplied from the operating console of a Rickadenki or Hewlett-Packard chart recorder. For the measurement of pressure changes in a pumping bore the transducer was strapped to the pump column 1 m above the pump; in a flowing bore it was screwed into an aperture at the head works. In an observation bore it was lowered on a cable to some predetermined depth below the initial water level and then fixed for the duration of the test. The barometric pressure transducer was connected to the side of the recorder console. One transducer was installed in the discharge pipe in the same position as the piezometer, to qualitatively monitor discharge.

The transducers provided a voltage output that was substantially linear with respect to pressure changes. When this output was used to drive a chart recorder with suitable attenuation or amplification for maximumsensitivity, an accurate record of pressure change versus time was obtained. Where several transducers were in use simultaneously, an appropriate number of recording channels were required. Either a Rickadenki six-channel or two Hewlett Packard two-channel recorders were used for the pumping or flow tests.

The recorders had variable chart speeds, such that 'early-time' drawdown data could be recorded at the fastest speed and the 'late-time' data at a slower speed. The chart speed could be varied from 40 mm /minute to 10 mm/hour. Attached to the chart recorders were controls necessary for adjusting the 'span' of the pens on the chart, and also for altering the sensitivity of the recording transducers.

Pump-testing procedure

The pumping tests were carried out during 1977 when drilling was almost completed. After the pump and other equipment had been assembled at the bore head, the following procedure was adopted.:

i. preliminary test run to assess suitable pumping rates.
ii. first step-drawdown test.
iii. constant discharge test.

iv. second step-drawdown test.

v. 24 hours of water-level and barometric observations.

Preliminary tests were run at the maximum pump capacity for one hour to ensure that the drawdown available was sufficient for conducting the rest of the tests. The preliminary test also allowed checks to be made on the electronic equipment to ensure that it was operating correctly. After the preliminary test, one hour was allowed for the bore to recover, prior to carrying out the first step-drawdown test.

The first step-drawdown test comprised five half-hour steps with half-hour recovery periods between steps. The pumping rates for each step in this test were 15, 30, 45, 60 and 75% of the discharge of the preliminary test. The fifth step of this test corresponded to the first half hour of the constant discharge test.

The constant discharge test was run for eight hours with an eight-hour recovery period at the end of pumping. The results from both the time-drawdown and time-recovery tests were used to calculate transmissivity, and, where possible, storage coefficient.

The second step-drawdown test was at the end of the recovery period from the constant discharge test. This test comprised five steps of discharges of 15, 30, 45, 60 and 75% of the preliminary test discharge. The results from this test were used to calculate the bore efficiency, in order to make corrections to drawdown and recovery data collected in the constant discharge test. The results from this test were also compared with the first step-drawdown test to determine whether development had taken place in the interim.

During the pumping and recovery phases of the tests barometric pressure wasrecorded continuously. At the start or end of testing the transducers were left in place and water levels and barometric pressurewere observed for 24 hours.

This was done so that barometric corrections could be allowed for in correcting drawdown and recovery data from the constant discharge test.

Flow-testing procedure

During 1973 flow tests were conducted in bores 4A, 8A and 8B. Results from constant discharge and constant drawdown tests were poor due to the inadequacy of 'early time' data which was then collected manually. Accurate determinations of transmissivity and storage coefficient could not be made from this testing programm (Leech, 1974).

The flow testing undertaken in 1977 followed the same sequency of stages as was adopted for the pumping tests. The discharge was kept constant by manual opening and closing of a gate value at the bore head.

GEOLOGY

GENERAL

The Canning Basin is the largest sedimentary basin in Western Australia and extends over 630 000 km^2, of which two-thirds is onshore. The sediments that it contains range from Ordovician to Recent in age, and reach a maximum thickness of over 8 km. The area included in the current investigation, 3 500 km^2, covers but a small portion of the basin and is confined to the western part of the Anketell Shelf which includes the Wallal Platform to the west and the Willara Sub-basin on the eastern margin. The maximum thickness of sediments penetrated by boring was 696 m.

STRATIGRAPHY

The geological succession encountered during this investigation either in bores or during mapping is given in Table 3. The surface geology is based on the Port Hedland (Low, 1965) and Yarrie (Wells, 1959; Hickman and Chin, 1976) 1:250 000 geological maps, and, in the northeastern area, on geological mapping by the writer (Fig. 5). The main stratigraphic problem was to easblish the correct Mesozoic succession. Several authors (West Australian Petroleum Pty Ltd (WAPET), 1957; Australia Bureau of Mineral Resources (BMR), 1958; McWhae and others, 1958; Veevers and Wells, 1961; and the Geolgoical Survey of Western Australia (GSWA), 1975) had produced conflicting geological successions; their stratigraphy, together with the sequence adopted in this report, is shown in Table 4.

Archaean

Archaean rocks of the Pilbara Block form the southern boundary to the investigation area, and also the basement to the Canning Basin in this area.

Gorge Creek Group: The Gorge Creek Group (Lipple, 1975) consists of metasediments and volcanic rocks of Archaean age. Metamorphic grade is low, and these rocks are intruded by Archaean granites which have produced contact metamorphism and granitization (Low, 1965). These rocks are unconformably overlain by Permian or Mesozoic sediments.

The Gorge Creek Group was intersected in project bores in the west of the investigation area (Figure 6). Rock types encountered were altered vitrophyre (bore 1), metamorphosed shale (bores 2C and 3A), altered amphibolite (bores 4A and 12A), intermediate igneous rock (bore 8A), schist (bores 11A and 13A), and quartzite (bore 14A). All other deep bores terminated in granitic rocks.

TABLE 3. STRATIGRAPHIC UNITS IN THE SOUTHWESTERN CANNING BASIN

Era	Period	Map symbol	Rock unit	Lithology
CAINOZOIC	QUATERNARY	Qa		Alluvium - clay, sand and gravel
		Qs		Sand - wind blown, red residual soil
		Qr		Tidal Flat Deposits - clay, silt and sand
		Qp	BOSSUT FORMATION	Calcarenite - sandy, cross-bedded
	TERTIARY	K		Calcrete - white, calcareous rock
		Tk		Laterite - pisolitic ironstone, unconsolidated
			UNCONFORMITY	
MESOZOIC	CRETACEOUS	Ms	BROOME SANDSTONE	Sandstone, with rare siltstone interbeds
	JURASSIC		JARLEMAI SILTSTONE	Siltstone, claystone and rare sandstone interbeds
			WALLAL SANDSTONE	Sandstone with rare siltstone and gravel interbeds
			unnamed unit	Claystone with rare lignite
			UNCONFORMITY	
PALAEOZOIC	PERMIAN		DORA SHALE	Interbeds of siltstone and claystone
			GRANT FORMATION	Interbeds of siltstone, claystone and sandstone
			UNCONFORMITY	
ARCHAEAN		Ag	(Muccan Batholith)	Granite - weathered, quartz, biotite and kaolinized feldspar
		Ai	GORGE CREEK GROUP	Metasediments and volcanic rocks - shale, amphibolite, schist and quartzite

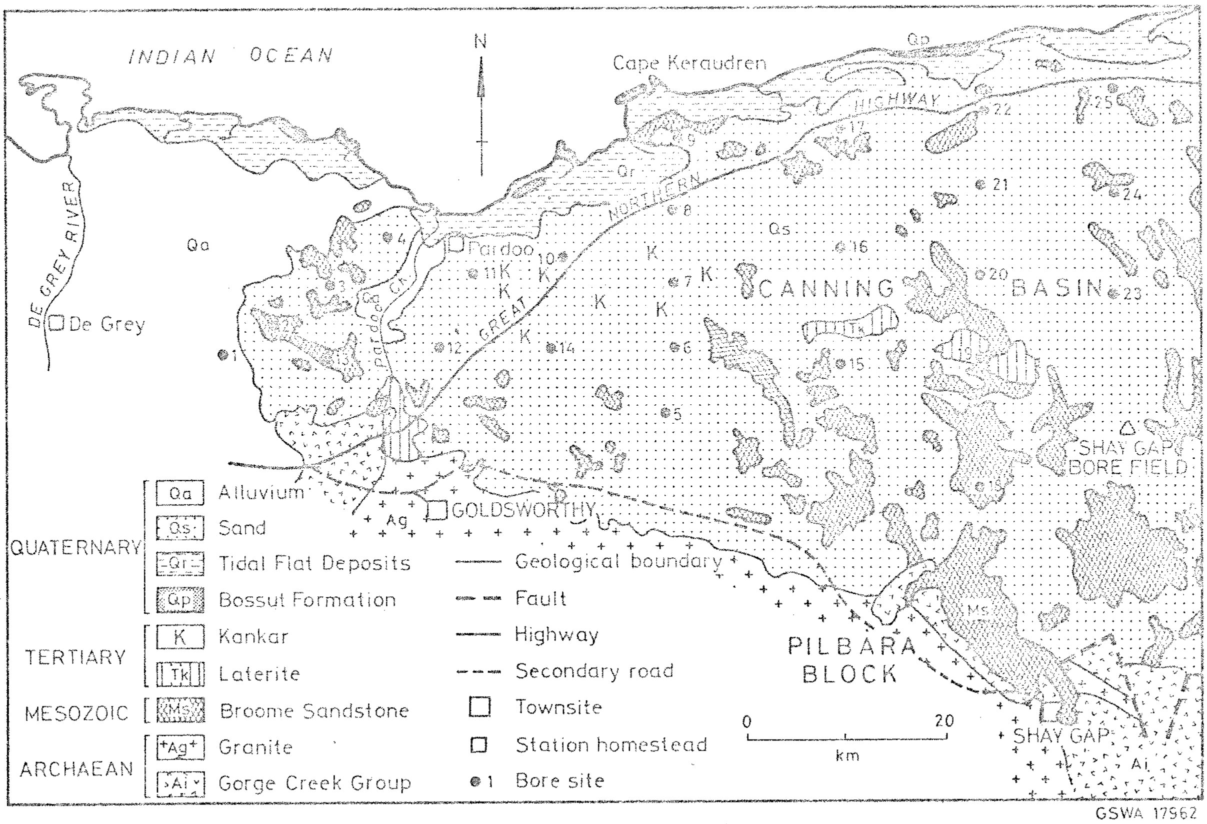


Figure 5 : Geological Map

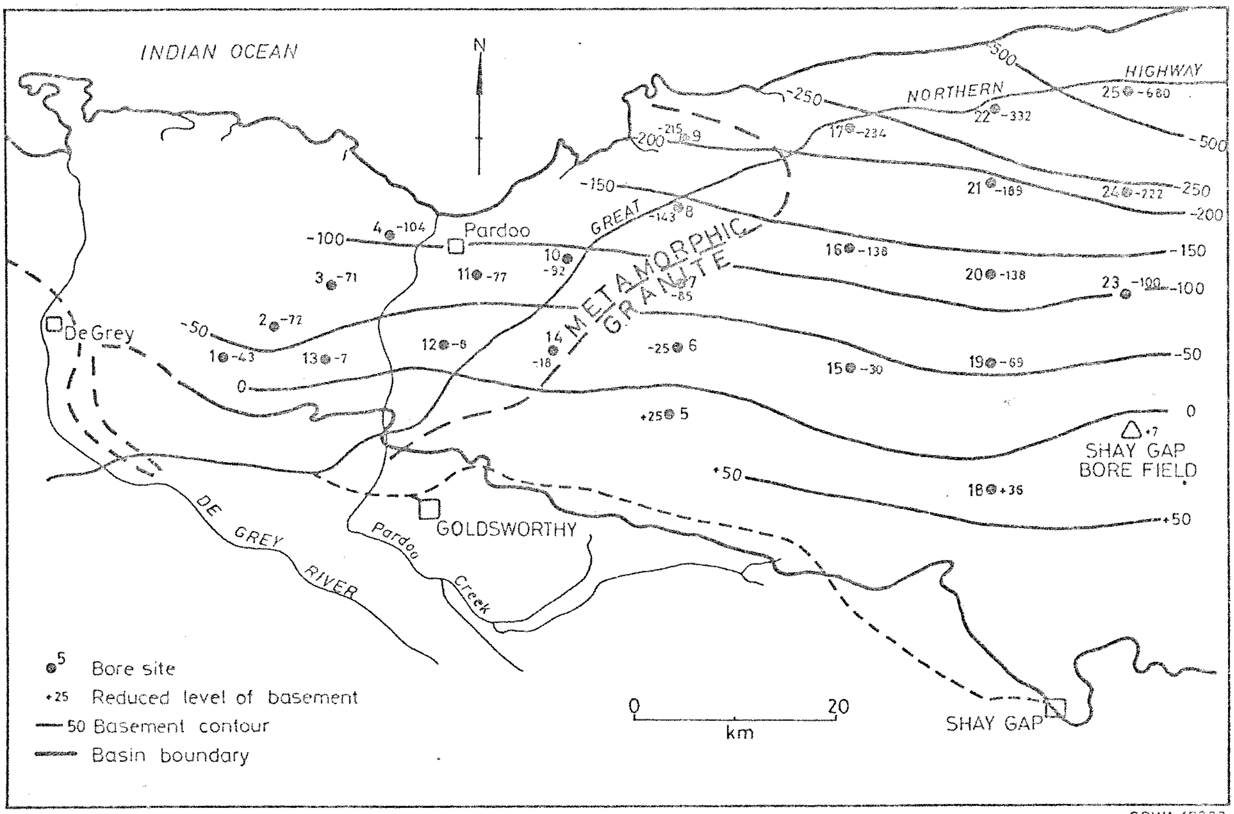


Figure 6 : Archaean basement contours (reduced to Australian Height Datum)

TABLE 4. MESOZOIC STRATIGRAPHIC NOMENCLATURE IN THE SOUTHWESTERN CANNING BASIN

Formal age	WAPET Wallal Core Hole No.1 (1957)	BMR 4 and 4A Wallal (1958)	McWhae et al (1958)	Veevers and Wells (1961)	GSWA Memoir 2 (1975)	Leech (this report)
Neocomian	Broome Sandstone	Broome Sandstone	Anketell Sandstone Callawa Formation Broome Sandstone	Broome Sandstone	Broome Sandstone	Broome Sandstone
Tithonian	Jarlemai Siltstone	Jarlemai Siltstone		Jarlemai Siltstone Anketell Formation		
Kimeridgian	Alexander Formation and Jugurra Sandstone Equivalent	Alexander Formation	Jarlemai Siltstone		Jarlemai Siltstone	Jarlemai Siltstone
Oxfordian		Wallal Sandstone		Callawa Formation	Alexander Formation ?	
Callovian			Alexander Formation		Wallal Sandstone and Jurgurra Sandstone	Wallal Sandstone
Bathonian						
Bajocian						Unnamed unit

Granitic rocks: Granitic rocks underlie the sediments to the east of drill line 2. Sidewall core samples of the granite show it to be weathered, with angular particles of quartz in a kaolinized feldspar groundmass with rare biotite. The granite has probably intruded the Gorge Creek Group.

The granites south of the investigation area are part of the Muccan Batholith (Hickman and Chin, 1976), and are of Archaean age. Granite bedrock from Samphire Marsh No. 1 well, 100 km east-northeast of the investigation area, gave a Rb-Sr age of between 500 and 700 m.y. (Johnstone, 1961). Eight Rb-Sr analyses from a similar granite near Mount Crofton on the Paterson Range sheet to the southeast of the Yarrie sheet, gave and age of about 600 m.y. (Trendall, 1974). For the purposes of this report an Archaean age is given to the basement granites, as the Archaean granites from the Muccan Batholith are nearer to the study area than the Proterozoic granites described above. Bottom hole 'core samples' of the granitic bedrock from the project area were too weathered for isotopic analysis.

Permian

Permian sediments were only intersected in bore 25C from 341 m to the bottom of the bore at 696 m. Bore 25C was drilled off the edge of the Wallal Platform where an abrupt thickening of the sediments occurs. Palynological studies of sidewall core samples taken from the claystones and siltstones between 341 and 696 m indicated a Permian age for the sediments, and spore evidence suggested a non-marine environment of deposition (Backhouse, 1975b). The Permian succession can be divided into two units on the basis of the palynological data and geophysical logs. These are a siltstone, claystone and sandstone unit between 565 and 696 m which correlates with the Grant Formation, and a siltstone and claystone unit between 341 and 565 m which correlates with the Dora Shale. There is a distinct change in the gamma-ray log at 565 m marking the base of this shale.

Grant Formation: The Grant Formation (Guppy and others, 1952) consists of interbedded siltstone, claystone and sandstone. The siltstone comprises fine-grained rounded quartz with rare accessory jasper grains and common coarse-grained quartz. The claystones are dark grey, usually silty, sticky to stiff, and rarely micaceous. Sandstones occur toward the base of the sequence and these are generally composed if fine- to medium-grained, rounded quartz, with traces of accessory mica. The Grant Formation unconformably overlies Archaean granite, and is conformably overlain by the Dora Shale.

The Grant Formation occurs only in the sub-surface in the southern and western parts of the basin, but outcrops on the eastern side of the basin. Palynology indicates it to be of Sakmarian age.

Aquifers in the Grant Formation were not tested, but geophysical log interpretation suggests the groundwater to be salty.

Dora Shale: The Dora Shale (Traves and others, 1956) is composed of interbedded siltstone and claystone. The siltstone contains fine-grained rounded quartz with rare accessory jasper. The claystones are dark grey, silty and puggy. The Dora Shale conformably overlies the Grant Formation, and is unconformably overlain by the Wallal Sandstone.

The Dora Shale outcrops in the southern Canning Basin, but is found only in the subsurface in the western part of the basin. It is of Artinskian age, based on palynological examination of samples from bore 25C (Backhouse, 1975b).

The Dora Shale is not considered to be a potential source for groundwater.

Jurassic

Four Mesozoic lithological units were recognized: a lower claystone unit (unnamed unit); a lower sandstone unit (Wallal Sandstone); an upper claystone-siltstone unit (Jarlemai Siltstone); and an upper sandstone unit (Broome Sandstone). The depositional relationships between these rock units could notebe determined from drilling, and the contacts are not exposed in outcrop. The abrupt changes in lithology between rock units is probably indicative of disconformities between them. The lower of the Mesozoic units rest unconformably on Permian or Precambrian rocks.

The stratigraphic nomencalture for Mesozoic sediments in the Canning Basin is confused, as different authors have given various names to laterally equivalent formations. Further, most of the sedimentary basin studies to date have been carried out in the northeastern part of the basin, and correlation of near-shore and continental deposits over long distances is unreliable. The sediments encountered during this investigation ranged from continental to marine in depositional environment.

Unnamed unit: This unit is a very fine-grained, dark-grey, indurated claystone, and contains small fragments of lignite. It is intersected only in the basal 5 m (219-224 m below surface) of bore 9D. Palynological evidence suggests this unit to be non-marine, and of Bajocian (middle Jurassic) age (Backhouse, 1978). This claystone locally forms an impermeable base to the Wallal Sandstone aquifer and rests unconformably on Archaean basement.

Wallal Sandstone: The Wallal Sandstone is a very coarse- to fine-grained, poorly consolidated, fawn to light-grey sandstone. Its constituent grains are poorly to well sorted and subangular to rounded. The sandstone also contains traces of carbonaceous material, pyrite, black heavy minerals, and rose-coloured garnets. Conglomerate is common in this formation and occurs mainly towards the base. The conglomerate is comprised of angular to rounded pebbles of quartz, quartzite, jasper and basic rocks.

The Wallal Sandstone occurs in the subsurface over most of the investigation area and reaches a maximum thickness of 218 m in bore 22A. This sandstone has been reported in other bores to be northeast. The Wallal Sandstone was defined by McWhae (in Johnstone, 1961). The age of this unit is Jurassic, older than Oxfordian (the palynologically determined age for the Jarlemai Siltstone) and younger than the unnamed claystone unit of Bajocian age. The most likely age is therefore Bathonian to Oxfordian (Geological Survey of Western Australia, 1975). The Wallal Sandstone unconformably overlies Precambrian rocks over most of the West Canning area. It also unconformably overlies Permian rocks at, and close to, bore 25C.

Jarlemai Siltstone: The Jarlemai Siltstone is a light-grey to black, puggy, silty clay with traces of carbonaceous material that is generally pyritized. It commonly contains thin bands of silt, and medium- to coarse-grained sand. It becomes more silty and indurated towards the south.

The Jarlemai Siltstone disconformably overlies the Wallal Sandstone and was first described by Brunnschweiler (1954), the type locality being 160 km south of Derby at Mount Jarlemai. Palynological analysis of sidewall core samples from project bores indicated a Jurassic age, in the range Oxfordian to Tithonian (Backhouse, 1973; 1974a,b; 1975a,b; 1976a,b,c,d,e,f), which is slightly older than the mid-Tithonian age given by Brunnschweiler (1954). The Jarlemai Siltstone occurs only in the subsurface in this part of the Canning Basin, and was intersected in most investigation bores. The maximum recorded thickness of this formation is 95 mm in bore 25C. The isopach map, Figure 7, and the cross-sections in Figure 11, show a southward-thinning and a pinching-out of the formation south of bores 2, 14, 5 and 18. This is probably the result of post-depositional erosion and the transgression of the succeeding Broome Sandstone which rests directly on the Wallal Sandstone near the southern margin of the basin.

Cretaceous

Broome Sandstone: The Broome Sandstone crops out in isolated mesas of ferruginous, cross- and graded-bedded sandstone with occasional interbeds of shale and conglomerate. It is a poorly consolidated, coarse- to fine-grained sandstone and sand. The quartz grains are subangular to rounded, poorly to moderately sorted, and may be clear or frosted. The sandstone generally has a ferruginous cement and may occasionally contain bands of fissile shale and siltstone. Black heavy minerals are rare. The colour various from red-brown near the surface to light brown, purple, yellow and white at depth.

The Broome Sandstone disconformably overlies the Jarlemai Siltstone over most of the western Canning Basin area; however, to the south, it rests on the Wallal Sandstone where the siltstone wedges out. The Broome Sandstone overlaps the Wallal Sandstone in most areas, so that at the southern margin of the basin the former rests on the Archaean basement. Figure 8 shows this margin and contours of the base of the Broome Sandstone.

This formation was defined by Reeves (1951) as the Broome Beds and later amended by Brunnschweiler (1957) as a sandstone sequence overlying the Jarlemai Siltstone. It is of Early Cretaceous, possibly Neocomian, age (Geological Survey of Western Australia, 1975). The Broome Sandstone may be correlated with the Callawa Formation (Traves and others, 1956) which outcrops to the southeast in the Callawa Hills.

Tertiary

Laterite: The laterite is mainly pisolitic, indurated and unconsolidated, and has a maximum thickness of about 5 m. It crops out close to Pardoo Creek and also towards the south of drill lines 3 and 4 (Fig. 5). The laterite forms small undulating ridges, and is developed on top of the Broome Sandstone.

Kankar: The kankar is a white to cream, indurated limestone with occasional residual quartz grains. It crops out east of Pardoo Creek to about longitude 120°, and has formed as a thin concretionary limestone along the flanks and valleys of palaeodrainages.

Quaternary

Bossut Formation: The Bossut Formation (Johnstone, 1961) or 'coastal limestone' is a sandy calcarenite with rare conglomerate lenses; it includes shoreline and lithified dune deposits. It crops out along the coastal margin of the basin, and is best exposed at Cape Keraudren.

Tidal-flat deposits: Tidal-flat deposits consist of grey clay, silt and sand. They occur along the coast where they are dissected by tidal creeks, which at high spring tides often flood the flats. Commonly, a white salt crust covers these deposits, which can only support salt-tolerant halophytic plants.

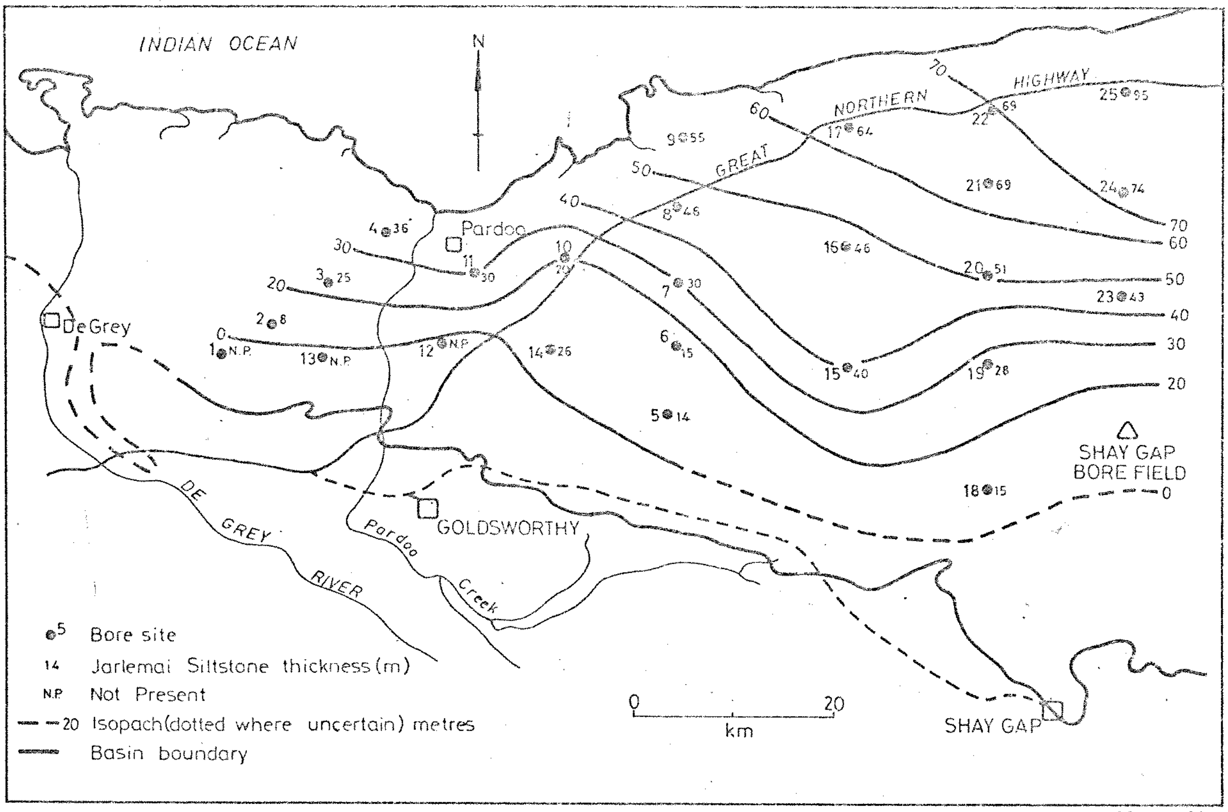
Sand: Wind-blown, coarse- to fine-grained, red sand and residual soils are common east of Pardoo Creek. It is these sands which form the fixed seif dunes in the desert area.

Alluvium: The alluvium comprises sand, clay and gravel. These deposits are extensive along the De Grey River and are thinly developed along Pardoo Creek. No alluvium is associated with the small creeks in the desert area.

STRUCTURE

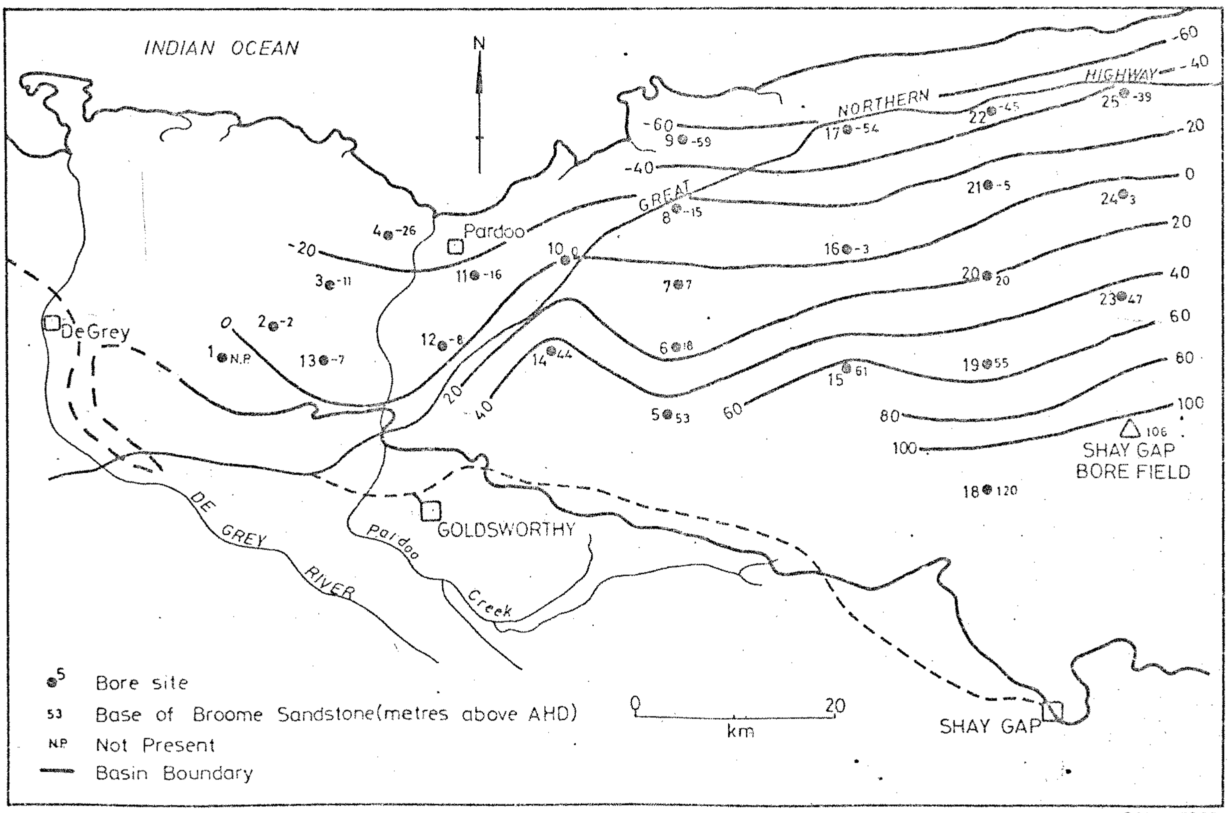
Structure contour and isopach maps (Figures 7, 8, 9 and 10) indicate that the Mesozoic sediments are essentially flat lying with presumed depositional dips of less and 1° to the north, and that folding and faulting are absent. The geological cross sections along drill lines 1 to 5 illustrate the relationship between the various rock units (Fig. 11). Table 5 shows thickness data and reduced levels of Mesozoic units.

Two structurally controlled subdivisions which affect the Canning Basin sediments in this area are the northwesterly trending Wallal Platform and an adjacent trough to the northeast named the Willara Sub-basin. Both form parts of the Anketell Shelf. The Wallal Platform is a basement high in this area, and all project bore sites with the exception of No. 25 are drilled on this platform. It can be seen from Figure 11, Line 5, that a much steeper gradient exists in the basement floor off the edge of the Wallal Platform. This suggests that this structure may be an ancient fault scarp, or a hinge line with greater subsidence to the northeast.



GSWA 17964

Figure 7 : Isopachs of Jarlemai Siltstone



GSWA 17965

Figure 8 : Contours on base of Broome Sandstone (reduced to Australian Height Datum)

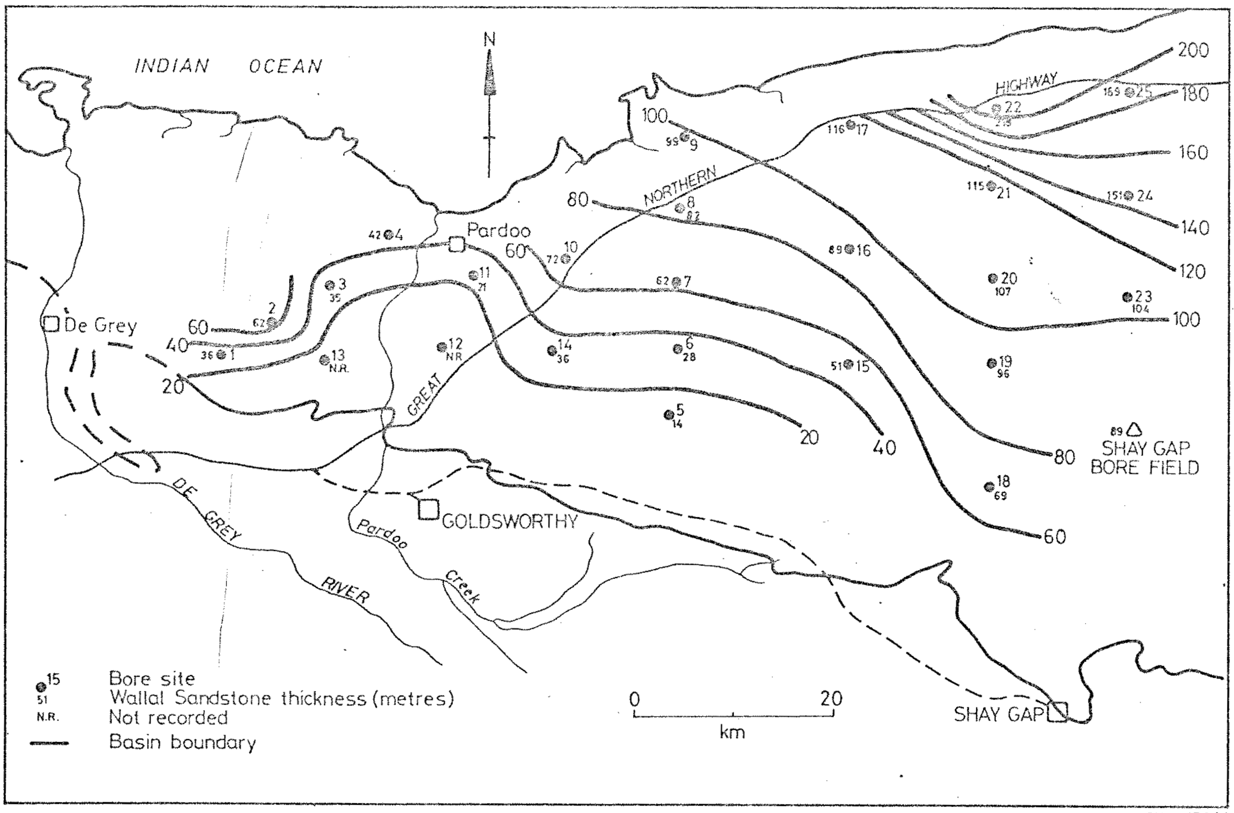


Figure 9 : Isopachs of the Wallal Sandstone

GSWA 17966

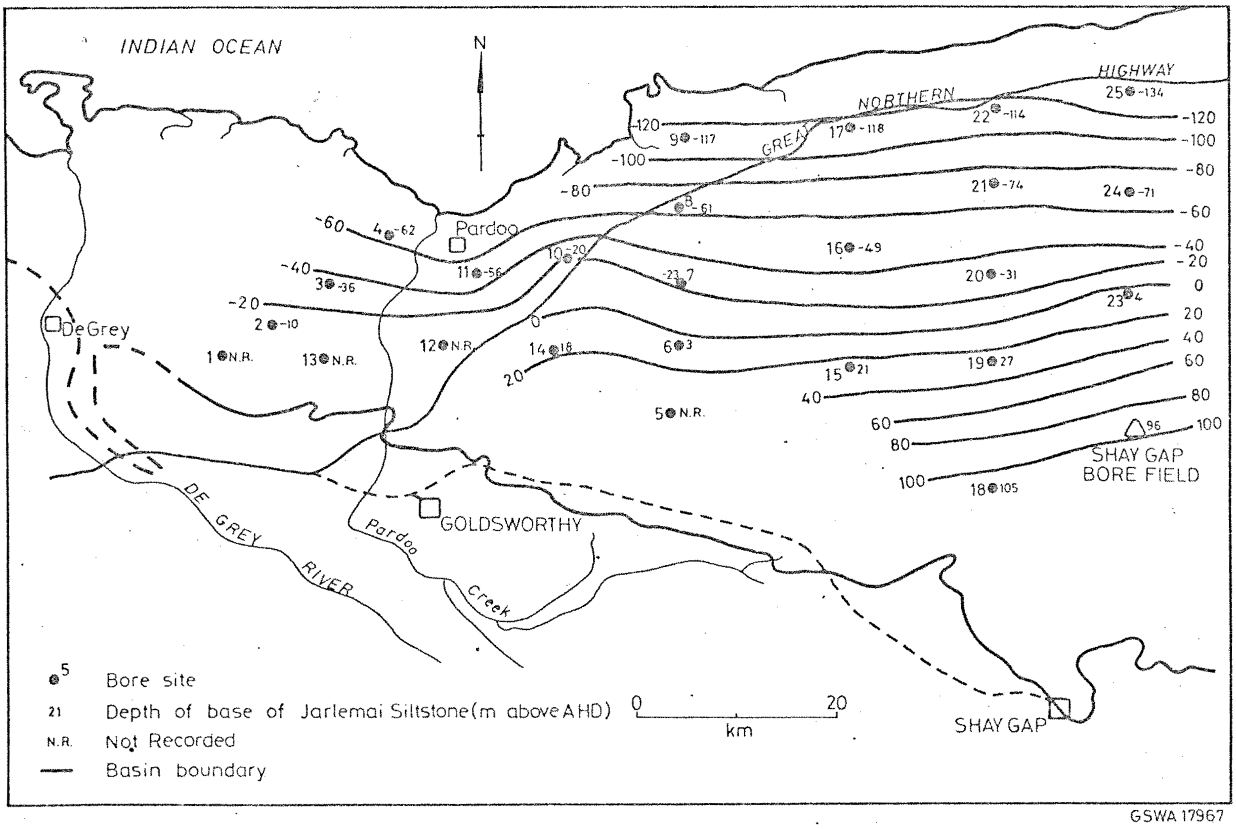


Figure 10 : Contours on base of Jarlemai Siltstone

GSWA 17967

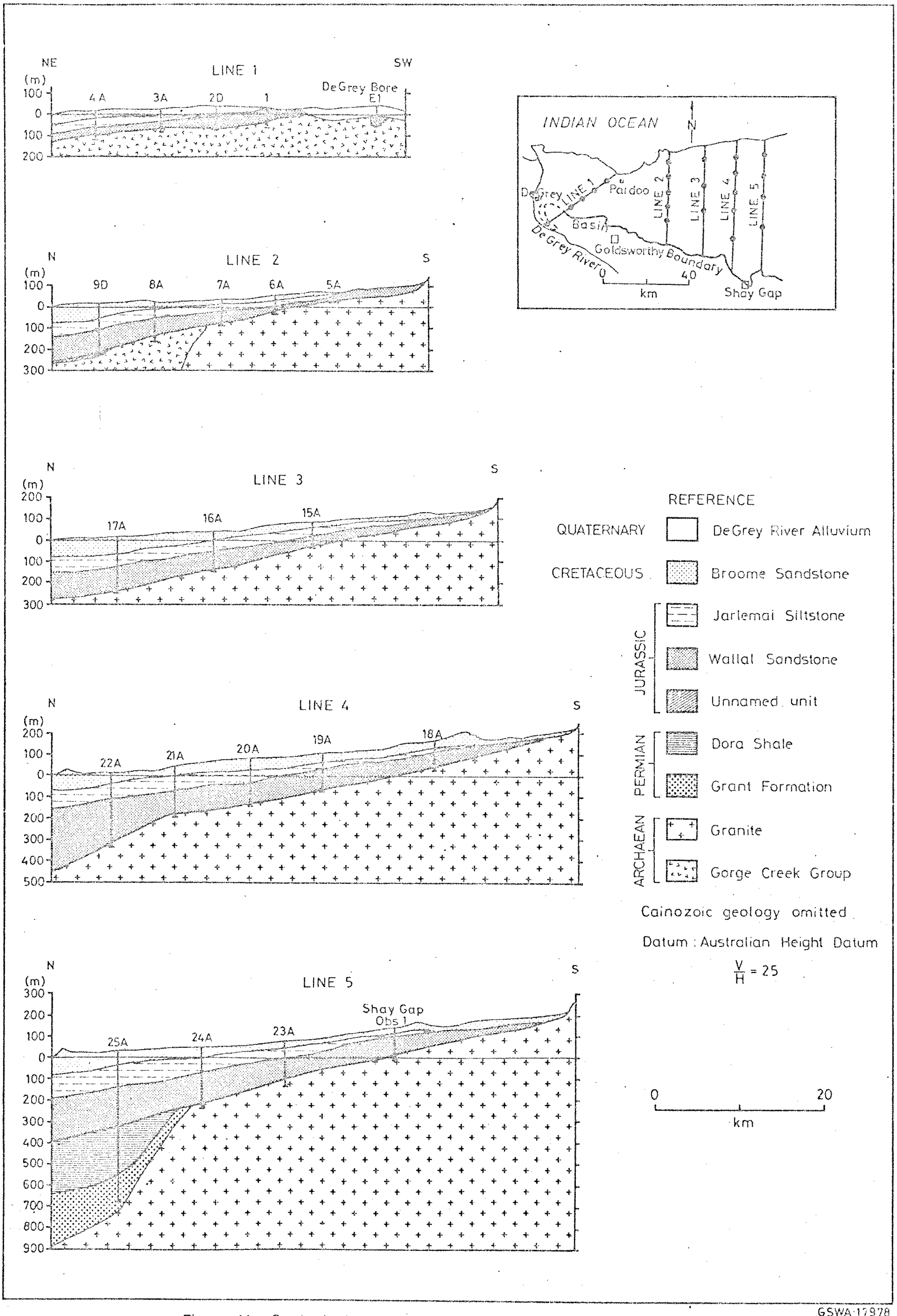


Figure 11: Geological cross-sections along lines 1 to 5.

TABLE 5. REDUCED LEVELS AND THICKNESS OF MESOZOIC ROCK UNITS*

Bore	Reduced level of natural surface (a) (m)	Wallal Sandstone			Jarlemai Siltstone			Broome Sandstone		
		Depth to base (b) (m)	Thickness (m)	Reduced level of base (m) (a)	Depth to base (b) (m)	Thickness (m)	Reduced level of base (m) (a)	Depth to base (b) (m)	Thickness (m)	Reduced level of base (m) (a)
1	19.666	63	36	-43.3	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED
2D	31.062	103	62	-71.9	41	8	-9.9	33	32	- 1.9
3A	19.170	90	35	-70.8	55	25	-35.8	36	35	-16.8
4A	12.675	117	42	-104.3	75	36	-62.3	39	38	-26.3
5A	64.712	40	14	24.7	26	14	38.7	12	5	52.7
6A	48.269	73	28	-24.7	45	15	3.3	30	24	18.3
7A	34.229	119	62	-84.8	57	30	-22.8	27	21	7.2
8A	15.115	158	82	-142.9	76	46	-60.9	30	18	-14.9
9D(c)	7.075	219	78	-211.9	141	69	-113.9	72	71	-64.9
10A	20.975	113	72	-92.0	41	20	-20.0	21	12	0.0
11A	19.732	97	21	-77.3	76	30	-56.3	36	31	-16.3
12A	32.168	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	40	15	-7.8
13A	46.100	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	NOT RECOGNIZED	53	26	-6.9
14A	53.704	72	36	-18.3	36	26	17.7	10	9	43.7
15A	84.314	114	51	-29.7	63	40	21.3	23	13	61.3
16A	41.976	180	89	-138.0	91	46	-49.0	45	41	-3.0
17A	18.750	253	116	-234.3	137	64	-118.3	73	62	-54.3
18A	157.641	122	69	35.6	53	15	104.6	38	37	119.6
19A	105.918	175	96	-69.1	79	28	26.9	51	45	54.9
20A	77.056	215	107	-137.9	108	51	-30.9	57	55	20.1
21A	37.877	227	115	-189.1	112	69	-74.1	43	33	-5.1
22A	11.081	343	218	-331.9	125	69	-113.9	56	55	-44.9
23A	70.912	171	104	-100.1	67	43	3.9	24	23	46.9
24A	43.768	266	151	-222.2	115	74	-71.2	41	40	2.8
25C(d)	16.212	339	189	-322.8	150	95	-133.8	55	43	-38.8
Shay Gap Obs 1	132.284	125	89	7.3	36	10	96.3	26	25	106.3

(a) Relative to AHD
(b) Relative to natural ground surface
(c) Bore 9D intersected an unnamed Middle Jurassic claystone unit between 219-224 m bns
(d) Bore 25C intersected 357 m of Permian sediments below the Wallal Sandstone.

GEOLOGICAL HISTORY

There are no indications of Palaeozoic sedimentation in the investigation area prior to the Early Permian. It is therefore likely that either this part of the basin was a land mass before this time or, if sediments had been deposited they had already been removed by erosion. During Permian times the glacigene Grant Formation of Sakmarian age was deposited unconformably on Archaean basement rocks. During Late Sakmarian or Early Artinskian times the basin subsided and the Dora Shale, a continental sequence of claystone, siltstone and sandstone, was deposited. At the end of the Permian an interval of uplift occurred and sedimentation ceased.

During Middle Jurassic times renewed subsidence resulted in a marine transgression, which by the Bajocian had reached the study area. The unnamed claystone unit was then deposited unconformably on Archaean basement. Further subsidence occurred in the Callovian, and the Wallal Sandstone was deposited. Over most of the Canning Basin this sandstone is the basal unit of the Jurassic marine transgression, and in the study area it was deposited unconformably on Archaean or Permian rocks. By Oxfordian times the sea had moved further inland, and the marine Jarlemai Siltstone was deposited disconformably on the Wallal Sandstone in a relatively low-energy environment. During Upper Jurassic and Early Cretaceous times the regressive Broome Sandstone was deposited in a non-marine, high-energy environment.

The sediments which comprise the Mesozoic and Palaeozoic formations of the Anketell Shelf were derived from the Pilbara Block to the south. The component grains of chert, jasper, quartzite and basic volcanic rock lithologically resemble the Gorge Creek Group and this confirms their origin.

From the Early Cretaceous until the present, uplift and erosion has taken place with only very minor deposition. Elsewhere in the Canning Basin there is evidence (Brunnschweiler, 1957) of several marine transgressions and regressions during this time.

HYDROGEOLOGY

AQUIFER RELATIONSHIPS

The Broome and Wallal Sandstones, which comprise the main aquifers, support two flow systems that are hydraulically separate over the investigation area. The separation is effected by the Jarlemai Siltstone. The flow system in the Broome Sandstone is essentially unconfined and recharge is either by direct percolation from rainfall or indirectly throught the thin Tertiary or Quaternary sediments. This may take place over quite large areas. In contrast, groundwater flow in the Wallal Sandstone takes place under confined conditions and recharge from rainfall is only possible over the limited area where the Jarlemai Siltstone is absent.

A limited interconnection between the two aquifer systems may occur in the area where the Jarlemai Siltstone is absent. However, elsewhere, groundwater movement in each aquifer is separate and differs markedly in direction.

The Tertiary and Quaternary deposits contain small groundwater storages that are probably in hydraulic continuity with the Broome Sandstone.

TERTIARY AND QUATERNARY

The Tertiary and Quaternary deposits are unimportant for the development of large supplies of potable groundwater from this area. These deposits have only a limited areal extent and are too thin to contain large volumes of groundwater. However, useful yields may be locally obtained for stock watering. The following brief descriptions of the hydrogeology of the superficial deposits are based on data collected from well census work in the investigation area.

Kankar

The limestone has only a small areal extent, and is probably up to 4 m thick. Two station wells tap the kankar and these have salinities of 2 500 mg/L and 6 050 mg/L.

Bossut Formation

The Bossut Formation occurs extensively along the coastal plain, and has a maximum thickness of about 25 m. This lithified dune deposit has numerous solution tubes which give it a very high secondary porosity, and it is therefore capable of yielding large supplies. Station wells sunk into this formation contain water whose salinity ranges from 1 020 to 10 800 mg/L (T.D.S.). The Bossut Formation's proximity to the coast means that heavy pumping would induce sea - water intrusion.

An analysis from Lambs Well which taps the Bossut Formation shows that the groundwater from this formation is unsuitable for domestic consumption. Concentrations of fluoride, boron and nitrate all exceed the normally accepted limits for human consumption (Hart, 1974); the analysis is given in Table 7.

Sand

The residual soils and sand which cover most of the area are less than 6 m thick. Most station wells penetrate the superficial sands and abstract groundwater from the underlying formations. The sands are considered to be too thin to provide a useful aquifer; they hold only a small amount of groundwater in storage.

Alluvium

The De Grey River alluvium contains a large groundwater resource; this aquifer system has been described by Davidson (1973).

Other alluvium in the investigation area occurs in the west along the coastal plain and along Pardoo Creek. These deposits are up to about 10 m thick and individual bores or wells which are sunk in them are reported by pastoralists to have yields of up to 350 m^3/day. The groundwater salinity is variable, ranging from 700 mg /L to 15 000 mg/L.

Coastal sand dunes

Small supplies of potable groundwater can be obtained from the coastal dunes. Station wells in these deposits have salinities of less than 2 000 mg/L (T.D.S.). Heavy pumping from these wells could cause sea-water intrusion.

BROOME SANDSTONE

The Broome Sandstone, which reaches a thickness of up to 71 m, is the largest unconfined aquifer in this part of the Canning Basin. Recharge is by direct percolation from rainfall, and groundwater movement is generally towards the north where the groundwater is discharged into the Indian Ocean (Fig. 12).

Hydraulic testing

Test pumping was undertaken on five single bores completed

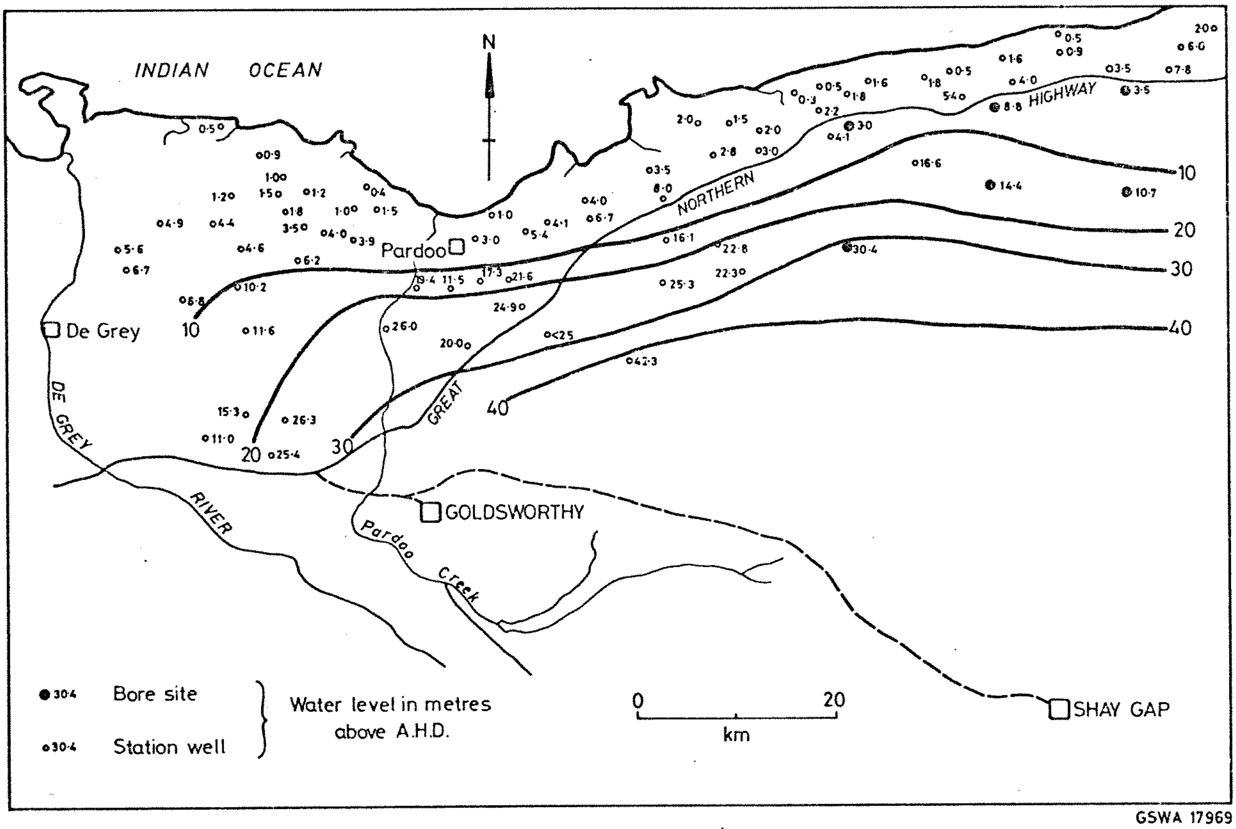


Figure 12: Water-table contours, 24th August 1977

in the Broome Sandstone. As observation bores were not provided, drawdown and recovery records were only available from the pumping bores. The drawdowns at selected times during the constant discharge tests were calculated from the pressure change recorded by the electronic equipment. These were corrected for bore inefficiency and partial penetration and then plotted on a logarithmic scale against log time and matched to the type curves described by Prickett (1965). These are based on theory developed by Boulton (1963), and allow for delayed gravity drainage from the sediments above a declining water table. Figure 13 is an example of an unconfined aquifer test analysis, and is on bore 16B.

Bore-hole inefficiency was determined from the analysis of step-drawdown tests. The general equation for drawdown in a pumping bore (after Sheahan, 1971) is:

$$s = (B_t + C')\,Q + CQ^p$$

Where s = drawdown

B_t = formation loss factor

C' = laminar flow bore loss factor

Q = discharge

C = turbulent flow bore loss factor

p = some power, usually between 1.7 and 4, often assumed to be 2.0.

The factor, C', is usually an order of magnitude smaller than the factor, B_t, so assuming $C'=0$, the general equation reduces to

$$s = B_tQ + CQ^p$$

Bore efficiency is given as $\frac{B_tQ}{s}$ (Lennox, 1966) and is usually

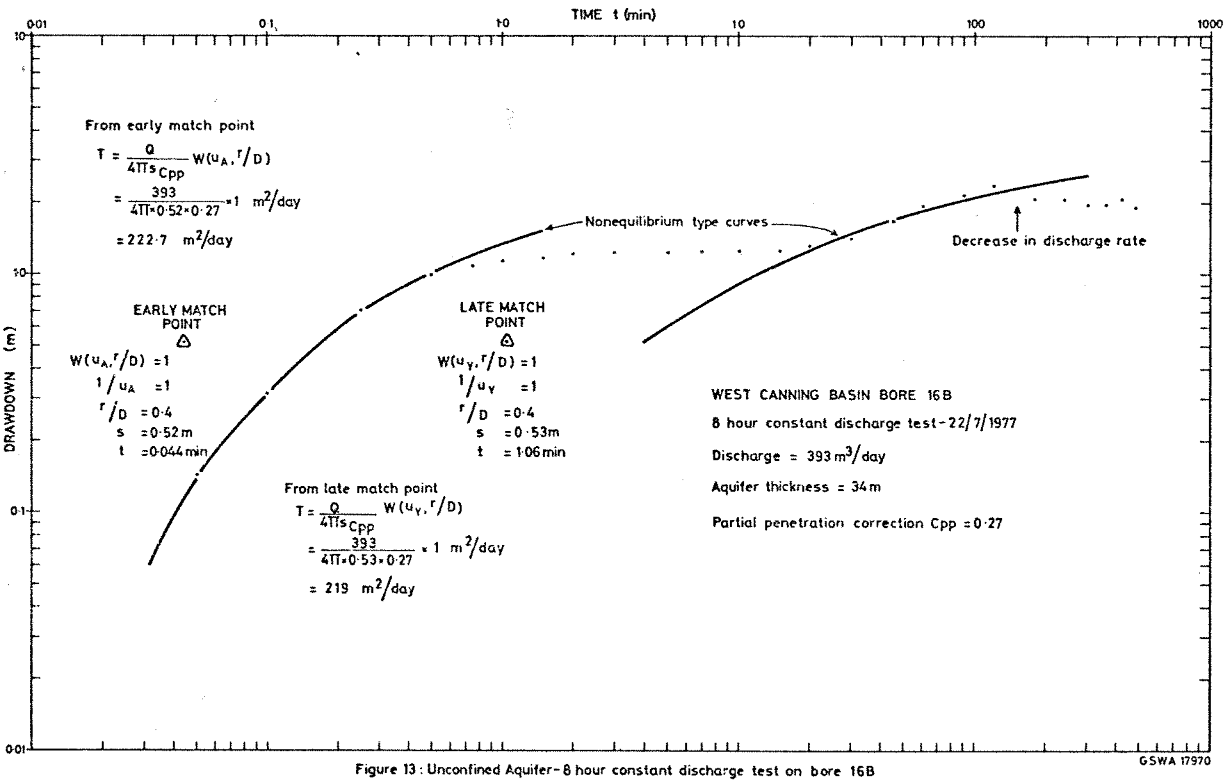


Figure 13: Unconfined Aquifer- 8 hour constant discharge test on bore 16B

expressed as a percentage. The constants B_t, C and p can be derived from a type curve solution to step-drawdown tests produced by Sheahan (1971). This method of analysis is quick and efficient, and can be completed in the field to ascertain whether bore development is occurring during pumping.

Partial penetration corrections were estimated from tables published by Walton (1962). In predicting the correction factor it is assumed that the horizontal and vertical permeabilities are equal. A dewatering correction was not applied to the drawdown data, as the dewatered depth of aquifer was small when compared to the aquifer thickness.

Results: The analytical results for the unconfined Broome Sandstone are shown in Table 6.

TABLE 6. BROOME SANDSTONE BORE INFORMATION AND PUMP-TEST RESULTS

Broome Sandstone Bore Site	Saturated aquifer thickness (m)	Dis-charge (m^3/day)	Corrected drawdown at 1 hour (m)	Trans-missivity (m^2/day)	Hydraulic conduct-ivity (m/day)
16B	34.2	393	1.91	222	6.5
17B	56.9	632	0.85	854	15
21B	19.9	29.4	0.05	159	8.0
22B	53.1	626	3.10	138	2.6
25D	48.1	735	1.27	250	5.2
Average	-	-	-	325	7.5

Transmissivity values varied from 138 to 854 m^2/day, and averaged 325 m^2/day. Hydraulic conductivity values ranged from 2.6 to 15 m/day, and averaged 7.5 m/day. The aquifer consists of a fine- to coarse-grained, moderately sorted sandstone for which the published results for similar rocks (Krumbein and Monk, 1943; Turneaure and Russell, 1947;

Johnson, 1963; and Lovelock, 1970) suggest a hydraulic conductivity of between 5 and 15 m/day.

The average values for transmissivity and hydraulic conductivity therefore appear to be of the correct order.

The specific yield of the Broome Sandstone aquifer could not be determined as observation bores were not installed in the cones of depression of the pumping bores.

Recharge

Recharge to the Broome Sandstone is generally by direct percolation from heavy rainfall, but some infiltration may take place locally through a thin covering of Tertiary or Quaternary sediments with which the sandstone is in hydraulic connection. The water table declines during winter to early summer, and rises, after cyclonic rainfalls, in late summer through to autumn.

It is possible to calculate a figure for the percentage of rainfall which reaches the water table during particular recharge events such as cyclones. This may be done for cyclones Karren and Leo which occurred in March, 1977. For this calculation a porosity has to be assumed. The Broome Sandstone at site 24 is mainly a fine- to coarse-grained, poorly sorted sandstone, which indicates a porosity of about 0.3 (Hazel, 1973). Cyclones Karren (6/3/1977) and Leo (27/3/1977) resulted in a rainfall of 159 mm and a corresponding rise of 32 mm in the water table (33 m below ground level). The percentage of rainfall reaching the water table can be calculated from the following equation by assuming a porosity of 0.3:

$$\text{percentage of rainfall reaching water table} = \frac{\text{porosity x change in water level x 100}}{\text{rainfall}}$$

$$= \frac{0.3 \times 32 \times 100}{159} \%$$

$$= 6\%$$

As there is no runoff a 6% recharge figure from rainfall means that the remaining 94% of rainfall is accounted for by evapotranspiration and in satisfying the soil moisture deficit. The recharge figure of 6% may be high in relation to smaller rainfalls as it is calculated for a particularly intense period of rainfall. For example, the 45 mm of rain which fell on 16/1/1977 did not affect the water table hydrograph as it was all lost by evapotranspiration or in satisfying the soil moisture deficit. It therefore seems likely that the rate of recharge will be variable, depending upon rainfall intensity and prevailing conditions at the time of rainfall.

Storage

The groundwater stored in the Broome Sandstone can be estimated as the product of the saturated volume and the specific yield. The volume is the product of the aquifer's areal extent and the average saturated thickness. The thickest known saturated interval is 56.9 m at site 17, and two bores constructed in the Broome Sandstone at sites 19 and 20 were dry. As control in this aquifer is limited to six sites in the eastern area, the average saturated thickness is taken to be 20 m. The 'effective area' from which groundwater can be abstracted is bounded to the south by a line joining site 1 to a point just north of site 23, to the west by line 1, to the north by the Indian Ocean, and to the east by line 5. This area is 1 575 km^2. As a specific yield could not be calculated from pumping tests, it is estimated to be 0.1 which may be a little low for the Broome Sandstone. The interstitial storage can be estimated from the following equation:

$$Q_s = V\ S_y$$

where Q_s = interstitial storage (m^3)

V = saturated aquifer volume (m^3)

S_y = specific yield (dimensionless)

Therefore,

$$Q_s = 1\ 575 \times 10^6 \times 20 \times 0.1\ m^3$$

$$= 3.2 \times 10^9\ m^3$$

Throughflow

A flow net was not constructed because it would not be meaningful, as too many parameters have to be estimated from the inexact data available. However, to appreciate the size of the resource it is possible to calculate the throughflow across the 10 m water-table contour (Fig. 12). The groundwater throughflow is the product of the hydraulic conductivity, hydraulic gradient and aquifer cross-sectional area. The mean hydraulic conductivity of 7.5 m/day has been derived from averaged pumping-test results; the hydraulic gradient has been estimated from Figure 12 as the average of the shallowest and steepest gradients and is 2.5×10^{-3}; and the aquifer width for this determination of throughflow is taken as the length of the 10 m contour (Fig. 12), which is 100 km. The mean saturated thickness may be derived from Figures 8 and 12 which give the contours on the base of the Broome Sandstone, and the water table, respectively. This is 29.3 m. Throughflow can be calculated from the following equation:

$$Q = Kbil$$

where Q = throughflow (m^3/year)

K = hydraulic conductivity (m/day)

b = saturated aquifer thickness (m)

i = hydraulic gradient (dimensionless)

l = length of section (m)

Therefore,

$$Q = 7.5 \times 29.3 \times (2.5 \times 10^{-3}) \times 100 \times 10^{3} \times 365 \text{ m}^3\text{/year}$$
$$= 20 \times 10^{6} \text{ m}^3\text{/year.}$$

Inspection of the salinity pattern (Fig. 14) discussed below, indicates that only about a third of this throughflow has less than 1 000 mg/L total dissolved solids. The calculated annual throughflow volume represents about 0.6% of the aquifer storage calculated above.

Discharge

Groundwater movement is essentially northwards, where it discharges into the Indian Ocean. There may also be a small evapotranspiration loss along the coastal strip where phreatophytes (normally eucalypts) make use of the water table. The only other loss from this aquifer system is from a few station wells; again this is small compared to the outflow.

To the west of drill line 1, the water-table contours show discharge to the west and northwest into the De Grey alluvial deposits. This indicates that hydraulic continuity exists between the Broome Sandstone and the De Grey alluvium.

Hydrographs

A Leupold-Stevens A35 water-level recorder with pluviometer attachment was installed on water-table bore 24B on the 4th November, 1975 and provided continuous records until October, 1977. Hydrographs showed the water level (at this site, 33 m below the surface) to be fairly static, except for a 32 mm rise after cyclones Karren and Leo during March, 1977, which together gave a total rainfall of 159 mm. The full water-table response to these events took 3 months, due to the time taken for downward percolation through the unsaturated zone above the water table. Other small rainfall events during the two year period of records had no effect on the water table.

Bore census results show that the water-table decline in shallow wells during winter and spring is variable and may be up to a maximum of 0.2 m per month. Water-table falls are largest in years following a dry summer season, when annual declines may be up to 2 m.

Hydrochemistry

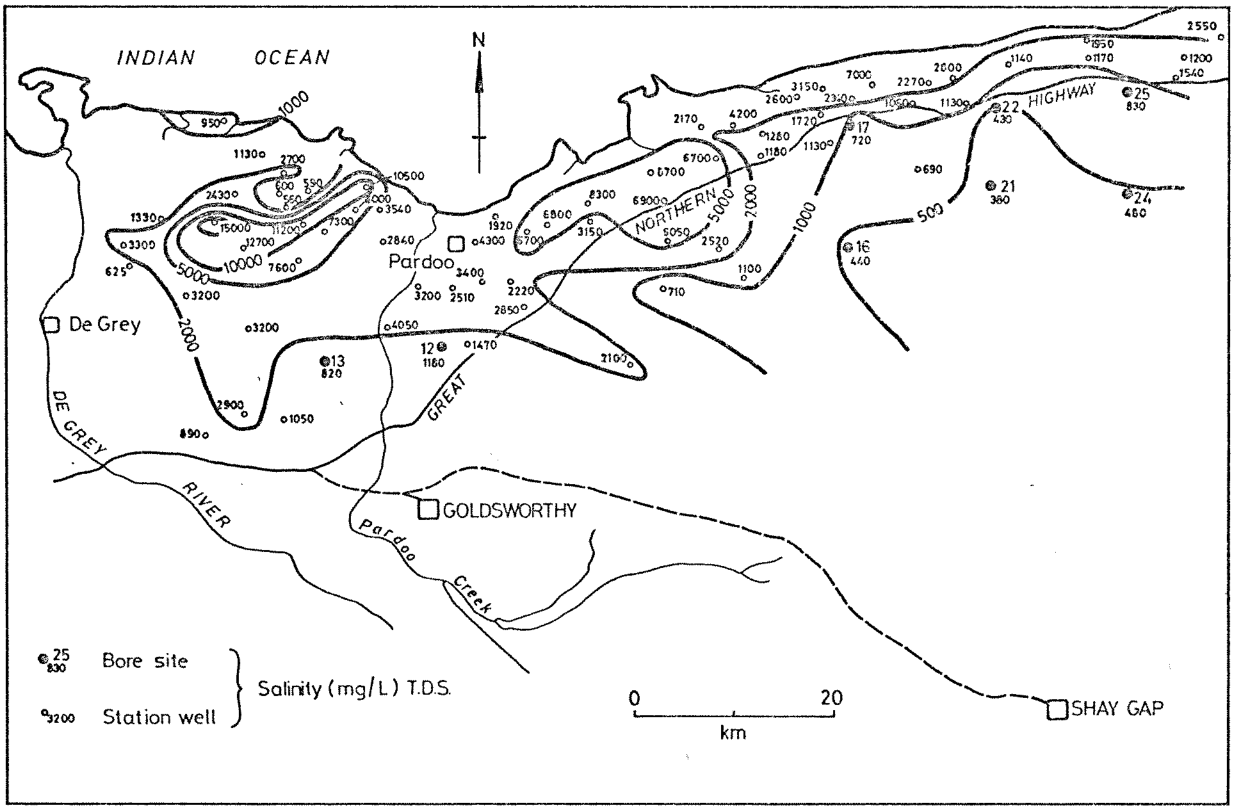
Eight standard analyses (Table 7) were completed by the Government Chemical Laboratores on samples collected from the Broome Sandstone; a ninth sample from Lambs Well which taps the Bossut Formation was also analysed. The areal variation in groundwater salinity (total dissolved solids) of this aquifer is shown in Figure 14; sixty-seven station wells and six project bores make up the sampling points. Of the station wells, forty of the sixty-seven are non-operational and the

TABLE 7. CHEMICAL ANALYSES OF NINE WATER SAMPLES FROM THE BROOME SANDSTONE AND BOSSUT FORMATION

Well/Bore GCL NO.(a)	12A 21540	13A 21536	16B 84193	17B 84195	21B 84197	22B 84199	24B 82754	25D 82753	Lambs Well 28009
pH	7.7	7.7	7.6	7.5	7.8	7.6	7.5	7.6	7.9
Odour	nil	nil	nil	nil	nil	nil	nil	nil	nil
TDS (Evap)(mg/L)	1180	820	440	720	380	430	480	830	1060
TDS (Cond)(mg/L)	1270	850	460	770	400	450	510	870	1120
Total hardness (mg/L)	383	166	179	196	143	153	167	304	156
Total alkalinity (mg/L)	281	205	181	190	153	138	133	195	336
Ca (mg/L)	81	40	47	49	34	38	49	89	43
Mg (mg/L)	44	16	15	18	14	14	11	20	12
Na (mg/L)	252	216	77	172	73	81	88	151	313
K (mg/L)	10	7	2	8	2	2	5	6	8
CO_3 (mg/L)	nil	nil	nil	nil	nil	nil	nil	nil	nil
HCO_3 (mg/L)	342	250	220	232	186	168	162	238	409
Cl (mg/L)	406	258	95	211	81	106	127	261	291
SO_4 (mg/L)	50	56	15	80	20	27	22	46	60
NO_3 (mg/L)	52	21	24	12	20	19	37	35	47
SiO_2 (mg/L)	58	52	56	59	58	54	49	82	69
B (mg/L)	0.4	0.3	0.65	0.65	0.51	0.65	0.41	0.44	1.2
F (mg/L)	0.7	0.5	0.50	0.50	0.60	0.50	0.50	0.40	2.1
CATIONS (b)									
Ca (me/L)	22	16	33	21	28	29	34	35	13
Mg (me/L)	19	10	18	13	19	17	12	13	6
Na + K (me/L)	59	74	49	66	53	54	54	52	81
ANIONS (b)									
HCO_3 (me/L)	31	33	55	33	53	44	40	32	41
Cl (me/L)	63	58	40	52	40	47	53	60	51
SO_4 (me/L)	6	9	5	15	7	9	7	8	8
S.A.R.	5.6	7.3	2.5	5.3	2.7	2.8	3.0	3.8	10.6
Cl/HCO_3 ratio	1.19	1.03	0.43	0.91	0.44	0.63	0.78	1.10	0.71

(a) Government Chemical Laboratories' sample number

(b) Percentage milliequivalents per litre



GSWA 17971

Figure 14 : Isohalines in the unconfined aquifers

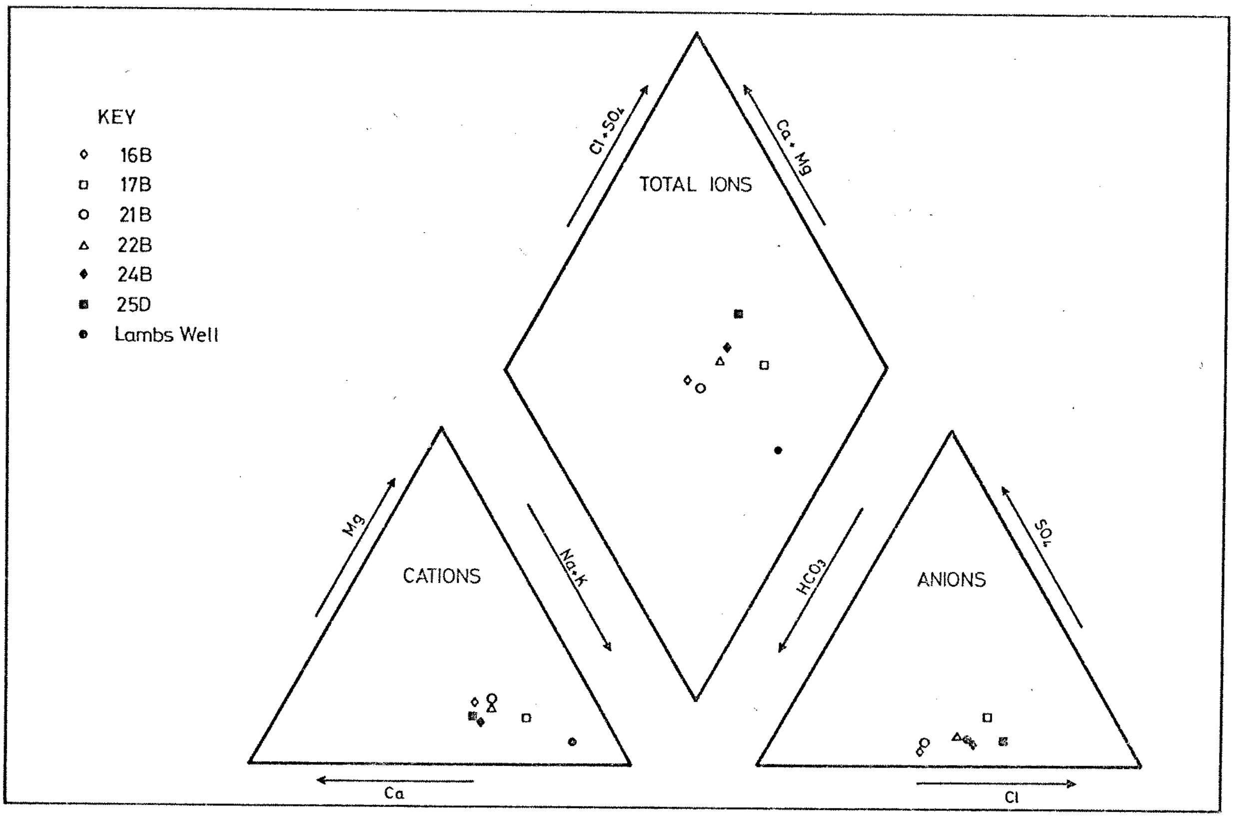


Figure 15: Trilinear diagram of unconfined groundwater analyses(per cent equivalents per million)

GSWA 17972

measured salinity may consequently not reflect that of water in the aquifer itself. For this reason, and the large variations in salinities over short distances, the isohaline shown on Figure 14 are only approximate;

Salinities in the Broome Sandstone east of drill line 2 are less than 1 000 mg/L, but to the west rise to more than 3 000 mg/L. Salinities from wells constructed in the coastal dunes are generally less than 2 000 mg/L. Further inland, on the coastal plain, salinities from the alluvium rise appreciably. This may be due to high soil salt caused by a Holocene high sea level; in this region salinities of up to 15 000 mg/L have been recorded.

Groundwater quality: A trilinear (Piper) diagram of the major cations and anions (Fig. 15) shows all analyses to have approximately the same ionic balances, except Lambs Well which has a large sodium content.

In general, the concentrations of the total soluble salts and the common ions in water from the Broome Sandstone make it acceptable for domestic use. However, the analyses in Table 7 show that nitrate varies from 12 to 52 mg/L. The recommended acceptable limit in Australia (Hart, 1974) is 23 mg/L, and that set by the World Health Organization (1971) is 45 mg/L. Several analyses exceed these limits and if untreated water is used for drinking it could cause methaemoglobinaemia in young children. A plot of the sodium absorption ratio (Figure 16) for analyses of groundwater from the Broome Sandstone indicates that the water has a medium to high salinity hazard, and is therefore probably not suitable for irrigation. High evaporation rates could be expected to exacerbate the hazard by producing increases in the amount of salt stored in soils.

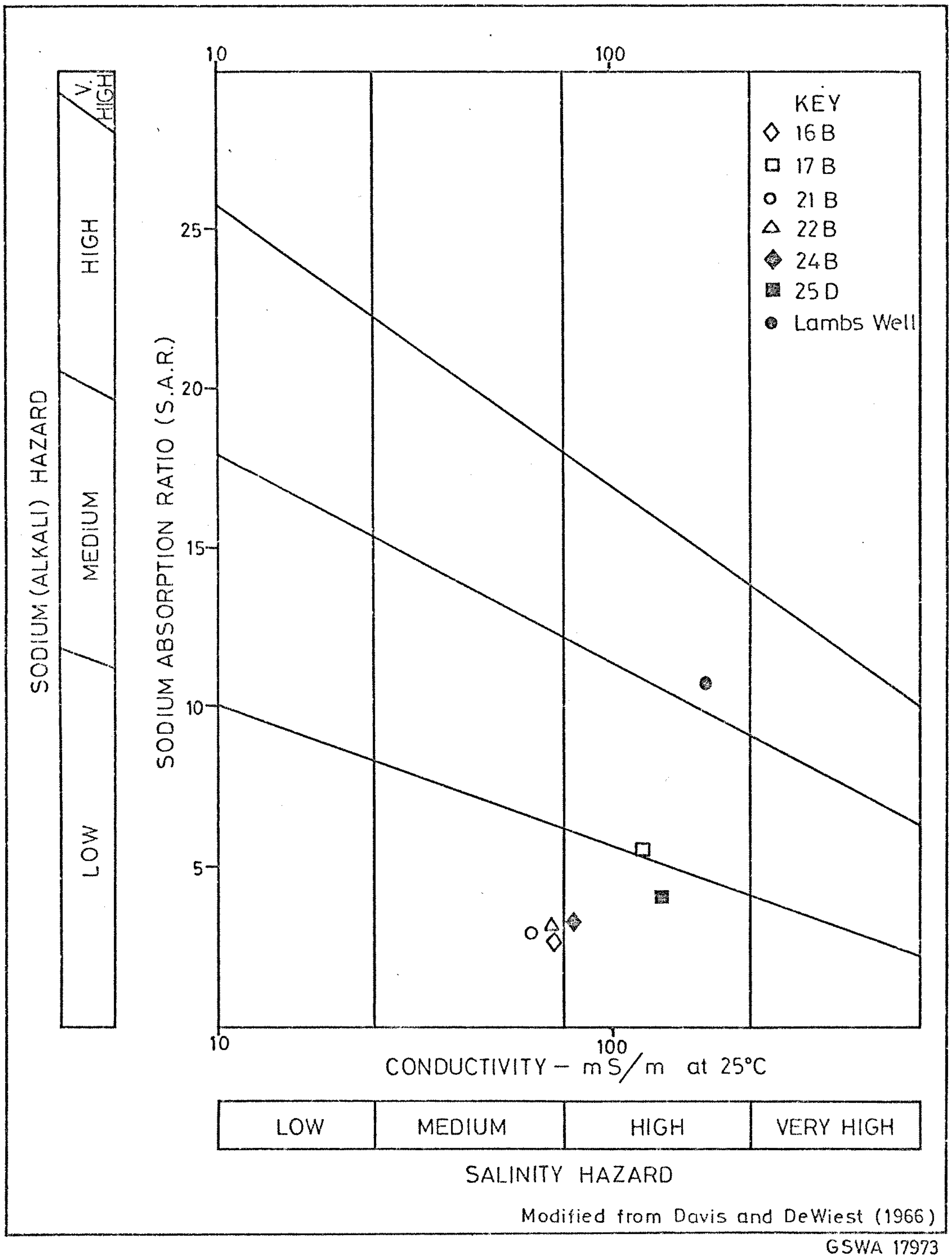


Figure 16: Unconfined Groundwater, classified for potential irrigation use.

Development

At present only station wells tap the Broome Sandstone for stock watering. Further development of this aquifer for water-supply purposes would depend upon the quality criteria imposed by the consumer. The salinity of groundwater to the east of drill line 2 makes it suitable for domestic purposes, but to the west it may only be acceptable for certain individual uses. If a production bore field is to be constructed in the investigation area it should develop both the Broome and Wallal Sandstone aquifers. Besides more fully developing the total water resources, this could have the effect of bringing the average nitrate concentration down to an acceptable level (subject to appropriate management). The alternative is to carry out expensive denitrification treatment to render the Broome Sandstone groundwater suitable for human consumption.

WALLAL SANDSTONE

The Wallal Sandstone occurs in the subsurface over most of the area, and consists of a fine- to very coarse-grained, poorly to well-sorted, unconsolidated sandstone. This aquifer provides large artesian flows from bores drilled into it along the coastal plain, where positive heads in excess of 30 m have been measured. The potentiometric contours for this aquifer (Fig. 17) indicate that recharge takes place in the southeast and that groundwater movement is to the west and northwest. Recharge is by infiltration of rainfall south of the Jarlemai Siltstone subcrop, where the aquifer becomes unconfined, and to the southeast outside the investigation area (Fig. 18). Groundwater discharge is mainly off-shore towards the northwest except for a few small springs in the Pardoo area (Fig. 17).

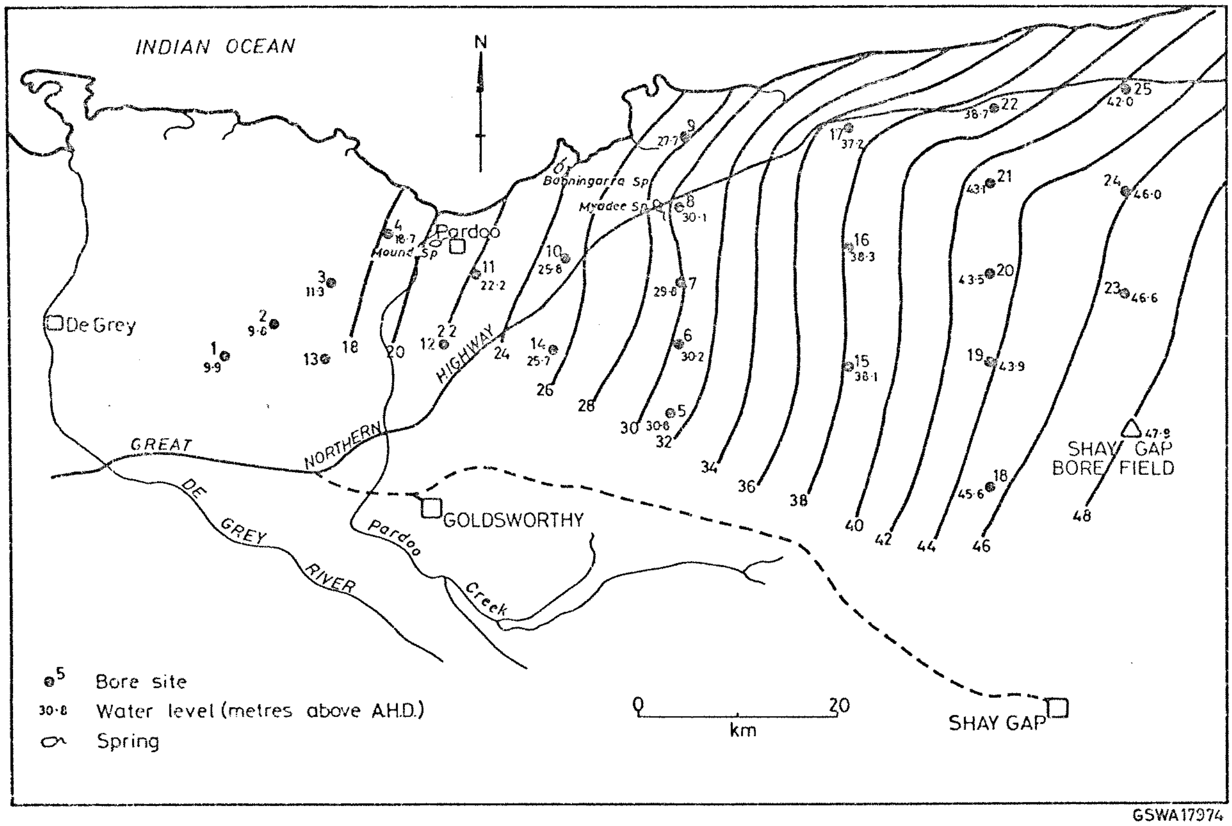


Figure 17: Wallal Sandstone potentiometric contours, 13th May 1977

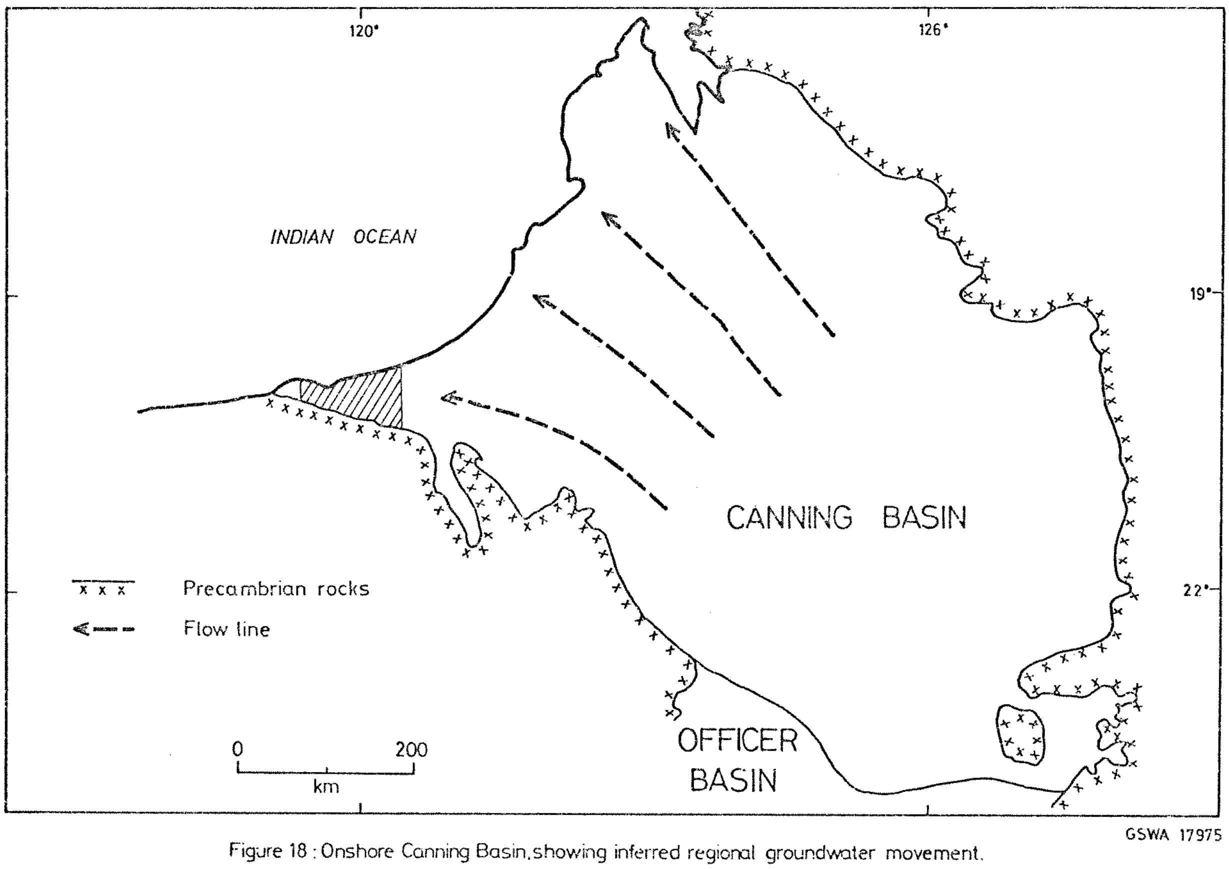


Figure 18: Onshore Canning Basin, showing inferred regional groundwater movement.

Hydraulic testing

The analysis of data collected by test-pumping single bores (i.e. tests not run in conjunction with observation bores) is subject to the difficulty of eliminating the hydraulic effects of the bore structure. It was therefore necessary to undertake step-drawdown tests to provide data to apply corrections for these effects. Constant discharge and step-drawdown tests were conducted on 18 sub-artesian and artesian bores. All pressure-head data from the Rickadenki or Hewlett-Packard recorder charts for selected times during constant discharge tests were converted to drawdown and then corrected for the bore inefficiency (assessed from the step-tests), and also in some cases for barometric pressure changes.

Plots of log drawdown against log time have been analysed using leaky artesian type curves described by Walton (1962), based on the leaky artesian formula developed by Hantush and Jacob (1955). Drawdown in test bores in the Wallal Sandstone all approach steady-state conditions after 1 to 3 minutes from the start of pumping.

The collection of 'early time' (up to 1 minute) data by continuously recording the output of pressure transducers allows matches to be made with the leaky artesian type curves. All responses to pumping follow the Theis non-equilibrium type curve for a short time before leakage occurs, even though the influence of bore casing storage may take several minutes before it ceases to have an effect in bores yielding small discharges. This allows a match point to be selected, and, therefore, a determination of transmissivity and hydraulic conductivity. Recovery data from several tests were used, and this data confirmed the results obtained from the analysis of the drawdown data. Figure 19 shows a typical response from a constant discharge test on bore 22A.

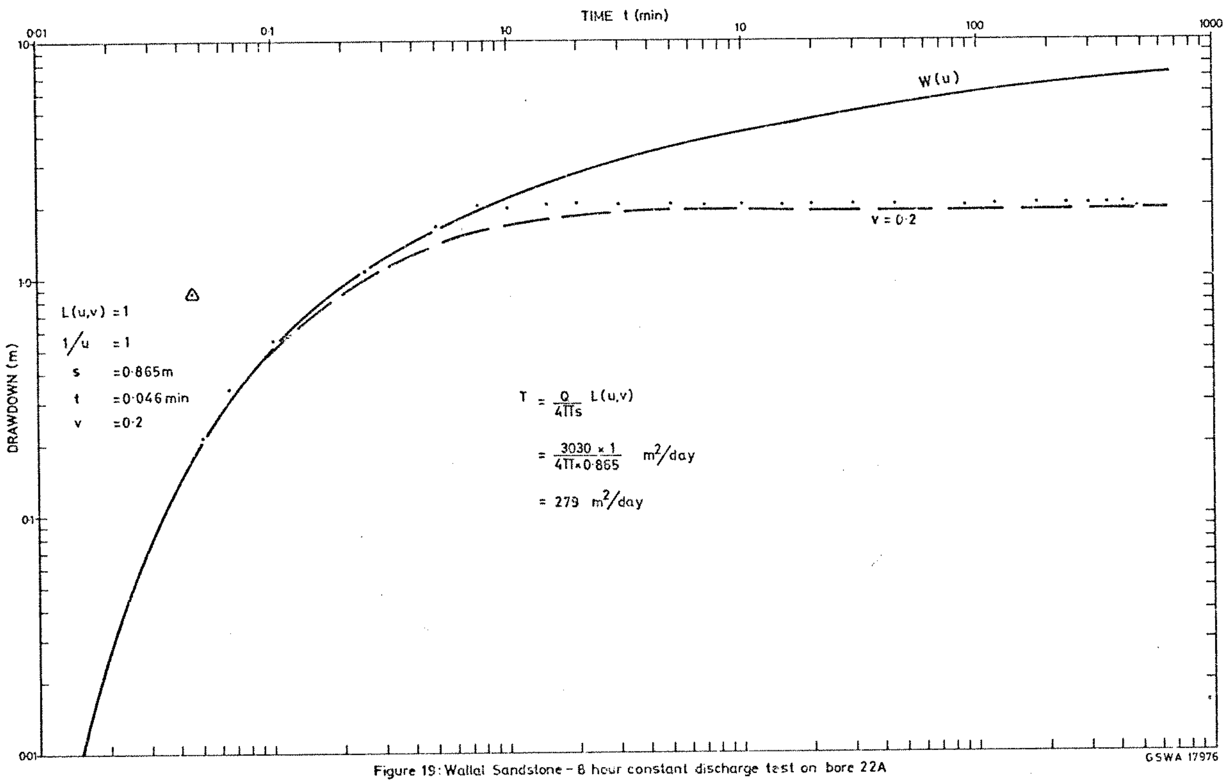


Figure 19: Wallal Sandstone – 8 hour constant discharge test on bore 22A

TABLE 8. PUMP- AND FLOW-TEST RESULTS FROM THE WALLAL SANDSTONE AQUIFER

Bore	Type of test	Aquifer thickness (m)	Screen length (m)	Discharge[a] (m^3/day)	Transmissivity[b] (m^2/day)	Hydraulic conductivity (m/day)	Storage coefficient
3A	Pump	35	18	614	145	8.1	
4A	Flow	42	42	199	69	1.6	
6A	Pump	28	24	650	129	5.4	
7A	Pump	62	24	641	204	8.5	
8A	Flow	14	12	1 464	40	3.3	
8B	Flow	24	18	939	104	5.8	
9D	Flow	99	18	508	10	0.6	
10A	Flow	72	42	769	272	6.5	
16A	Pump	89	15	672	145	9.7	
17A	Flow	116	24	2 100	142	5.9	
19A	Pump	96	18	532	54	3.0	
20C	Observation bore	107	18	626	2 490	138.3	2.0×10^{-4}
20D	Pump	107	16.8	626	720	42.9	
21A	Flow	115	24	247	409	17.0	
22A	Flow	218	18	3 030	279	15.5	
23A	Pump	104	18	645	569	31.6	
24A	Flow	151	8.3	69	200[c]	24.1	
25C	Flow	189	24	1 394	130	5.4	
Average	-	100			340	18.5	2.0×10^{-4}

(a) Discharges shown are those for the constant discharge test

(b) Transmissivity values are for the screened interval only

(c) Estimated from specific capacity calculation

Results: Table 8 shows the analytical results from all constant discharge tests on the confined aquifer. Although drawdown data were corrected where applicable, there is still a wide range of values for transmissivity and hydraulic conductivity.

The hydraulic conductivity values shown in Table 8 were calculated for only the screened interval of the aquifer; the reason for this is outlined in the discussion below. Transmissivity values range from 10 to 2 490 m^2/day and average 340 m^2/day (Table 8). The corresponding range of hydraulic conductivity values is 0.6 to 138.3 m/day, and the average is 18.5 m/day (Table 8). These results do not show any consistent geographic distribution but, in general, transmissivities decrease from east to west.

Storage coefficients can only be reliably calculated from tests where observation bores are used. Three such test bores were conducted at sites 16, 20 and 23. Results from two of these (at sites 16 and 23) were poor and storage coefficients could not be derived due to inadequate drawdown responses in the observation bores. The constant discharge test at site 20 yielded a storage coefficient of 2.0×10^{-4}. This value compares favourably with the storage coefficient of 3.3×10^{-4} which was derived from barometric efficiency (see page 69).

Discussion: All plots of drawdown against time showed steady-state conditions after about three minutes. These plots were matched to leaky artesian type curves. The lithology of the Jarlemai Siltstone, a thick impermeable clay formation, suggests that the vertical leakage from this confining bed would be too small to allow steady-state conditions to be reached in such a short time after the start of pumping. Further, the potentiometric head of the Wallal Sandstone, where it is confined, was above the water table during the flow and pump tests. This means that during the test there was a potential for upward groundwater movement from the Wallal Sandstone to the confining bed. The observed response indicates that the cone of influence has ceased expanding and that the discharge is sustained by a recharge boundary or by leakage. There is no geological or hydrological evidence to support the presence of recharge boundaries. Therefore, it is concluded that the observed response results from leakage within the aquifer, caused by inhomogeneity and stratification of the sediments which together produce anistropic conditions. If the stratification argument is accepted then no partial penetration correction is needed as the bore is 'fully penetrating', because the aquifer is only yielding groundwater from the screened interval and by leakage from above and below the screen.

Because the response time before leakage occurs is very rapid (less than three minutes), the stratification argument seems realistic. Theoretically, analytical solutions of drawdown equations assume the aquifer is isotropic, homogenous and of infinite areal extent; this is never the case in real aquifers. Stratification within the aquifer was probably caused by variations in sediment supply at the time of deposition. Further, cross-bedding and alignment of grains would result also in greater hydraulic conductivities in a horizontal than in a vertical direction.

If this is the case the transmissivities derived from the analyses of tests are applicable only for the screened interval, and a corresponding mean hydraulic conductivity can be derived for that interval. This figure may then be applied to the entire aquifer thickness to derive the aquifer transmissivity.

As the sands of the Wallal Sandstone have a fairly uniform grain size throughout the extent and thickness of the formation, its hydraulic conductivity should be reasonably uniform. Several workers (Krumbein and Monk, 1943; Turneaure and Russell, 1947; Johnson, 1963; and Lovelock, 1970) have derived relationships between grain size and hydraulic conductivity (permeability). Sieve analyses of several samples from the Wallal Sandstone give a mean particle diameter of 0.4 mm. Published data indicate that sands of this mean grain size have hydraulic conductivity values in the range 25 to 100 m/day. The average value of 18.5 m/day derived for the Wallal Sandstone aquifer (Table 8) seems to be conservative; therefore a value of 20 m/day is adopted for flow net analysis on page 61. Some hydraulic conductivity values generated from flow net analysis (page 63) exceed those obtained from test pumping (Table 8). This is described in more detail under flow net analysis.

Recharge

Recharge to the Wallal Sandstone is to the south and southeast of the investigation area where the Jarlemai Siltstone pinches out (Fig. 7). Recharge in this region is by direct percolation from rainfall, and probably occurs only as a result of the high intensity falls associated with cyclones. The area lies on a cyclone track of relatively high frequency.

A Leupold-Stevens A71 water-level recorder with pluviometer attachment was installed on bore 20C. Water-level records were measured from 4th November, 1975 to 31st October, 1977. No responses to possible recharge events, such as cyclones Karren and Leo were recorded. The only water-level fluctuations recorded were due to barometric and earth-tide effects, which showed amplitudes of up to 20 mm.

A storage/flow ratio (Chapman, 1963) can be used to indicate the response to recharge in a confined aquifer. The storage/flow ratio is defined as: the ratio of the storage upstream of any cross section to the flow through that section; the ratio is expressed in units of time, usually years.

To calculate a storage/fow ratio the total aquifer volume upstream of a given section is required; this volume is not known for the southwestern Canning Basin as the investigation did not extend far enough to the east and southeast. However, it is possible to calculate a minimum figure which can be accurately defined within the project area. If the flow section is taken to be along the 42 m potentiometric contour, and the upstream limit is defined as the 46 m contour, then the aquifer storage between the two contours can be accurately determined. The area between these contours (Fig. 20) is 5.87×10^8 m^2, and the average aquifer thickness along the 44 m potentiometric contour is 115 m. Therefore, the aquifer volume is 6.75×10^{10} m^3. The total volume of water in storage is the product of the aquifer volume and the specific yield. This has been determined for the Wallal Sandstone to be approximately 0.28 (see p. 14). Therefore, the volume of water in storage between the 42 and 46 m potentiometric contours is 1.89×10^{10} m^3. The flow through the 42 m potentiometric contour is the product of the aquifer cross-sectional area and the rate of groundwater movement. This cross section has a length of 62 km and an average aquifer thickness of 114 m, and the rate of groundwater movement is 8 m/year (page 70). Therefore, the flow through the 42 m potentiometric contour is 5.66×10^7 m^3/year. Dividing the flow into the storage gives a storage/flow ratio of 330 years for this part of the aquifer. It is again stressed that this figure for storage/flow ratio is very much a minimum value.

Chapman stated that in arid zones a storage/flow ratio greater than 50 years represents steady state conditions; that is, the hydraulic heads measured in boreholes do not respond to recharge as the effects of recharge are dampened out. The storage/flow ratio derived above the 42 m potentiometric contour gave a value of 330 years. This minimum figure indicates that steady state conditions have been reached in the Wallal Sandstone. This evidence is confirmed by the hydrograph record from bore 20C which shows no response to likely recharge events.

Storage

Groundwater storage in the Wallal Sandstone is comprised of two components: the interstitial storage and the elastic storage. As the elastic storage is only a small proportion of the interstitial storage, it is the latter component that will be calculated here.

The interstitial storage is the product of the aquifer volume and the specific yield. To derive an accurate estimate of the aquifer volume the area between adjacent isopachs (Fig. 9) is multiplied by the mean thickness, and the incremental volumes are then summed to give the total volume. Table 9 gives the data required to calculate the volume of the Wallal Sandstone. The area considered is bounded to the west by line 1, to the north by the Indian Ocean, to the east by line 5, and to the south by the 20 m isopach and an east-west line from the eastern end of the 20 m isopach to line 5. This excludes the area over which the aquifer is not fully saturated and conditions are unconfined.

TABLE 9. WALLAL SANDSTONE - DATA REQUIRED TO CALCULATE THE VOLUME OF WATER HELD IN INTERSTITIAL STORAGE.

Isopach Interval (m)	Mean Aquifer Thickness (m)	Incremented Area (km^2)	Incremental Volume x 10^9 (m^3)
20-40	30	289.88	8.696
40-60	50	225.13	11.257
60-80	70	298.38	20.887
80-100	20	460.13	41.412
100-120	110	483.75	52.213
120-140	130	57.88	7.524
140-160	150	62.88	9.432
160-180	170	51.00	8.670
180-200	190	46.88	8.907
>200	210	123.50	25.935
	Totals	2 099.41	195.933

The specific yeild has previously been estimated to be 0.28 from porosity tests (page 9); this figure compares favourably with that quoted by Hazel (1973) of 0.27 for a medium-grained sandstone. Therefore, for estimating the volume of groundwater in storage (Q_s) a specific yield (S_y) of 0.28 is adopted and substituted in the equation:

$$\begin{aligned} Q_s &= S_y V \\ &= 0.28 \times 195.933 \times 10^9 \ m^3 \\ &= 54.9 \times 10^9 \ m^3 \end{aligned}$$

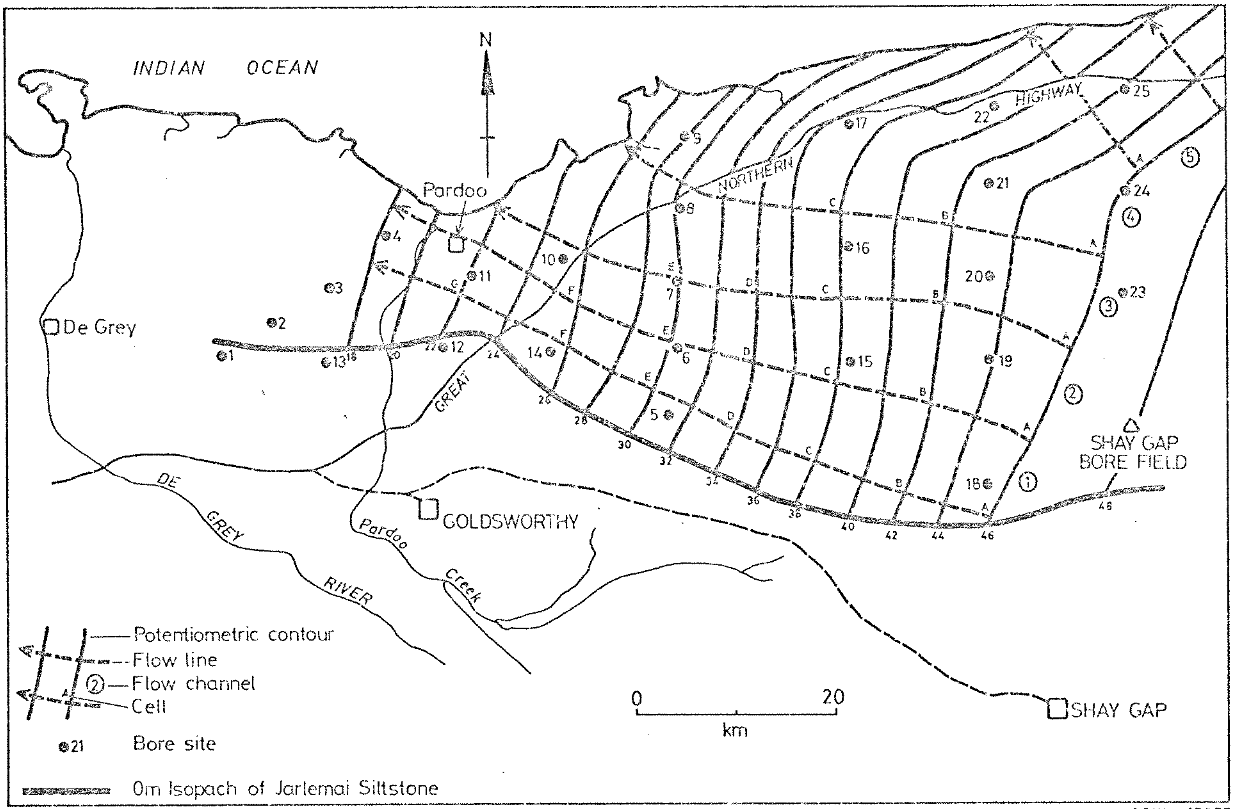
where V is the aquifer volume. This is a very large storage, equivalent to approximately 275 times the annual water consumption of the Perth metropolitan supply (based on 1975-1976 figures). However, all of the insterstitial storage cannot be withdrawn from the aquifer due to many factors, some of which are: the economics of bore-field design, increasing power demand at larger pumping lifts, and the possible induction of salt-water intrusion.

Flow net

The flow net for the Wallal Sandstone aquifer is given on Figure 20, using the potentiometric contours given on Figure 17. An analysis of the flow net has been undertaken as a means of generating representative hydraulic conductivity values over the investigation area and as a means of identifying areas having high or low values.

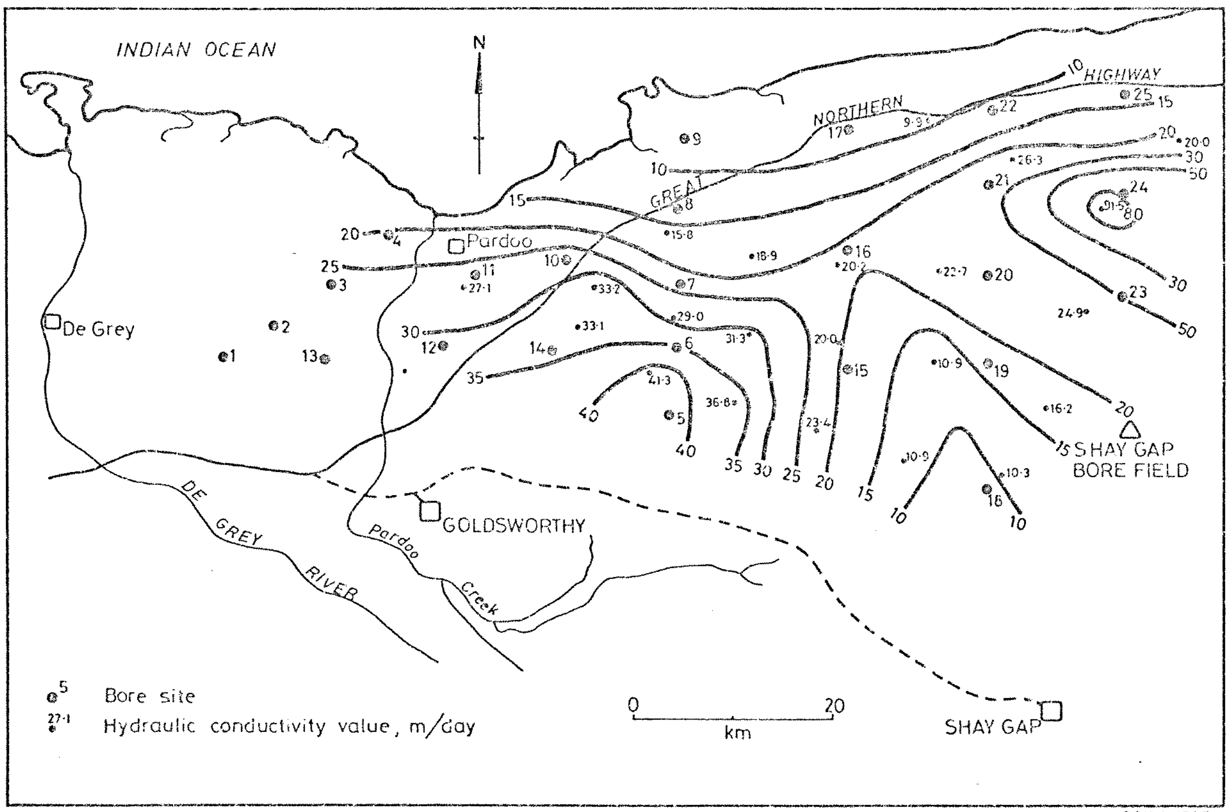
The procedure used for the flow net analysis included the following steps :-

(i) Flow channels were constructed (using 10 km flow sections at the contour of origin) such that they excluded areas where the aquifer becomes unconfined.



GSWA 17977

Figure 20: Flow net for the Wallal Sandstone



GSWA 17978

Figure 21: Hydraulic conductivity contours generated from the flow net analysis

(ii) Mean transmissivity values were calculated for each cell from the product of aquifer thickness and the mean hydraulic conductivity derived from aquifer tests (20 m/day, Table 10).

(iii) The underflow for each cell was calculated.

(iv) The Wallal Sandstone aquifer is confined and, therefore, there are virtually no losses from, or gains to, the system. Each cell along a flow channel should transmit the same quantity of water, but, as can be seen from the sixth column of Table 10, this is not so, principally because of the assumption of a constant hydraulic conductivity. The initial underflow values were, therefore, averaged to derive a true underflow for each flow channel.

(v) Values for hydraulic conductivity for each cell were then calculated from the average underflow for each channel, the hydraulic gradient and flow cross-section.

(vi) The calculated values of hydraulic conductivity were then plotted on the area map and contoured (Fig. 21), and hydraulic conductivity values could then be extrapolated for each bore site for comparison with those derived from aquifer tests.

Comparison of the hydraulic conductivity values from flow net and hydraulic testing (Table 11) shows that nearly all of the former values are larger, but that close agreement does occur at several sites where good time-drawdown matches were made.

The average of the hydraulic conductivity values derived from the flow net analysis is 26.1 m/day which is somewhat higher than the assumed average value of 20.0 m/day based on test pumping results. It is therefore probable that the sum of the average throughflow for each of the five flow channels of 57 400 m^3/day or 20.9 x $10^6 m^3$/year is close to or

TABLE 10. WALLAL SANDSTONE FLOW-NET ANALYSIS DATA AND RESULTS

Cell	Aquifer thickness (m)	Transmissivity[a] (m^2 / day)	Hydraulic gradient[b] ($x10^{-4}$)	Flow channel width (m)	Underflow (m^3 / day)	Average underflow for each channel (m^3 / day)	Hydraulic conductivity (m / day)
1A	70	1 400	3.3	10 000	4 620	2 389	10.3
1B	50	1 000	4.4	10 000	4 400	2 389	10.9
1C	25	500	4.6	8 875	2 041	2 389	23.4
1D	20	400	4.4	7 375	1 298	2 389	36.8
1E	25	500	4.3	5 375	1 156	2 389	41.3
1F	40	800	3.8	4 750	1 444	2 389	33.1
1G	40	800	4.2	5 250	1 764	2 389	27.1
2A	87	1 740	2.9	10 000	5 046	4 083	16.2
2B	85	1 700	4.1	10 750	7 493	4 083	10.9
2C	55	1 100	4.3	8 625	4 080	4 083	20.0
2D	42	840	4.6	6 750	2 608	4 083	31.3
2E	45	900	5.0	6 250	2 813	4 083	29.0
2F	63	1 260	3.9	5 000	2 457	4 083	33.2
3A	105	2 100	2.4	10 000	5 040	6 280	24.9
3B	105	2 100	3.4	7 750	5 534	6 280	22.7
3C	85	1 700	4.3	8 500	6 214	6 280	20.2
3D	75	1 500	5.0	8 875	6 656	6 280	18.9
3E	76	1 520	5.3	9 875	7 955	6 280	15.8
4A	135	2 700	2.5	10 000	6 750	30 880	91.5
4B	140	2 800	4.2	20 000	23 520	30 880	26.3
4C	165	3 300	7.0	27 000	62 370	30 880	9.9
5A	160	3 200	4.3	10 000	13 760	13 760	20.0
Total of average underflow						57 392	

(a) Based on hydraulic conductivity of 20 m/day. (b) Dimensionless quantity.

TABLE 11. COMPARATIVE VALUES OF HYDRAULIC CONDUCTIVITY DERIVED FROM AQUIFER TESTS AND FLOW NET ANALYSIS

Bore	Hydraulic conductivity from aquifer tests (m / day)	Hydraulic conductivity from flow net (m / day)
3A	8.1	27.0
4A	1.6	20.0
6A	5.4	35.0
7A	8.5	23.0
8A	3.3	13.0
8B	5.8	13.0
9D	0.6	7.0
10A	6.5	27.0
16A	9.7	20.0
17A	5.9	8.0
19A	3.0	17.0
20C	138.3	24.0
20D	42.9	24.0
21A	17.0	27.0
22A	15.5	12.0
23A	31.6	30.0
24A	24.1	80.0
25C	5.4	13.0
Mean	18.5	23.3

may slightly exceed the true value of the total underflow.

Hydrographs

From June until November, 1975 an A.Ott water-level recorder with barograph attachment was operating on bore 16A. Between 27th June and 19th September the recorder was operating on a seven-day cycle, and between 19th September and 9th November a 30-day cycle was used. The hydrographs show no discernable trend in hydrostatic pressure head over the period of record. However, the hydrographs do show two periodic fluctuations: a semi-diurnal cycle and an irregular fluctuation whose wave length varies from 4 to 11 days; these two features can be related to earth-tide and barometric effects respectively as described below. The hydrograph, together with derived gravimetric corrections, barometric pressure, moon phases and ocean tides is given in Figure 22.

Barometric effects: Whereas barograph records show a semi-diurnal cycle with peaks and troughs occurring at approximately the same time each day, the hydrographic fluctuations advance approximately 30 minutes each day. This means that the semi-diurnal changes in water level cannot be explained by direct correlation with barometric fluctuations.

The 4 to 11 day periodicity in the hydrograph is attributed to a barometric fluctuation of the same wave length. This is clearly demonstrated if the hydrograph is smoothed by drawing an average line through the semi-diurnal fluctuations and comparing it to the barometric trace. When a barometric high occurs the water level is at a low, and vice versa (e.g. 24th September and 3rd October; Fig. 22). Therefore, the 4 to 11 day cyclicity is due to changes in the weather pattern.

Barometric efficiency and storage coefficient: The barometric efficiency of the Wallal Sandstone aquifer can be determined from the 4 to 11 day fluctuations. Barometric efficiency is

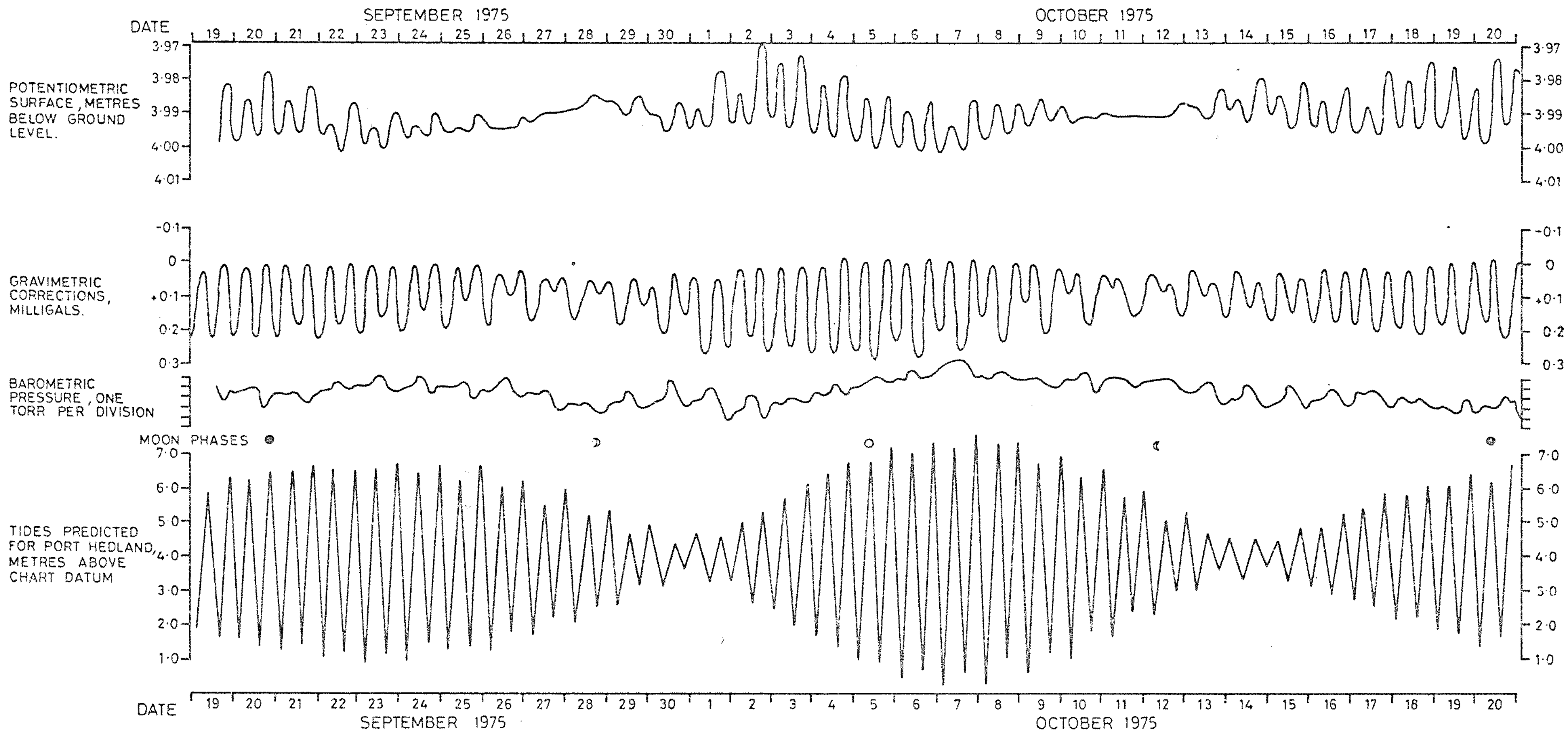


Figure 22: Hydrograph from bore 16A screened in the Wallal Sandstone, relation between water level and ocean tides, moon phases, barometric pressure and luni-solar gravimetric corrections.

GSWA 17979

a measure of aquifer elasticity, and is defined as the ratio of change in water level in metres to the change in barometric pressure in metres of water, hence:-

$$B.E. = dh/dp$$

where B.E. = barometric efficiency
dh = change in water level
dp = change in barometric pressure in metres of water.

By 'smoothing' the hydrograph and barometric pressure curves associated with the 4 to 11 day effect, the barometric efficiency can be calculated. Several determinations were made and the barometric efficiencies ranged from 0.29 to 0.66, with an average of 0.50.

The storage coefficient of the aquifer can be derived from the barometric efficiency (Jacob, 1940) using the following equation:-

$$S = \frac{bn\rho g\beta}{B.E.}$$

where S = storage coefficient
b = aquifer thickness
n = porosity
ρ = density
g = acceleration due to gravity
β = compressibility of water
B.E. = barometric efficiency
and $\gamma = \rho g$ = specific weight.

The aquifer thickness at bore 16A is 89 m and the porosity determined from the same aquifer at bore 20A is 0.39 (determined from a recompacted laboratory sample). The specific weight of water is 1 000 kg/m^3 and the compressibility is the reciprocal of the bulk modules of elasticity which is 2.1092×10^8 kg/m^2, and the barometric efficiency is as shown above.

Hence

$$S = \frac{89 \times 0.39 \times 1000}{2.1092 \times 10^8 \times 0.5}$$

$$= 3.3 \times 10^{-4}$$

This value of storage coefficient compares favourably with that of 2.0×10^{-4} which was determined from the pump test at Site 20.

Earth tides: A definition of earth tide is given by Takeuchi (1950) as "The deformation of the Earth by the tidal attractions of the Sun and Moon..." This means that when there is a strong luni-solar attraction the earth's surface bulges. When applied to confined aquifers this means a dilation of the aquifer takes place which results from a slightly reduced static loading. This produces a fall in water level.

The earth's gravity field varies semi-diurnally and predictably. Corrections can be applied to the earth's gravity field measured at a particular place to adjust it to a constant value. The gravimetric corrections (after Goeguel, 1974) for the luni-solar influence are plotted on Figure 22. It can be seen that when large luni-solar attractions occur they correspond closely to a fall in water level, and small attractions result in a rise in water level. It therefore seems most likely that the major effects on the semi-diurnal nature of water levels in the Wallal Sandstone aquifer are due to earth tides.

Ocean tides are related to lunar and to a lesser extent solar gravity fields. The effect of ocean tides was also considered as a possible explanation for the semi-diurnal fluctuations. The ocean tides for Port Hedland are shown on Figure 22, and it can be seen that a high tide corresponds to a low groundwater level. As a high tide should correspond to a high water level, this precludes ocean tides as an explanation of the observed hydrograph.

Rate of groundwater movement

The rate of groundwater movement or average interstitial (bulk) velocity can be calculated from the equation:

$$v = -\frac{ki}{n}$$

where v = interstitial velocity (m/day)
k = hydraulic conductivity (m/day)
i = hydraulic gradient (dimensionless)
n = porosity (dimensionless)

The interstitial velocity of water in the Wallal Sandstone is calculated using a hydraulic conductivity of 20 m/day, a hydraulic gradient of 4.2×10^{-4} (average from Table 10) and a porosity of 0.39 (laboratory determination on recompacted sludge sample, page 14).

Therefore,

$$v = -\frac{20\ (4.2 \times 10^{-4})\ 365}{0.39}\ \text{m/year}$$

$$\simeq -8\ \text{m/year}$$

Regional flow system

Figure 18 shows the extent of the Canning Basin, and shows hypothetical flow lines indicating recharge from the central basin area discharging into the Indian Ocean. This small-scale map shows the groundwater flow in the study area is to the west, although further east, flow is to the north. This flow system needs refining by further exploratory drilling to define the stratigraphy and potentiometric surface.

Hydrochemistry

A total of 30 standard analyses were made on samples collected from 23 project bores, 3 springs and 4 privately owned bores. The results of these analyses are show in Table 12, together with the calculated values for percentage milliequivalents per litre, sodium adsorption ration (S.A.R.) and chloride/bicarbonate ratio.

Isohalines of the confined groundwater are shown on Figure 23. The water sample from bore 5A is not included in Figure 23 as it was contaminated with drilling mud, and bore development was not successful. The isohalines show the groundwater salinity increasing from about 300 mg/L T.D.S. in the east to 13 700 mg/L (private bore) in the extreme western part of the area. The sharp increase in salinity gradient in the west is thought to be due to the displacement of saline water by fresher recharge water. It is not known whether the saline water was introduced during a high Quaternary sea level which encroached into the recharge area, or whether the aquifer was previously subjected to another source of saline intrusion. Radiometric dating of the groundwater could possibly solve this problem.

TABLE 12. CHEMICAL ANALYSES OF WATER SAMPLES FROM THE WALLAL SANDSTONE

Sampling point	1A	2A	3A	4A	6A	7A	8A	8B	9D	10A	11A
GCL No.[(a)]	20547	20546	84200	84191	84821	84822	83615	83616	85831	83617	21739
pH	7.8	7.6	6.8	6.8	7.3	7.5	7.6	7.2	7.0	7.3	6.9
Odour	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
TDS (Evap) (mg/L)	790	1590	1860	1680	490	360	1010	960	1190	1120	1160
TDS (Cond) (mg/L)	870	1830	2100	1840	530	350	1130	1080	1360	1290	1310
Total hardness (mg/L)	136	764	382	347	199	94	274	270	293	293	333
Total alkalinity (mg/L)	341	248	53	60	181	135	93	110	67	67	55
Ca (mg/L)	33	156	79	73	47	23	57	57	63	63	74
Mg (mg/L)	13	91	45	40	20	9	32	31	33	33	36
Na (mg/L)	242	276	501	446	89	75	246	237	306	288	275
K (mg/L)	9	12	26	18	4	4	11	12	11	10	11
CO_3 (mg/L)	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
HCO_3 (mg/L)	415	302	64	73	220	165	113	134	82	82	67
Cl (mg/L)	225	718	874	728	123	68	394	364	528	498	546
SO_4 (mg/L)	12	71	216	243	16	18	170	168	152	159	114
NO_3 (mg/L)	3	55	<1	<1	33	16	<1	<1	<1	<1	<1
SiO_2 (mg/L)	13	65	16	15	66	56	21	19	15	22	20
B (mg/L)					0.23	0.23					0.3
F (mg/L)			0.3	0.3	0.4	0.4	0.3	0.3	0.2	0.2	0.2
CATIONS[(b)]											
Ca (me/L)	12	28	13	14	29	22	17	18	16	17	19
Mg (me/L)	8	27	12	12	21	14	16	16	14	15	16
Na+K (me/L)	80	45	75	74	50	64	67	66	70	68	65
ANIONS[(b)]											
HCO_3 (me/L)	51	19	3	5	49	54	11	14	7	7	6
Cl (me/L)	47	76	82	76	47	39	67	64	77	75	82
SO_4 (me/L)	2	5	15	19	4	7	22	22	16	18	12
S.A.R.	9.0	4.3	11.2	10.4	2.7	3.4	6.5	6.3	7.8	7.3	6.5
Cl/HCO_3	0.54	2.38	13.7	9.97	0.56	0.41	3.49	2.72	6.44	6.07	8.15

(a) Government Chemical Laboratories' sample number

(b) Percentage milliequivalents per litre

14A	15A	16A	17A	18A	19A	20D	21A	22A	23A	24A
18430	10807	84192	84194	26868	86114	86115	84196	84198	82755	84201
9.0	8.9	7.2	7.3	10.2	7.8	7.9	7.3	7.8	7.3	7.8
Nil	Nil	Nil	Musty	Nil	Nil	Nil	Nil	Nil	Nil	Nil
770	940	310	420	310	330	300	320	320	290	240
770	860	340	470	330	310	290	340	360	290	260
53	43	62	70	53	135	96	73	46	115	53
90	306	112	143	80	108	120	108	133	112	105
15	14	15	15	18	31	22	16	10	28	13
4	2	6	8	2	14	10	8	5	11	5
232	276	83	124	82	44	58	79	102	43	65
14	5	4	6	7	5	5	5	5	5	4
12	12	Nil	Nil	36	Nil	Nil	Nil	Nil	Nil	Nil
85	348	137	174	Nil	131	146	131	162	137	128
261	163	69	102	74	68	57	72	69	55	49
102	109	30	59	44	13	10	31	42	7	24
14	3	9	<1	11	26	22	12	<1	23	1
46	22	40	19	42	60	48	41	17	54	25
0.3	0.5	0.76	0.74	0.32	0.26	0.28	0.66	0.76	0.53	0.71
0.5	0.9	0.3	0.5	0.4	0.5	0.5	0.4	0.5	0.3	0.5
6	6	15	11	19	33	24	16	9	32	16
3	1	10	10	3	24	18	13	8	21	10
91	93	75	79	78	43	58	71	83	47	74
13	45	47	41	28	50	57	44	48	57	53
68	37	40	41	50	44	38	42	36	39	35
19	18	13	18	22	6	5	14	16	4	12
13.7	18.3	4.6	6.4	4.9	1.7	2.6	4.0	6.6	1.8	3.9
3.07	0.47	0.50	0.59	-	0.52	0.39	0.55	0.43	0.40	0.38

25C	Myadee Spring	Mound Spring	Anna Plains Bore 1	Sandfire Bore	BMR 4	Shay Gap Bore 1	Banningarra Spring
84202	15416	15408	21409	84823	21410	21405	15719
7.5	7.0	7.4	7.0	6.6	7.5	7.1	7.3
Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
300	1030	2130	1770	790	840	320	3250
350	1130	2460	1910	920	950	315	3570
52	307	560	350	142	212	110	923
117	110	90	76	55	85	80	158
11	67	112	66	29	47	21	144
6	34	68	45	17	23	14	137
91	220	564	500	225	213	51	791
5	12	25	42	9	10	4	42
Nil	Nil	Nil	Nil	Nil	Nil	Nil	
143	134	110	92	67	104	98	192
72	389	1060	776	311	340	84	1620
36	135	228	306	142	118	7	240
<1	<1	<1	<1	1	<1	24	6
16	16	2	16	17	15	57	2
0.62			0.1	0.23	0.1	0.4	
0.5			0.6	0.1	0.4	0.3	
11	21	16	11	11	17	23	13
9	18	16	12	11	14	26	21
80	61	68	77	78	69	51	66
46	14	5	5	9	12	39	6
40	69	82	74	68	70	57	85
14	17	13	21	23	18	4	9
5.5	5.4	10.3	11.6	8.2	6.3	2.1	11.3
0.50	2.90	9.64	8.43	4.64	3.27	0.86	8.44

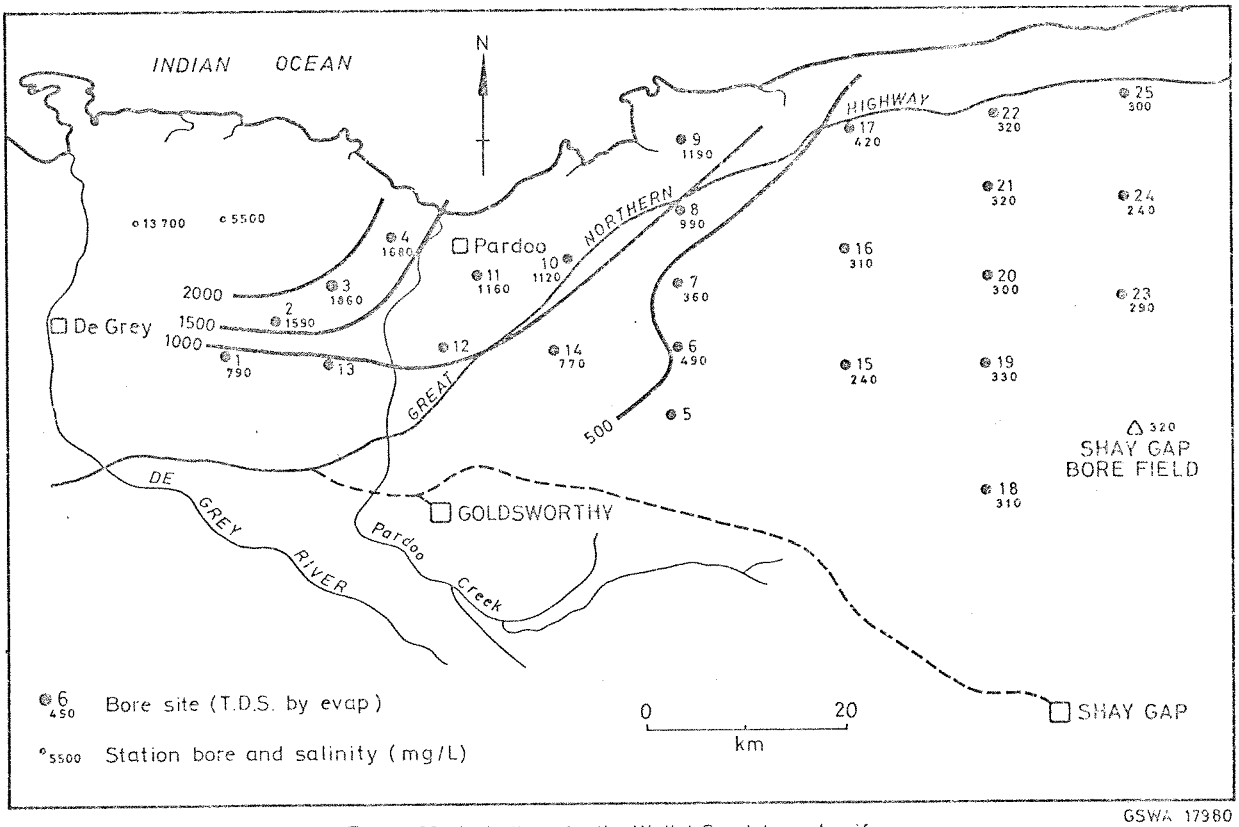


Figure 23 : Isohalines for the Wallal Sandstone Aquifer

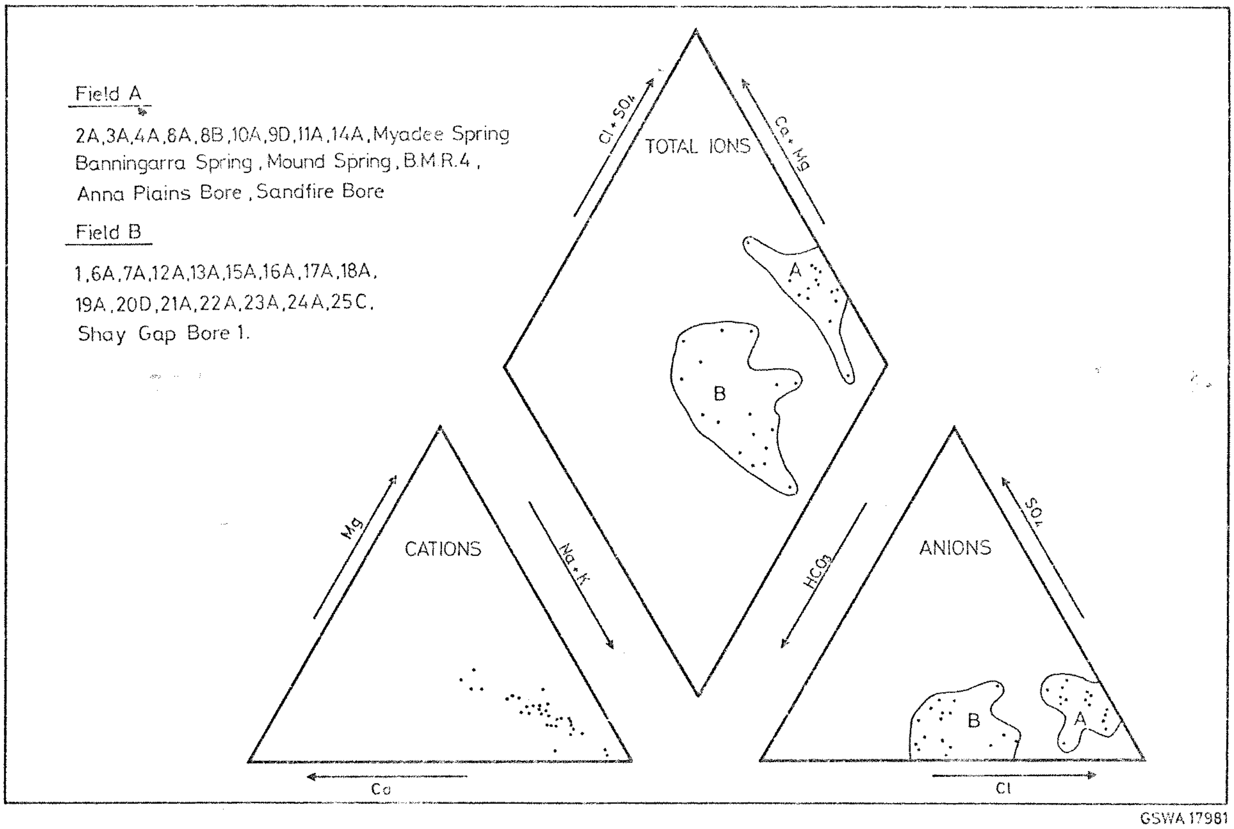


Figure 24: Trilinear diagram of confined groundwater analyses (per cent equivalents per million)

Groundwater quality: The confined groundwater is a sodium-chloride type, with somewhat more bicarbonate in the east towards the recharge area. A trilinear (Piper) diagram (Fig. 24) shows the chemical analyses fall into two fields, marked A and B. Field A encloses analyses from bores and springs west of drill line 2 and private bores along the coast northeast from the project area. This field contains analyses of water distant from the recharge area. Chloride and sulphate comprise a majority of the anions with bicarbonate representing less than 10% of the total ions. The analyses which fall into field B are those east of drill line 2, closer to the recharge area. Bore 1 whose position is west of drill line 2 falls into field B; this is because it is likely to be subject to small amounts of local recharge south of the Jarlemai Siltstone subcrop.

The flow line which separates flow channels 1 and 2 on Figure 20 passes close to bores 19A, 15A, 6A, 11A and 4A. A comparison of the chemical analyses for these bores shows that the groundwater composition changes with distance from the recharge area. The reliability of the sample analysis from bore 15A is open to doubt, as the chemical analysis does not show the same trend as the other bores, and it has a pH of 8.9 which suggests the sample was probably contaminated with drilling mud. The remaining samples from bores 19A, 6A, 11A and 4A exhibit changes in the cation balance of a relative increase in sodium and decrease in both magnesium and calcium with distance travelled. The anion plot shows that chloride ion concentrations increase down gradient with a relative decrease in bicarbonate, while the sulphate concentration remains approximately the same.

East of the 500 mg/L isohaline the groundwater quality is wholly acceptable for domestic consumption. However, a zone of high nitrate ion concetration does occur in an area bounded by the Shay Gap bore field and project sites 19 and 23. In this zone the nitrate concentration ranges from 23 to 26 mg/L; this is just above the acceptable limit for human consumption as defined by Hart (1974).

West of the 500 mg/L isohaline the groundwater quality deteriorates and hardens; calcium, sodium and chloride concentrations are all above the derived working levels (Hart, 1974). However, the water could still be used if mixed with water from the east.

The irrigation potential of groundwater from the Wallal Sandstone aquifer is variable. Groundwater from sites east of the 500 mg/L isohaline is generally suitable for irrigation as it has a medium salinity hazard and a low S.A.R. or sodium (alkali) hazard (Fig. 25). Groundwater from the rest of the area is probably unsuitable for irrigation, except for special salt-tolerant crops.

Groundwater temperature

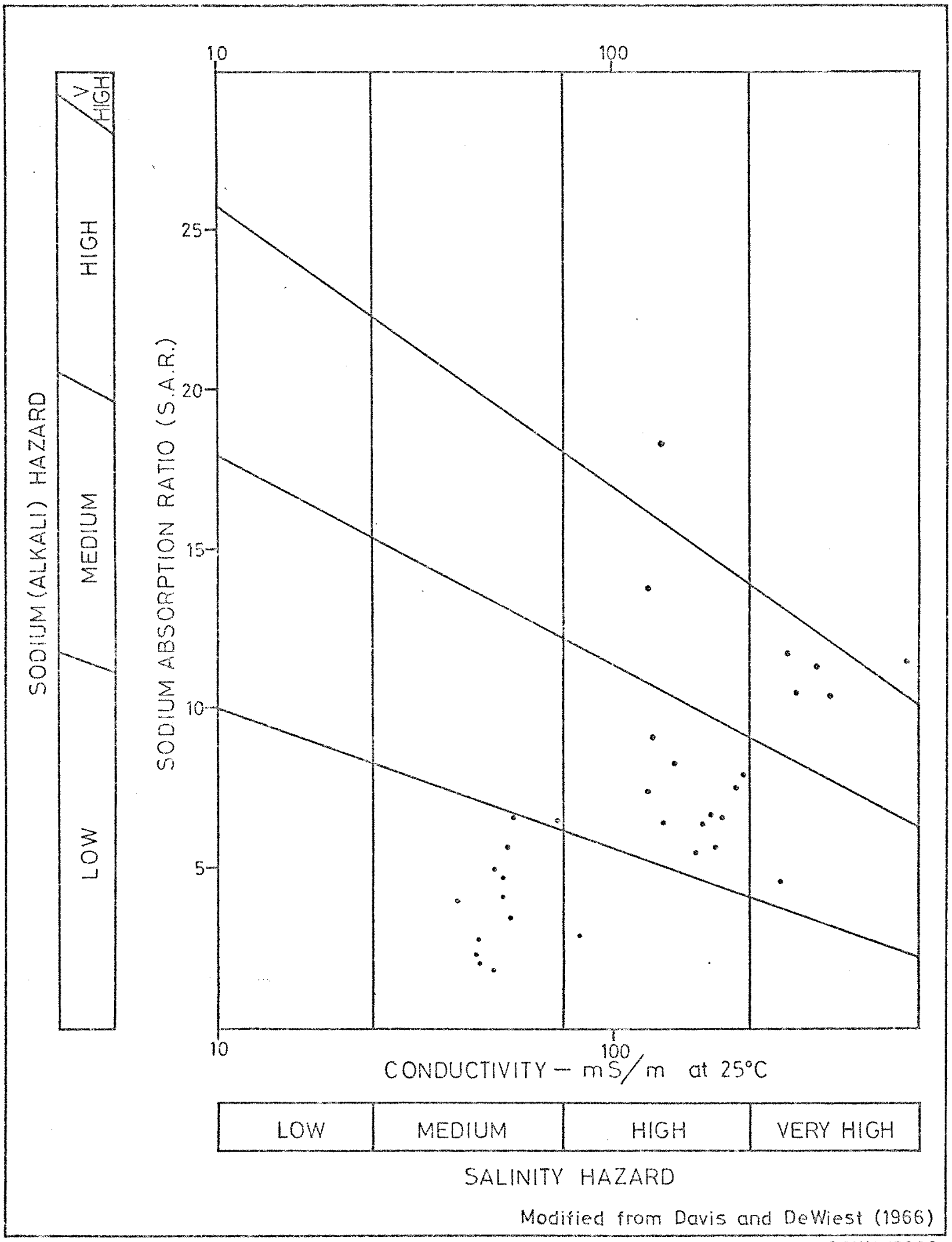
Groundwater temperature was measured at the bore head during most pump/flow tests. The temperature increased with depth of burial and ranged from 27 to 38°C. No temperature logs were run, but temperature gradients were estimated for each bore using the following relation:

$$\text{Temperature gradient per 100 m} = \frac{(\text{Water temperature} - \text{Mean air temperature}) \times 100}{\text{mean aquifer depth}}$$

The mean annual air temperature from Goldsworthy of 28.5°C was used in gradient calculations. Gradients varied from 2.6 to 4.5°C per 100 m and averaged 3.5°C per 100 m.

Development

The Wallal Sandstone contains a large volume of groundwater



GSWA 17982

Figure 25 : Confined Groundwater, classified for potential irrigation use.

whose salinity varies from 300-13 000 mg/L (T.D.S.). A large proportion of this storage is suitable for domestic, irrigation or industrial use. The main contraints imposed on developing this aquifer are those of remoteness and groundwater quality for a given use.

If a production bore field is constructed, it should be designed to intercept the throughflow by locating the production bores parallel to the potentiometric contours. Rates of abstraction from bores should be appropriate to the throughflow in their vicinity. Exploitation in excess of the throughflow may be justifiable either as a means of postponing a larger capital expenditure or as an interim solution until an alternative supply is found.

At present the main consumer of groundwater from the Wallal Sandstone is Shay Gap townsite, whose annual abstraction rate is approximately $1.2 \times 10^6 m^3$/year; this amount is less than 6% of the throughflow calculated in the flow net analysis. Continuous abstraction from the Shay Gap borefield since 1972 has resulted in a decline of less than 2 m in the potentiometric surface. A few station bores tap this aquifer, but their flows are only small and would have an insignificant effect on the potentiometric surface.

SPRINGS

Several springs occur on the coastal plain, from 3 km west to 19 km east of Pardoo homestead (Fig. 17). The springs form small ponds at the surface which are surrounded by vegetation, usually reeds, but at some springs a few introduced palm trees flourish. The water temperature of the springs varies from 24 to 26°C.

Two springs are worthy of note: they are Myadee Spring and a spring at the edge of Pardoo Creek called Mound Spring in this report. Myadee Spring (Fig. 17) has been known since about 1890 and was used as a watering point on a stock route from the Kimberley to the shipping settlement of Condon, close to the De Grey River estuary. This spring can now be recognized from the Great Northern Highway by the large palm tree which taps water from this spring. Mound Spring is located on the eastern bank of Pardoo Creek 3 km west of Pardoo Homestead. It occurs on top of a small hill, hence its name. The surface area of the spring is only about 2 m^2 and has been dug out as a watering point for cattle. There is no evidence of a travertine precipitate around this spring.

All the springs have been dug out as watering points for stock. They do not have flowing discharges at the surface; the only discharges are by evapotranspiration and the consumption of water by stock. The springs originate from minor leakages from the Wallal Sandstone confined aquifer through the Jarlemai Siltstone. Chemical analyses of spring waters (Table 12) show the ionic composition to be similar to that of the confined aquifer but dissimilar to that of the unconfined aquifer.

CONCLUSIONS

The stratigraphic sequence in the western part of the Canning Basin has been elucidated and an unnamed claystone unit of Mesozoic age has been discovered. The western limit of the Permian subcrop is now known.

The major aquifers in the area have been explored. These are the Wallal and Broome Sandstones. The Wallal Sandstone has the greater volume of groundwater in storage and in general this is of better quality than that of the Broome Sandstone.

The extent of the Wallal Sandstone has not been fully determined, but it is known to occur from De Grey Station to at least as far northeast as Anna Plains Station, a distance of 270 km. The salinity of groundwater from this aquifer is acceptable for domestic purposes over more than half of the area, but varies from 300 mg/L (T.D.S.) in the southeast nearest the recharge area, to 13 000 mg/L at De Grey Station. This confined aquifer is a substantial resource and has a larger storage than any other known aquifer within the Pilbara and West Kimberley Regions of Western Australia.

The Broome Sandstone occurs throughout the investigation area and extends further east into the basin. Much of the groundwater stored in this formation is of marginal quality for domestic consumption by reason of its high salinity or nitrate content, but could be used for some industrial processes or mixed with other water of lower salinity or nitrate content.

The large-scale development of groundwater resources in the Canning Basin sediments in the near future is unlikely due to its remote location. However, when large-scale abstraction does occur it would be advantageous to utilize conjunctively the groundwater from the Wallal and Broome Sandstones. A desirable preliminary to such development would be an extension of exploratory drilling to the east of the present study area to delineate recharge areas to the Wallal Sandstone. However, such drilling could be done with a larger bore grid spacing than used in this project as the geology is now well known.

APPENDIX 1. SUMMARY OF PROJECT BORE DATA

Bore	Elevation of natural surface[a] (m)	Total depth (m)	Casing		Screens[b]		Elevation of water surface[a] (m)	Discharge and drawdown at 8 hrs		Trans-missivity (m^2 / day)	Salinity TDS (mg/L)	Aquifer
			Length (m)	Diameter ID (mm)	Interval (m)	Diameter (mm)		Discharge (m^3 / day)	Drawdown (m)			
1	19.666	83.2	60.0	206	Open hole		9.96	-	-	-	790	Wallal
2A	31.030	65.0	52.0	206	52-58	200	9.90	-	-	-	1590	Wallal
2B							BORE ABANDONED					
2C							BORE ABANDONED					
2D	31.062	104.0	84.0	143	84-102	100	9.87	-	-	-	-	Wallal
3A	19.170	103.4	5.0 64.5	206 143	64.5- 82.5	76	11.18	614	4.3	145	1860	Wallal
4A	12.675	133.5	5.4 67.4	206 143	67.4- 109.4	76	19.22[c]	199	4.7	69	1680	Wallal
5A	64.712	43.5	6.0 26.3	206 143	37.1- 43.1	76	30.81	-	-	-	-	Wallal
6A	48.269	78.5	6.2 50.0	206 143	50.7- 74.7	76	30.17	650	4.4	129	490	Wallal
7A	34.229	125.0	6.0 91.0	206 143	91.7- 115.7	76	29.76	641	2.7	204	360	Wallal
8A	15.115	183.0	6.0 137.5	206 143	138.1- 150.1	76	31.24[c]	1464	4.8	40	1010	Wallal
8B	14.982	103.0	6.0 82.0	206 143	82.7- 100.7	76	31.26[b]	939	3.3	104	960	Wallal
9A							BORE ABANDONED					
9B	5.875	120.0	65.0 74.4	206 143	74.4- 95.4	143	32.85[c]	-	-	-	860	Jarlemai
9C							BORE ABANDONED					
9D	7.075	224.0	43.9 130.0 168.0	259 189 143	193.0- 211.0	50	27.70[c]	508	15.5	10	1190	Wallal
10A	20.975	116.4	41.0 71.0	206 143	71.1- 113.1	76	25.74[c]	769	1.7	272	1120	Wallal

11A	19.732	129.7	35.0 55.0	206 143	61.0- 85.0	76	22.20 (c)	-	-	-	1160	Wallal
12A	32.168	45.7	26.0 31.0	206 143	31.0- 43.0	76	18.26	-	-	-	1180	Broome
13A	46.100	69.7	41.0 71.0	206 143	42.0- 54.0	76	11.05	-	-	-	820	Broome
14A	53.704	77.1	35.0 55.0	206 143	57.7- 70.1	100	25.78	-	-	-	770	Wallal
15A	84.314	120.5	26.0 31.0	206 143	101.0- 113.0	100	38.01	-	-	-	240	Wallal
16A	41.976	184.0	29.0 42.0	206 143	138.0- 153.0	100	38.22	672	6.1	145	310	Wallal
16B	41.792	45.0	6.0 57.7	189 143	37.0- 43.0	100	30.43	393	5.6	222	440	Broome
16C	41.772	155.0	30.0 101.0	206 143	135.2- 153.4	76	38.24	-	-	-	-	Wallal
17A	18.750	259.0	29.0 220.0	206 143	220.0- 244.0	100	37.17 (c)	2100	6.9	142	420	Wallal
17B	18.558	70.0	29.0 64.0	206 143	64.0- 70.0	100	2.95	632	5.0	854	720	Broome
18A	157.641	126.5	106.0	143	108.7- 120.7	100	45.6	-	-	-	310	Wallal
19A	105.918	176.0	21.0 158.0	189 143	158.0- 176.0	100	43.86	532	2.8	54	330	Wallal
19B	105.878	54.0	45.0	143	45.0- 51.0	100	Dry	-	-	-	-	Broome
20A	BORE ABANDONED											
20B	77.000	56.0	50.0	143	50.0- 54.5	100	Dry	-	-	-	-	Broome
20C	78.164	190.0	169.0	143	169.5- 187.5	76	43.50	-	-	2490	-	Wallal
20D	76.949	185.0	167.0	143	167.0- 183.8	100	43.39	626	2.7	720	300	Wallal

21A	37.877	235.0	29.0 200.0	189 143	200.0- 224.0	104	43.64 (c)	247	0.7	409	320	Wallal
21B	37.552	42.0	30.0	143	30.0- 39.0	104	14.35	29	0.03	159	380	Broome
22A	11.081	344.0	36.7 278.0	237 143	278.0- 296.0	100	38.74 (c)	3030	10.0	279	320	Wallal
22B	11.078	55.0	49.0	143	49.0- 55.0	100	7.82	626	5.6	138	430	Broome
23A	70.912	210.0	96.9	143	96.9- 114.9	100	46.60	645	1.3	569	290	Wallal
23B	70.481	122.0	97.0	143	97.0- 114.5	100	46.60	-	-	-	-	Wallal
24A	43.768	267.0	32.0 170.7	259 143	170.7- 179.0	100	45.99 (c)	69	0.5	200	240	Wallal
24B	43.807	45.0	34.0	143	34.0- 40.0	100	10.70	-	-	-	480	Broome
24C	43.822	47.0	34.0	143	34.0- 40.0	100	10.70	-	-	-	-	Broome
25A							BORE ABANDONED					
25B							BORE ABANDONED					
25C	16.212	696.0	34.0 231.0 286.0	259 143 105	286.0- 310.0	100	41.99 (c)	1394	14.7	130	300	Wallal
25D	16.158	102.0	30.9	143	30.9- 39.9	100	3.62	735	3.0	250	830	Broome

(a) Reduced level relative to AHD

(b) The interval between the top of the screen and the base of the casing is occupied by either a packer or a length of blank pipe

(c) Flowing bore.

REFERENCES

Australia Bureau of Mineral Resources, 1958, Bore completion report for B.M.R. 4 and 4A (Wallal): Australia Bur. Mineral Resources Rept (unpublished).

Backhouse, J., 1972, Palynology of West Canning Basin No. 2: West. Australia Geol. Survey Palaeontology Rept 83/1972 (unpublished).

_______ 1973, Palynology of West Canning Basin No. 414 Borehole: West. Australia Geol. Survey Palaeontology Rept 60/1973 (unpublished).

_______ 1974a, Palynology of samples from West Canning Basin Nos. 5A, 6A, 7A, 8A and 9B boreholes, and De Grey Station Bore No. 7: West. Australia Geol. Survey Palaeontology Rept 30/1974 (unpublished).

_______ 1974b, Palynology of West Canning Basin No. 17A Borehole: West. Australia Geol. Survey Palaeontology Rept 95/1974 (unpublished).

_______ 1975a, Palynology of West Canning Basin Nos. 11A, 15A and 16A Boreholes and De Grey River Nos. T1 and W1 Boreholes: West. Australia Geol. Survey Palaeontology Rept 38/1975 (unpublished).

_______ 1975b, Palynology of West Canning Basin No. 25 Borehole: West. Australia Geol. Survey Palaeontology Rept 145/1975 (unpublished).

_______ 1976a, Palynology of West Canning Basin No. 19A Borehole: West. Australia Geol. Survey Palaeontology Rept 1/1976 (unpublished).

_______ 1976b, Palynology of West Canning Basin No. 23A Borehole: West. Australia Geol. Survey Palaeontology Rept 2/1976 (unpublished).

_______ 1976c, Palynology of West Canning Basin No. 24A Borehole: West. Australia Geol. Survey Palaeontology Rept 3/1976 (unpublished).

_______ 1976d, Palynology of West Canning Basin No. 20A Borehole: West. Australia Geol. Survey Palaeontology Rept 4/1976 (unpublished).

______ 1976e, Palynology of West Canning Basin No. 21A Borehole: West. Australia Geol. Survey Palaeontology Rept 5/1976 (unpublished).

______ 1976f, Palynology of some samples from the bottom of West Canning No. 22A Borehole: West. Australia Geol. Survey Palaeontology Rept 14/1976 (unpublished).

______ 1978, Palynology of a core from West Canning Bore 9D: West. Australia Geol. Survey Palaeontology Rept 15/1978 (unpublished).

Boulton, N.S., 1963, Analysis of data from nonequilibrium pumping tests allowing for delayed yield from storage: Inst. Civil Engineers Proc., v. 26, No. 6693.

Brunnschweiler, R.O., 1954, Mesozoic stratigraphy and history of the Canning Desert and Fitzroy Valley, Western Australia: Geol. Soc. Aust. Jour., v. 1, p. 35-54.

______ 1957, The geology of Dampier Peninsula, Western Australia: Australia Bur. Mineral Resources Rept 13.

Chapman, T.G., 1963, Effects of groundwater storage and flow on the water balance: Australian Academy of Science, National Symposium on Water Resources Use and Management.

Davidson, W.A., 1973, De Grey River groundwater investigation: West. Australia Geol. Survey Rec. 1973/27 (unpublished).

Davis, S.N., and De Wiest, R.J.M., 1966, Hydrogeology: Sydney, John Wiley and Sons.

Geological Survey of Western Australia, 1975, The geology of Western Australia: West. Australia Geol. Survey Mem. 2.

Goeguel, J, 1974, Tidal gravity corrections for 1975; European Association of Exploration Geophysicists.

Guppy, D.J., Lindner, A.W., Rattigan, J.H., and Casey, J.N., 1952, The stratigraphy of the Mesozoic and Permian sediments of the Desert Basin, Western Australia: Internat. Geol. Congress, 19th, Algiers, 1950, Symposium Séries de Gondwana, p. 107-114.

Hantush, M.S., and Jacob, C.E., 1955, Non-steady radial flow in an infinite leaky aquifer: Amer. Geophys. Union Trans., v. 36 (1).

Hart, B.T., 1974, a compilation of Australian water quality criteria; Australia Water Resources Council, Technical Paper No. 7.

Hazel, C.P., 1973, Lecture notes on groundwater hydraulics: Australia Water Resources Council, 1973, Groundwater School, Adelaide.

Hickman, A.H., and Chin, R.J., 1976, Explanatory notes on the Precambrian part of Yarrie 1:250 000 geologial sheet: West. Australia Geol. Survey Rec. 1976/16 (unpublished).

Jacob, C.E., 1940, On the flow of water in an elastic aquifer: Amer. Geophys. Union Trans., Part 2, p. 574-586.

Johnson, A.I., 1963, Application of laboratory permeability data: U.S. Geol. Survey Water Resources Division, Open File Report.

Johnstone, M.H., 1961, Samphire Marsh No. 1 well Western Australia: Australia Bur. Mineral Resources Petroleum Search Subsidy Acts Pub. 5.

Krumbein, W.C., and Monk, G.D., 1943, Permeability as a function of the size parameters of unconsolidated sand: Amer. Inst. Mining and Met. Engineers Trans., v. 151, p. 153-163.

Leech, R.E.J., 1972, Derby Town water supply: West. Australia Geol. Survey Rec. 1972/15 (unpublished).

_______ 1974, West Canning Basin groundwater investigation progress report, March, 1974: West. Australia Geol. Survey Rec. 1974/18 (unpublished).

Lennox, D.H., 1966, Analysis and application of step-drawdown test: Amer. Soc of Civil Engineers, Hydraulics Div. Jour. v. 92, No. HY6, p. 25-48.

Lipple, S.L., 1975, Definitions of new and revised stratigraphic units of the Eastern Pilbara Region: West. Australia Geol. Survey Ann. Rept 1974, p. 58-63.

Lovelock, P.E.R., 1970, The laboratory measurement of soil and rock permeability: Natural Environment Research Council, Institute of Geological Sciences, Technical Communication No. 2.

Low, G.H., 1965, Port Hedland, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Maitland, A.G., 1904, Geological features and mineral resources of the Pilbara Goldfields: West. Australia Geol. Survey Bull. 15.

McWhae, J.R.H., Playford, P.E., Lindner, A.W., Glenister, B.F., and Balme, B.E., 1958, The stratigraphy of Western Australia: Geol. Soc. Australia Jour., v. 4, pt. 2.

O'Driscoll, E.P.D., 1964, Report on groundwater prospects - Derby Town Water supply: West. Australia Geol. Survey Hydrology Report No. 129 (unpublished).

Prickett, T.A., 1965, Type curve solution to aquifer tests under water-table conditions: Groundwater, v. 3, No. 3, p. 5-14.

Reeves, F., 1951, Australian oil possibilities: Am. Assoc. Petroleum Geologists Bull., v. 35, p. 2479-2525.

Rowston, D.L., 1973, West Canning Basin hydrology investigation Geophysics, 1972 progress report: West. Australia Geol. Survey Rec. 1973/7 (unpublished).

______ 1974, West Canning Basin hydrology investigation geophysics, 1973 progress report: West. Australia Geol. Survey Rec. 1974/6 (unpublished).

______ 1976, West Canning Basin groundwater geophysics, final report: West. Australia Geol. Survey Rec. 1976/9 (unpublished).

Sheahan, N.T., 1971, Type-curve solution of step-drawdown test: Groundwater, v. 9, No. 1, p. 25-29.

Takeuchi, H., 1950, On the Earth tide of the compressible Earth of variable density and elasticity: Amer. Geophys. Union Trans. v. 31, No. 5, Part 1, p. 651-689.

Traves, D.M., Casey, J.N., and Wells, A.T., 1956, The geology of the south-western Canning Basin, Western Australia: Australia Bur. Mineral Resources Rept. 29.

Trendall, A.F., 1974, The age of a granite near Mount Crofton, Paterson Range Sheet: West. Australia Geol. Survey Ann. Rept. 1973, p. 92-96.

Turneaure, F.E., and Russell, H.L., 1947, Public water supplies (4th ed.): New York, John Wiley and Sons, 704 pp.

Veevers, J.J., and Wells, A.T., 1961, The geology of the Canning Basin, Western Australia: Australia Bur. Mineral Resources Bull. 60.

Walton, W.C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey Bull. 49.

Wells, A.T., 1959, Yarrie 4 - mile geological series: Australia Bur. Mineral Resources, Explanatory Notes. 16.

West Australian Petroleum Pty. Ltd., 1957, Bore completion report for Wallal Core Hole No. 1, by R.M.L. Elliott.

World Health Organization, 1971, International standards for drinking water (3rd ed.): Geneva, W.H.O.