INSTITUTE of HYDROLOGY

WEST BAY GROUNDWATER MODEL STUDY, DOHA

Final Report

INSTITUTE of HYDROLOGY

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West Bay Groundwater Model Study
Doha, Qatar

Final Report

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SUMMARY

Existing, but limited hydrogeological data for the West Bay district was supplemented by a field investigation programme to provide appropriate and reliable information for the design and calibration of a groundwater model of the West Bay and the immediate area inland.

The model was used to examine the water table response to occasional but heavy rainfall events, to an expected increase in recharge from the ongoing urban development, and to a combination of both of these conditions.

The results suggest that:

(a) Water levels in the West Bay area are likely to rise by 10 to 40cm when the development is complete if the proportional level of recharge and discharge continue. In itself, this will be unlikely to result in surface flooding as water levels will still be 1m or more below ground level even in the low lying areas.

(b) After development is complete, heavy rainfall events are likely to result in an increase in the area of flooding which presently occurs in the low lying area along the old shoreline but are not expected to cause new areas of flooding. A combined surface-groundwater drainage scheme would be appropriate to reduce water levels in this particular area.

The implications of these results are that a widespread network of drains would not be required throughout the area and there would be no need for a pilot drainage scheme.

WEST BAY GROUNDWATER MODEL

Chapter 1

BACKGROUND

1.1 INTRODUCTION

The West Bay district of Doha is formed from reclaimed land along the northern shore of Doha Bay. The low lying parts of this district are subject to flooding after heavy rainfall due to the presence of a shallow water table and the collection of surface run-off in closed depressions. These floods can persist for several days but occur only infrequently, the last occasion prior to this study being in February 1988.

Urban development of the West Bay area is now taking place and the associated water demands will increase the amount of recharge from garden irrigation and from leaking pipes whilst current renovation works will decrease the infiltration losses into sewers. This could result in a permanent rise in the water table causing more frequent and persistent flooding unless water level control measures are implemented.

It was considered that a network of groundwater drains would be needed to combat the expected rise in groundwater levels and prevent future flooding. The design of this network would require an understanding of the local hydrogeological conditions, particularly concerning the hydraulic characteristics of the fill deposits. However, the lithology of the area is highly variable and the existing information very sparse. Consequently, a programme of data collection was undertaken during 1989 to provide the necessary information for the construction of a numerical groundwater model of the West Bay area. This model was then used to predict areas at greatest risk from flooding and to assist the design of a drainage network to alleviate such flooding.

1.2 STUDY AREA

The study area is shown in Figure 1.1. It covers an area of about 25 km2, which includes the West Bay district and, for modelling purposes, a zone extending 6 km inland.

The development of West Bay is already about 50% complete. The extent of built-up areas is shown in Figure 1.2. The present development includes two large housing estates just inland of the former coastline and, on the peninsula itself, offices and an hotel along the southern shore as well as diplomatic buildings along the eastern and northern shores. A number of major urban development projects are planned in the central area, but most new development is scheduled for the northern part of the area and on the peninsula.

Reclamation of West Bay began in the late 1970's and continued into the early 1980's. The materials used for this reclaimation consist of " hydraulic fill" dredged from near shore deposits and "desert fill", which consists of rubble brought from inland for the final stage of backfilling. These have been placed over a sequence of coastal silts, sands and gravels, which in turn rest on dolomitic limestone.

Backfilling and compaction are still taking place and the best estimate that can be made of the current topography is shown in Figure 1.1. This was compiled from 1:2000 scale maps prepared in 1983 supplemented by elevation data obtained from the new boreholes drilled during this study. The main topographic features include:

- a marked increase of slope inland of the 4m Qatar National Datum (QND) contour, which marks the position where dolomite bedrock rises from beneath the cover of coastal deposits and fill material;

- the low elevation (generally less than 3m QND) over most of the peninsula and the original foreshore;

- a ridge about 5m high parallel to the coast along the eastern and northern perimeters of the peninsula;

- and the former shoreline, which is based on a pre-reclamation map of 1964.

The area of particular interest lies seaward of the 4m QND contour where a significant rise in water levels would have the greatest impact.

Chapter 2

DATA COLLECTION PROGRAMME

2.1 DRILLING AND TESTING PROGRAMME

Whilst some geological information has been obtained from existing reports for various building projects carried out in the West Bay area over the past 10 years (see list in Appendix 1), these reports do not contain sufficient information to design a model of the area. A programme of data collection was therefore undertaken between April and November 1989 to obtain information on the geometry and hydraulic characteristics of the main lithological units.

The field investigations were carried out within well defined hydraulic boundaries selected specifically to assist the modelling. These are described in Section 7.3.2 and shown in Figure 2.1.

2.1.1 Drilling Programme

A total of 58 boreholes were drilled within the model area during the present investigation. Their locations are shown in Figure 2.1, which also shows those building projects for which existing geological data were available. The project boreholes were grouped into five series, prefixed GWS 1 to GWS 5. Each series had specific objectives as summarised in Table 2.1.

Series GWS 1 and GWS 2 comprised 37 shallow boreholes drilled to a depth of 1m below the water table to obtain water level information. The GWS 4 series comprised six boreholes drilled on the outcrop of the Dammam dolomite. Each fully penetrated the dolomite and provided essential water level control data for this western part of the study area. Series GWS 3 and GWS 5 comprised 15 boreholes drilled through the full thickness of the fill and coastal deposits to the top of the Dammam Formation. These were used to obtain information on the hydraulic characteristics of these deposits and for geological and water level data.

A summary of the borehole information is given in Appendix 2. Water level monitoring data are listed in Appendix 3.

Table 2.1 Project Borehole objectives

		Information Objective					
Borehole no.	Depth	Water Table Elevation	Depth of Fill	Thickness of Dammam Limestone	Slug Tests	Pump Tests	Tidal Efficiency
GWS1/1-1/19 2/1-2/18	1 metre below water table	•					
GWS3/1-3.1	To top of Dammam Limestone	•	•		•		
GWS4/1-4/6	To base of Dammam Limestone						
GWS5/1-5/5	To top of Dammam Limestone						
GWS5/3 1/18 2/3							

2.1.2 Testing Programme

Several techniques were employed to obtain information on the hydraulic characteristics of the sequence:

input tests. These tests involve the instantaneous removal of a "slug" of water from the borehole and monitoring the subsequent recovery. They were undertaken on the series 3 and 5 boreholes.

pumping tests. These tests were carried out on the series 5 boreholes for estimates of the transmissivity, hydraulic conductivity and storage coefficient.

grain size data. The information available from grain size analyses given in earlier site investigation reports were also used to estimate hydraulic conductivity.

tidal response. Values of storage coefficient were derived from a correlation of water level response to tidal fluctuations.

The results are presented and discussed in Chapter 6.

2.1.3 Water Balance Study

A parallel study was undertaken to quantify the recharge from garden irrigation and leaking pipes and the discharge of groundwater into sewers for the period from November 1988 to November 1989 to update earlier estimates made in 1983. The results for the study area are presented in Chapter 5.

Chapter 3

GEOLOGY

3.1 GENERAL

West Bay is an area of reclaimed land built out from an original, low lying coastline fringed with saline sand flats (Sabkhas). A mixture of sand, silt and gravel dredged from the adjacent sea floor has been used for the reclamation, which spreads some distance inland from the original coastline. It overlies and largely conceals coastal silts and sands associated with the old shoreline, which still outcrops inland of the fill, although the precise position of the boundary between the two formations is uncertain.

The bedrock of the area is the Upper Dammam Formation, a series of indurated fractured dolomites of Eocene age. Where the dolomite emerges from beneath the cover of fill and coastal deposits, along the line of the 4m ground surface contour, there is a distinct break of slope. From this point the dolomite rises inland to over 20m QND within the model area. A generalised map of the geology is shown in Figure 3.1 and a simplified cross section presented in Figure 3.2.

All of the formations above the Midra Shale in the area are permeable and can be considered as 'aquifers'. An impermeable base to the sequence is taken as the Midra Shale, a variably thick calcareous mudstone that underlies the Dammam dolomite. Above the shale there is free regional hydraulic connection between the fractured dolomite and the overlying coastal deposits and hydraulic fill. The water table passes laterally from the dolomite into the overlying material approximately along the line of the former coast. Although there is free hydraulic connection on a regional scale, impersistent silt and mudstone horizons within the hydraulic fill and particularly the coastal deposits provide local barriers to groundwater movement.

3.2 DISTRIBUTION AND LITHOLOGY

3.2.1 Dammam Formation

The entire study area is underlain by the Damman Formation, which consists of fractured dolomites and limestones with a recorded thickness of between 13 and 35m. Typically the formation is an off-white to grey dolomite. The dolomite and carbonate mud mixture is generally indurated with much of the dolomite having a blue-grey siliceous appearance.

The upper 10m of the Dammam Formation contains numerous large vugs (cavities, which are mostly filled with carbonate mud) and has the appearance of a weathered horizon. Commonly the vugs are between 2 and 20cm in diameter but are not interconnected. Most of the open vugs have originated by the removal of soluble material infilling fossil shells. The lower part of the formation below 10m is characteristically a zone of massive off-white dolomites with few vugs and little fracturing. This part of the sequence is significantly less permeable than the upper 'weathered' zone. (ASCO, 1983; JICA, 1987).

Groundwater flow in the dolomite does not take place uniformly throughout the entire saturated thickness but along well-defined, widely spaced networks of fissures that have little or no hydraulic connection. Small irregular fractures are common, although many have been re-cemented. Larger fractures are less common, but where present are frequently sub-horizontal, up to 30cm in width and extend laterally for many tens of metres. Increased fracturing in the upper 10m ensures that the highest permeability, and thus most flow, takes place in this part of the formation.

The elevation of the top surface of the Dammam formation is shown in Figure 3.3. To the west of the 4m ground contour the formation outcrops at the surface, its top being reflected by the ground topography. To the east, where it disappears beneath the cover of fill and coastal deposits, the dolomite dips gently toward the coast reaching its lowest point in the vicinity of the Sheraton Hotel, where it lies at -7m QND. Otherwise the most noteworthy feature is a slight ridge which extends along the northern part of the peninsula.

The Midra Shale forms an impermeable base to the dolomite. This is an alternating sequence of brown and green carbonate shales and thin dolomites of Lower Dammam age. It is between 5-10m thick and acts regionally as a confining layer, preventing large scale vertical movement into and out of the overlying dolomite. The elevation of the top surface of the Midra shale is shown in Figure 3.4. There is a tendency for high and low regions on the Midra surface to coincide with ground surface highs and lows which is due to the solution and collapse of evaporite deposits in formations lying below the Midra. This unsystematic collapse has created numerous unconnected depressions that are characteristic of the Qatar landscape. Because collapse is initiated by removal of material below the Midra, the shale itself subsides in the same way as the ground surface. Locally, the shale has been fractured and broken allowing some limited vertical migration of groundwater. However, on a regional scale the amount of water transferred is very small so the shale can still be considered an efficient 'aquitard'.

3.2.2 Coastal deposits

The original coastline is characterised by a number of flat inter- and supra-tidal deposits or 'sabkhas', interspersed with other areas of silts, sands and gravels. The sediments extend from below the former low tide mark to approximately the line of the 4m ground surface contour.

Sabkhas are salt encrusted, flat lying areas of silt and sand. They are common in coastal areas of the Arabian Gulf (Evans *et al.*, 1969; Fookes *et al.*, 1985). Evaporation from shallow water tables within these flat-lying areas provide an important mechanism for the discharge of coastward moving groundwater, leading to increase pore water concentration and the precipitation of aragonite, calcite, gypsum, anhydrite and halite salts, all of which are commonly present in sabkha sequences.

In the West Bay area, sabkhas form the floor of several embayments along the original coastline. The major areas are shown in Figure 3.5 although most have now been covered by a thin mantle of backfill. However, they still show through in small isolated patches, for example immediately to the south east of the West Bay sports stadium and alongside the coast road in the northern part of the region.

From a drainage point of view the areas of thinly-covered sabkha are important for several reasons: they form depressions where the water table is shallow and into which surface run-off concentrates and they have a low permeability. As a result serious groundwater and surface water drainage problems are associated with these areas.

The original coastal deposits form an extremely complex sequence of carbonate rich silts, sands and shelly gravels. Vertical and horizontal variation is such that it is impossible to devise any simple division. Correlation between boreholes is very difficult, even over distances of a few tens of metres. This is illustrated by Figure 3.6, which shows the lithology encountered in six boreholes drilled during construction of the West Bay Sports Club, where, although distances between boreholes are generally less than 100m, there is no consistent pattern in the sedimentary sequence.

At any single location the succession is likely to consist of a variable sequence of silts, sands and shelly gravels with silty sands being perhaps the most commonly encountered lithology. The presence of silt horizons means that vertical movement of groundwater will be restricted locally. However, on a regional scale the succession can be treated as a single hydraulic unit due to the impersistent nature of individual beds.

The thickness of the coastal deposits is shown in Figure 3.7. This ranges from zero below parts of the West Bay peninsula to over 6m in areas inland of the former coastline.

3.2.3 Fill Deposits

The fill consists of two types of material:-

(a) 'Hydraulic Fill'. This is sediment dredged from the nearby sea floor and pumped as a slurry behind bunds to build up reclaimed areas. It comprises a mixture of silty sands, shelly gravels and limestone cobbles. Having been deposited as a slurry it is well mixed and thus tends to be more uniform in composition than the underlying coastal sediments.

(b) 'Desert Fill'. This material has been placed on top of the 'hydraulic fill' during later stages of the reclamation work but is unevenly distributed and where present tends to form only the top metre of the succession. It consists of various types of natural and man-made rubble bought from inland and dumped by lorry. It is much more variable in composition than the hydraulic fill; pieces of wood, concrete and plastic are commonly encountered, along with large blocks of dolomite.

The hydraulic fill is simply re-worked coastal sediment and as such is difficult to distinguish from the underlying coastal deposits. Consequently, the elevation and thickness of the base as shown in Figures 3.8 and 3.9 are to some extent speculative. A means of distinguishing the two has been to assume that all material to the east of the former shoreline lying above present day sea level is hydraulic fill. The elevation of the base of the fill declines steadily eastward to below -3m QND whilst the thickness increases uniformly in the same direction to over 8m along the eastern coast of the peninsula.

Chapter 4

WATER LEVELS

4.1 WATER TABLE ELEVATION

The general configuration of the water table is shown in Figure 4.1. The main features to note are:

each of the three major lithological units above the Midra Shale are in regional hydraulic continuity. The water table is therefore a composite of all three formations and passes west to east from the dolomite, into the coastal deposits and finally into the hydraulic fill (Figure 3.2.). Water is able to pass from one to the other, despite the local presence of impersistent silt horizons in the coastal sediments.

gradients of up to 1 in 150 occur in the western part of the associated with the prominent groundwater mound marking the south-western boundary. This mound rises to elevations in excess of 8m QND within the Dammam dolomites and is caused by high recharge from garden irrigation and leaking water pipes within the Madina Khalifa district compounded by local areas of low permeability in the dolomite.

elevations within the sequence of fill and coastal deposits are less than 1m QND; on the peninsula they do not exceed 0.6m QND. Hydraulic gradients are low in the coastal area, reducing to as little as 1 in 4500 on the peninsula itself.

a distinct groundwater ridge extends along the southern part of the peninsula. This can be attributed to extensive irrigation along the central reservations and sides of the roads converging on the Sheraton Hotel. Otherwise there is little other evidence to suggest the water table has yet been affected by imported water recharge.

4.2 DEPTH TO WATER TABLE

The depth to water is shown in Figure 4.2. Two distinct provinces exist: the backfill-coastal deposit areas, where groundwater generally lies within 3m of the surface, and the dolomite outcrop, where depths are greater than 3m. The dividing line between the two coincides with the 4m ground surface contour.

The dolomite outcrop faces no immediate threat from rising groundwater since depths are commonly in excess of 10m. However, the backfill-coastal deposit areas are obviously at risk.

Backfilling of the peninsula has raised ground elevations to more that 3m above QND in many places, such as along the northern and eastern coasts where it is above 5m QND. However, although backfilling has extended westward and inland of the original shoreline, it has not been built up as high as on the peninsula itself with the result that the old coast-line has a lower elevation than areas further east. This general area has the lowest ground elevation in the region. Consequently, the areas with the shallowest water table are not located, as might otherwise be expected, nearest the coast, but in this narrow zone which extends parallel to and just inland of the former shoreline.

This area of low lying ground was severely affected by the heavy rainstorms in February 1988 when the total monthly rainfall was 140mm, with 39.8mm falling within a 24 hour period (Table 4.1).

Table 4.1 Rainfall at Doha Airport 15 - 25 February 1988

FEBRUARY 1988	15th	16th	21st	22nd	24th	25th
AIRPORT (mm rain)	10.1	49.8	3.8	47.4	3.8	25.8

An area badly affected by the storms in February 1988 was the West Bay Sports Stadium where the combination of a topographic depression, shallow water table and the presence at the surface of patches of silty sabkha combined to cause serious flooding. This particular flood event was caused by an exceptionally intense rainstorm and much of the problem lay with inadequate surface drainage from low lying areas.

Rainfall data from Montaza Park during December 1989 (Table 4.2) were also used to examine the groundwater level reponse to rainfall events described in Section 6.3.3.

Table 4.2 Rainfall at Montaza Park: 6 15 December 1989

DECEMBER 1989	6th	12th	13th	14th	15th
MONTAZA PARK (mm rain)	4.4	2.6	1.2	48.6	10.0

Chapter 5

RECHARGE AND DISCHARGE

The natural and artificial sources of recharge to and discharge from the West Bay area need to be quantified to assist the design of the drainage network. These various sources are as follows:

Recharge:	Natural	rainfall
		- subsurface inflow
	Artificial	- mains distribution losses
		- irrigation
		- leakage from sewers
		- reservoirs
		- domestic
Discharge:	Natural	- direct evaporation
		- evapotranspiration
		- subsurface outflow
		- downward leakage to deeper aquifers
	Artificial	- leakage to sewers

These sources are described briefly in the following sections.

5.1 RECHARGE

5.1.1 Rainfall

As in most arid zones the coefficient of variation of rainfall in Doha is very high. Rainfall usually occurs between November and May as intense local storms, which can account for as much as 65% of the annual rainfall, as indicated in Table 5.1.

A long term record of rainfall is available for Doha Airport dating from 1962. The annual and mean monthly rainfall from this station are shown in Figures 5.1 and 5.2. A shorter record dating from 1979 is also available for the port.

Table 5.1 Probability of annual and storm rainfalls: Doha airport

Recurrence interval (years)	Annual (mm)	Storm (mm)
5	35	7
10	75	18
15	120	40
20	180	62
25	260	105
30	360	170

The maximum and minimum annual rainfall recorded at Doha Airport are 303mm (1964) and 0.4mm (1962), respectively. The average annual rainfall over the 26 year period 1962 to 1988 is 74.7mm. However, the average annual rainfall should not be considered as very meaningful given the high degree of variability in the total annual rainfall. The spatial distribution of the rainfall can also be very different as the storm cells are often very localised.

The likelyhood of direct recharge from rainfall is small except where water levels are particularly shallow. The various factors influencing the amount of recharge from this source include the storm intensity, pre-existing soil moisture conditions, the permeability of the soil, and the rate of evaporation. The topography has an important effect as local depressions allow the concentration of run-off thereby increasing the recharge potential.

Water balance studies carried out in individual topographic depressions in Qatar indicate that recharge from individual storms ranges from zero to 64%, with a weighted mean of 15% of storm rainfall. On the basis of these studies a mean annual recharge of 10 to 12% of annual rainfall was adopted for water resource assessments.

The water table response to rainfall events in February 1988 and December 1989 has been examined with the numerical model to provide estimates of recharge in the West Bay area. The results are discussed in Sections 7.3.3 and 7.4.3.

5.1.2 Subsurface Inflow

An important source of recharge to the study area is the lateral movement of groundwater from the groundwater mound on the western boundary. The amount of inflow from this source has been quantified by the model using the standard Darcy equation.

5.1.3 Seawater Ingress

During high tide conditions sea level is raised above groundwater levels near the coast for short periods causing seawater to flow inland until the tide recedes. The amount of flow from this source has been estimated by the model by setting the initial tidal conditions at high tide and applying the standard Darcy equation.

5.1.4 Pipe Distribution Losses

ASCO (1983) estimated that losses from the piped distribution system in Doha were 20%. This is comparable to distribution systems throughout developed countries. The results of the recent water balance study undertaken during 1989 are given in Table 5.2. This indicates that distribution losses in the study area are about 1.1 Mm3/y, or 17% of the total losses, all of which is assumed to reach the water table. About 50% of losses from the distribution system occur in QAR zones 10, 34 and 37 (see Figure 7.2) which have the highest number of water mains.

5.1.5 Irrigation

Recharge from irrigation within the study area is estimated to be as follows: garden irrigation, 0.9 Mm3/y; landscape irrigation 0.55 Mm3/y; and treated sewage effluent (TSE) irrigation, 1.1 Mm3/y. The distribution of recharge from these sources in each QAR zone is given in Table 5.2. About 60 to 70% of the recharge from landscape irrigation and the use of TSE for irrigation occurs in QAR zones 60 and 61.

These recharge estimates assumed that 23.5% of the potable water supply is used for garden watering and that 45% of this reaches the water table. Landscape irrigation rates were taken to be 16 litres/m2 of which 81% reaches the water table. These are the same assumptions as applied by ASCO in 1983.

5.1.6 Recharge from Sewerage

Recharge within the study area from sewage is estimated to be 1.3 Mm3/y, of which 1.29 Mm3/y is contributed from septic tanks in areas not served by piped systems. About 34% of the recharge from this source occurs in QAR zone 10 (Table 5.2). The piped sewerage system is not pressurised but some leakage losses are likely where the pipes are laid above the water table and a nominal loss of 1% of the piped sewage is assumed to contribute to recharge.

TABLE 5.2

SUMMARY OF THE MAN-MADE RECHARGE AND DISCHARGE SOURCES FOR THE MODEL AREA

SUMMARY SHEET

QAR ZONE	DOMESTIC M3/YR	POTABLE GARDENING M3/YR	WATER LANDSCAPING M3/YR	RECHARGE LOSSES RES. M3/YR	LOSSES DIST M3/YR	OTHER SEWERS RECHARGE M3/YR	RECHARGE TSE IRRIGATION M3/YR	OUTFLOW INFILTRATION M3/YR
10	9172	33209	16425	0	100482	450775	65115	0
20	2292	4649	9855	4599	4815	4015	45376	0
31	126	2847	0	0	2401	0	0	0
32	1900	49055	27885	0	34690	22265	24800	0
33	5087	125104	57879	0	92159	168995	47418	0
34	7862	145908	49275	0	124502	120815	40556	0
35	5745	81600	4106	0	96080	250025	49651	0
36	21	474	0	0	400	0	0	0
37	14994	170364	4106	0	271063	248200	12116	0
60	1467	0	162115	0	0	38690	523484	0
61	5271	9488	205313	0	1867	5110	101605	256595
62	175	0	9855	0	0	0	37993	0
63	2355	9726	0	0	42772	1095	58517	97455
64	3427	61888	0	0	65418	1460	55092	159505
65	4799	108642	0	0	91626	2190	0	220095
66	3647	82549	0	0	69620	1825	0	174835
67	3490	78991	0	2704	66519	1825	0	167900
TOTAL	71830	964494	546814	7303	1064514	1317285	1061723	1076385

5.1.7 Domestic Water

It is assumed that about 2%, or 0.07 Mm3/y, of all water supplied for domestic use contributes to groundwater recharge.

5.1.8 Reservoir Losses

Recharge from reservoirs occurs only in QAR zones 20 and 67 and contributes about 20 m3/d, or 0.007 Mm3/y.

5.2 DISCHARGE

5.2.1 Evaporation

Significant groundwater discharge occurs by direct evaporation from the shallow water table in the coastal sabkhas. In eastern Saudi Arabia, evaporation from sabkhas are reported to vary from 1.1 mm/d in winter to 1.8 mm/d in summer (Pike,1971).

Many of the original sabkha areas in West Bay have now been covered by backfill deposits. However, groundwater evaporation is still expected to occur where water levels are within 1m of the surface. It has been assumed for modelling purposes that evaporation takes place at a rate of 2 mm/d at a depth of 1m increasing to the potential evaporation rate when flooding occurs.

5.2.2 Subsurface Outflow

The model calculates the groundwater discharge at the coast in the same way as for flow into the area (see 5.1.2).

5.2.3 Downward Leakage to Deeper Aquifers

Any increase in water levels in the formations overlying the Midra Shale could result in downward leakage through fractures into deeper aquifers. However, the quantities involved will be small and can be ignored as the permeability of the underlying formations is low (ASCO, 1983).

5.2.4 Leakage into Sewerage Pipes

It was assumed by ASCO in 1983 that some 36% of sewerage flow was actually derived from groundwater leaking into the sewer pipes in those areas where the pipes occur below the water table. This would apply to QAR zones 61 and 63 to 67, where the total discharge into sewers is estimated to be 1.1 Mm3/y (Table 5.2). Recent renovation of the sewers will have reduced these losses.

Chapter 6

AQUIFER CHARACTERISTICS

6.1 GENERAL

Estimates of hydraulic conductivity (K) were derived from pumping and input tests undertaken as part of the field programme. These were supplemented by estimates based on grain size data. Values of storage coefficient (S) were also obtained from the pumping tests but supplemented by a comparison of water level changes associated with tidal fluctuations.

6.2 HYDRAULIC CONDUCTIVITY

6.2.1 Pumping Test Estimates

Pumping tests were carried out at sites GWS5/1 to 5/5. The location of each test site is shown in Figure 2.1 and information on each site is summarised in Table 6.1. Each site had two observation boreholes fully screened through the unconsolidated deposits, which at all sites consisted of silty, fine to coarse sand with gravel. The coastal sands form the whole saturated sequence at sites 5/1 to 5/3 but 65% and 73% of the sequence at 5/4 and 5/5.

Table 6.1 Details of pumping test boreholes

Site Number	Ground Level Elevation (m)	Depth to Water (m)	Depth to Bedrock (m)	Saturated Thickness (m)
5/1	2.95	2.80	6.5	3.7
5/2	2.08	1.26	4.0	2.7
5/3	2.43	2.20	4.5	2.3
5/4	2.30	2.40	5.0	2.6
5/5	2.59	1.60	4.0	2.4

The pumping tests were undertaken during October and November 1989 at rates ranging from 0.5 to 5.75 l/s. Three tests with up to 2 days continuous pumping were performed at sites 5/2, 5/3 and 5/4. A single, constant rate test was undertaken at 5/5. Unfortunately, the low yield of site 5/1 prevented a successful test from being carried out. A summary of the test programme is given in Table 6.2.

Table 6.2 Summary of Pumping Test Programme

Borehole Site	Date of Test	Rest Water Level (m) below datum	Rate l/s (m^3/d)	Duration (mins)	Recovery (mins)
5-2-1	25/10/89 (A)	1.280	5.67 (490)	77.5	50.5
5-2-1	29/1089 (B)	1.260	5.75 (497)	450.0	45.0
5-2-1	30/10 → 1/11/89 (C)	1.245	5.75 (497)	2885.0	120.5
5-3-1	5/10/89 (A)	1.990	0.71 (61)	61.0	2.0
5-3-1	7/10/89 (B)	2.00	0.967 (84)	345.0	40.0
5-3-1	8/10 → 9/10/89 (C)	2.010	0.85 (73)	1320.0	152.5
5-4-1	15/10/89 (A)	2.830	0.85 (73)	255.0	
			0.967 (84)	44.5	
5-4-1	16/10/89 (B)	2.550		240.0	180.0
			1.060 (92)		
5-4-1	17/10 → 19/10/89 (C)	2.490		3225.0	120.0
			0.95 (82)		
5-5	5/11/89 (A)	1.639		1605.5	60.0

The pumping test data were affected by complex tidal fluctuations and no reliable correction could be determined to remove the effect of these fluctuations. Hence whilst the data appear to fit a Boulton or Neuman type curve, which would suggest water table conditions, the type curve analytical techniques could not be applied with any confidence. The test well data were also affected by considerable dewatering during the tests which reduced the saturated thickness by 90 and 96% at sites 5/3 and 5/5, respectively, and by 52 and 54% at sites 5/2 and 5/4 respectively.

Due to these limitations, estimates of transmissivity (T) and storage coefficient were based on approximation methods at early pumping times and from Jacob's method for distance and time drawdown data and recovery phase. The results are summarised in Table 6.3. Whilst the T values appear to show a wide range, the various methods suggest that a typical value for the unconsolidated deposits would be about 100 to 150 m2d.

6.2.2 Input Tests

Estimates of hydraulic conductivity were also obtained from "input" tests, which involved the rapid removal of a fixed volume of water using a bailer and monitoring the water level recovery with a transducer and millivolt recorder until equilibrium levels were re-established. These tests were carried out on 15 holes: 10 of the series 3 boreholes (diameter 168mm) and 5 of the series 5 boreholes (diameter 203mm). The test site locations are shown in Figure 2.1.

Table 6.3 Results of Pumping Tests

	5/2	5/3	5/4	5/5
1. Logan Approximation @ t = 5 mins.				
	Tm^2/d 1240	90	145	140
	Km/d 460	48	69	72
2. Distance-drawdown (early data)	T	125	105	1975** ?
	K	40	45	820 ?
	S	0.2%	0.2%	$3x10^{-4}$
3. Time-drawdown (Jacob)	Test well			
	Te 1300	25	ξ	140
	Tl 80	?		5
	K 30 · 480			
	Observation 1			
	T 6000 ?**	105	70 ~ 90	75
	S 11%	0.3%	0.25%	0.2%
	Observation 2			
	T 14000 ?**		115 · 135	
	S 11%		0.15 0.2%	
4. Recovery	T	100	140	

Te = early data Tl late data * = rapid ** = influenced by leakage

The water level data were analysed using methods derived by Cooper (1967) and by Bouwer and Rice (1976), which both assume that well losses are negligible and that the aquifer is isotropic and homogeneous. The Cooper method takes well storage and aquifer storativity into account, whereas the Bouwer and Rice method only takes account of well storage.

In the Cooper method, values of head divided by initial head are plotted on a semi-log scale against log time. The data plots are then compared to type curves to derive a value of T from which K is obtained from K= T/D, where D is aquifer thickness. The Bouwer and Rice method involves plotting the head change (H) against time on a semi-log scale to then obtain K from the following equations:

$$\ln r_c / r_w \quad \left[\frac{1.1}{\ln(H/r_w)} \qquad \frac{C}{L/r_w} \right]^{-1} \tag{1}$$

$$K = r_c^2 \frac{\ln (r_c/r_w)}{2L} \frac{1}{t} \ln \frac{Ho}{H} \qquad (2)$$

where:
- C = dimensionless parameter
- L = length of the perforated screen
- r_c = effective radius over which head changes
- r_e = radius of the well casing
- r_w = well radius

The test results are presented in Table 6.4. It was not possible to obtain any results for sites 3/1 to 3/3 and 5/1 due to exceptionally low or high permeabilities. The wide range of K values obtained from the tests reflects the variability of the sequence, although this variability must also be due to the subjectivity of the analytical methods themselves. This type of test also represents only the permeability of the deposits immediately surrounding the screen and is therefore usually considered less representative than controlled pumping tests.

Table 6.4 Results of Input Tests

Borehole	No.. of tests conducted	Saturated thickness (m)	Zones of saturation	K (m/d) Method of Analysis: Cooper	Bouwer & Rice
3/1	1	3.20	limestone	too high for test	too high for test
3/2	3	dry	limestone		
3/3	1	3.28	limestone	too low for test	too low for test
3/4	5	3.24	sand	242	20 35
3/5	5	1.57	fill	18	15 81
3/6	4	4.70	sand	338	141 398
3/7	4	2.05	fill	No type curve fit	33
3/8	4	2.05	sand	135	55 228
3/9	4	3.70	fill/sand	12	35
3/10	4	2.50	fill/sand	55	11 34
5/1		3.64	sand	too low for test	too low for test
5/2		3.90	sand	No type curve fit	40
5/3		2.39	sand	No type curve fit	9 130
5/4	3	2.60	sand	196	28 88
5/5	5	2.40	sand	322	22 103

Hydraulic conductivities of 15 to 80 m/d for the fill deposits and 10 to 400 m/d for the coastal deposits are generally consistent with estimates based on the pumping tests and grain size analyses.

6.2.3 Grain Size Estimates

Grain size data are available for the general area from site investigations although grain size analyses were not undertaken on the samples collected during the field programme. The distribution of sites with grain size data is shown in Figure 2.1.

The samples for which grain size data are available were assigned to either the fill or coastal deposits based on an interpretation of the borehole log. The number of such samples relating to each were 68 and 38, respectively. The specific surface method was used to provide initial estiamtes of K from the grain size data for this study. A value of 50000 was assumed for the constant used for this method. Table 6.5 gives the ranges and arithmetic and geometric means in m/d. The geometric mean is about 50% of the arithmetic mean and should be a more accurate estimate of the mean K as the few high K values have less effect on the geometric mean. The results indicate that the K of the fill and coastal deposits are very similar, although there is a wide variation in the K of both types of deposits. The constant applied was based on well sorted, marine sands and, despite the variability in K, produces a mean K similar to that derived from the input and pumping tests.

Table 6.5 Permeability from grain size data (m/day)

	Fill	Coastal Deposits
Min K	2.13	2.31
Max K	515	277
Arithmetic mean K	68.6	53.6
Standard Deviation	89.4	64.3
Geometric mean	35.4	26.5

A plot of the K values (Figure 6.1) shows a skewed distribution. The values were therefore converted to a logarithmic form to produce a lognormal distribution (Figure 6.2). A frequency analysis was also undertaken by assigning K values to classes in units of 10 m/d. These were then expressed as a cumulative percentage to overcome the difference in the number of samples from each type of deposit. The results are plotted as Figure 6.3, which further confirms the similarity in K of the fill and coastal deposits.

Values of permeability assigned in the numerical model are 35 m/d for the hydraulic fill and 25 m/d for the coastal deposits. No tests were carried out to determine the permeability of the dolomite. Instead values have been taken from the ASCO (1983) report. In the model an average value of 145 m/d has been assigned, although it is recognized that the actual value will vary by several orders of magnitude due to the prescence of fracture zones.

6.3 STORAGE COEFFICIENT

The storage coefficient (S) will largely determine the rise in water level in response to recharge and has been estimated from pumping tests and from groundwater fluctuations caused by tides or rainfall events.

6.3.1 Pumping Test Estimates

Values of S obtained from the pumping test range from about 0.2 to 0.3% as shown in As the late test data could not be analysed due to the combined effects of tidal fluctuations and small drawdowns, these estimates were based on the early data and are considered to underestimate the true specific yield (Sy).

6.3.2 Tidal Fluctuations

Storage coefficients can be estimated from the ratio of the change in groundwater level to the change in tidal level at a known distance from the coast using the following formula from Ferris, 1951:

$$S = \frac{t_0 T}{\Pi} \left[\frac{1}{x} \quad \log \left(\frac{2 S_0}{S_r} \right) \right]^2$$

where:
t_0 = Tidal period (days)
T = Transmissivity of aquifer (m^2/day)
x = Distance from coast (m)
S_0 = Half amplitude of tidal variation (m)
S_r = Amplitude of groundwater variation (m)

This method was applied to water level data from 13 locations (see Figure 4.6) and gave the results shown in Table 6.6.

Discounting the very high S value of 17% from site 1/20 and the low value of 0.1% from site 3/7, the results have a reasonably consistent range from 0.5 to 4% averaging 1.8%.

Table 6.6 Estimates of S based on groundwater fluctuations

BOREHOLE No.	Distance from coast (m)	Amplitude ratio (2So/Sr)	Storage %
1/5	570	6.07	.72
1/14	550	21.85	2.27
1/17	230	3.62	2.27
1/20	260	53.9	17.0
2/3	470	3.86	0.6
2/7	200	4.46	4.05
2/9	460	3.27	0.48
2/10	460	11.07	1.98
2/13	400	12.76	2.21
2/15	480	17.73	2.6
3/4	590	16.19	1.6
3/7	160	1.21	0.1
3/9	900	37.5	1.2

6.3.3 Rainfall Events

The change in water level in response to the rainfall event of December 1989 has also been used to estimate storage coefficients based on an infiltration rate of 20%. This approach gave values for S of 2% for the coastal deposits and dolomite and 4% for the hydraulic fill, which are very similar to those obtained from the tidal fluctuation data.

Chapter 7

MODELLING

7.1 INTRODUCTION

The aim of the modelling was to describe in mathematical terms the main processes influencing the distribution and movement of subsurface water in the West Bay area. In outline, the model was designed from field information on aquifer geometry, aquifer properties and sources of recharge and discharge. Simulations of water levels at borehole locations were then computed and compared with measured data in order to calibrate the model, which was then used to predict the effects of expected changes in recharge due to the urban development of the West Bay area.

7.2 MODEL STRUCTURE

Two principles are fundamental to groundwater modelling; first, water which moves from one location must appear elsewhere; and, secondly, the rate of movement of groundwater between two locations is proportional to the slope of the water table between them. The first of these principles is expressed mathematically as the continuity equation, and the second as Darcy's Law. In two horizontal dimensions these may be written:

$$S \frac{\partial h}{\partial t} \qquad \frac{\partial q_x}{\partial x} \qquad \frac{\partial q_y}{\partial y} \tag{7.1}$$

$$T \frac{\partial h}{\partial x} \tag{7.2}$$

$$q_y \qquad T \frac{\partial h}{\partial y} \tag{7.3}$$

The terms appearing in these equations are: S storage coefficient (dimensionless); h head (l); q_x flux in x direction ($\ell^2 t^{-1}$); q_y flux in y direction ($\ell^2 t^{-1}$); R sources and sinks ($\ell^2 t^{-1}$) and, T transmissivity ($\ell^2 t^{-1}$)

The two horizontal coordinates are represented by x and y. With an average gradient to the sea of the order of 1:1000, vertical flow is small in relation to horizontal flow and is assumed negligible for this application. Vertical flow due to infiltration of rainwater was accommodated by adding the appropriate amount of water to the water table, rather than describing its movement through the soil. Equations 7.1 to 7.3 then give the spatial and temporal relationship between heads over the model area.

Simulated values of head at specific points in time and space were found by solving these equations 7.1 to 7.3 for h using finite element analysis, in which the equations were discretised in space and time. These were calculated over a grid defined by a network of nodes dividing the area into quadrilateral elements with the head values at intermediate points are found by interpolation. The gridding technique reduces the model to a set of linear equations which are solved at time steps of 0.1 days.

The model grid which consists of 160 nodes and 139 elements as, shown in Figure 7.1. The distribution of nodes was based on a number of criteria:

> nodes were located at the intersections of main roads;
>
> the coarsest mesh was used for the areas of the Dammam dolomite outcrop except towards the south-western boundary where steeper groundwater gradients required some fining of the mesh;
>
> a fine mesh was used for areas overlain by hydraulic fill or natural coastal deposit; and,
>
> no surface element had all three surface nodes assigned as fixed heads.

The finite element solution used the Galerkin formulation with linear basis functions and integration using 2x2 Gaussian quadrature. The half bandwidth of the system of linear equations is 41, and was solved by an efficient direct method. An implicit finite difference scheme was used to approximate the derivative with respect to time. Aquifer characteristics were computed iteratively when head changes were large, based on the arithmetic mean of their values at the start and end of the relevant time step.

7.3 MODEL INPUTS

The information required to run the model consisted of numerical values for the aquifer geometry, aquifer properties, boundary conditions and internal sources and sinks at nodes or elements.

7.3.1 Aquifer geometry and properties

At each model node the height above QND of the base and top of each of the Dammam, sabkha and hydraulic fill were assigned by interpolation from borehole logs at locations shown in Figure 2.1

Numerical values of the storage coefficient and transmissivity must be specified at each node. Transmissivity is the product of the hydraulic conductivity of the aquifer and its saturated thickness. For an aquifer with several layers, such as at Doha, this can be approximated by the weighted sum of the transmissivities of each layer. Initial estimates of the hydraulic conductivity of the Dammam was taken from the ASCO report (1983), whose findings were based on pumping tests, and for the sabkha and hydraulic fill were derived as described in Chapter 6.

The storage coefficient(s) of the aquifer is defined as the change in water content of the aquifer for a given change in head. It consequently relates only to that part of the aquifer in which the head is changing at a particular time. The storage coefficient at each node is therefore computed as the value for that component in which the water table presently lies. Initial values for the Dammam were taken from the ASCO report (1983), and for the sabkha and hydraulic fill were computed as described in Chapter 6.

7.3.2 Boundary conditions

The model requires knowledge of either the heads or the fluxes across the boundaries. Generally it is convenient to seek natural no-flow boundaries, either along flow lines or at watersheds. Where surface water is present this may form a measured head boundary. In the West Bay model area shown in Figure 7.1 the southwest boundary corresponds approximately to a groundwater divide. Recharge to the north-east flows towards the sea within the model area, while recharge to the south-west flows away from the model area towards the desert. The north-west and south-east boundaries coincide approximately with flow lines and therefore form no-flow boundaries. At the coast the sea forms a measured head boundary, varying with the tide whose height is taken from tidal records. The northern boundary follows the line of a depression which is roughly at sea level and is also treated as a fixed head boundary independent of tidal fluctuations.

7.3.3 Recharge and discharge

Numerical values of recharge and discharge are required for each element of the model.

Besides infrequent heavy rainfall the main sources of groundwater recharge to the West Bay area are seepage from irrigation and leakage from pressurised water mains. Drainage of groundwater to the sewage system and its subsequent pumped removal is the most significant internal sink. Information on these sources and sinks for 1988 is given by the QAR zones shown in Figure 7.2 and quantified in Table 5.2. As information on the possible seasonal variation in recharge and discharge is not available, they are assumed to be constant throughout the year and redistributed to elements of the model by partitioning according to overlapping areas.

Recharge due to rainfall is computed from measured rainfall at Montaza Park, Doha. An accurate allocation of rainwater to surface runoff, replenishment of moisture in the unsaturated zone, or recharge to groundwater cannot be made. The ASCO report (1983) suggests a recharge rate of 10% over the Dammam, reducing to 7.5% in urban areas, and any remaining rainfall is assumed to be held in the unsaturated zone until it evaporates.

The use of a percentage recharge is inappropriate when the water table is close to or even at the ground surface, as occurs in parts of the West Bay area. In such regions proper accounting of the water balance is necessary. For the larger storms we have assumed that the amount of rainwater reaching groundwater as recharge is 20% when the water table is more than 1m below the ground surface. When groundwater is within 1m of the surface, it is assumed that all rainfall infiltrates such that the moisture content of the unsaturated zone is in equilibrium with groundwater. The moisture characteristic used to calculate the moisture profile of the unsaturated zone is derived from a grain size analysis of the hydraulic fill and sabkha.

Evaporation is computed as varying linearly from 2mm per day at 1m depth to its potential rate when the surface is fully saturated.

7.3.4 Initial conditions

Initial estimates of the head at each node must be specified for transient (time-varying) runs. For steady state runs they are not essential, but are useful for comparison with simulated steady state heads. Initial heads at each node are computed from borehole measurements by interpolation. Depending on the particular model run, these may be adjusted for tidal effects.

7.4 MODEL RUNS FOR PRESENT CONDITIONS

7.4.1 Steady state runs

The model was first run in steady state and the measured and predicted heads compared. The comparison was complicated by the fact that borehole measurements were made at different states of the tide, and this has a significant effect on levels at some locations near the coast. Measurements were adjusted to estimated high tide levels, and the boundary heads in the model fixed at their high tide values. The difference between simulated and observed heads is shown in Figure 7.3. The major discrepancies are along the southwestern boundary where borehole information is sparse and interpolated initial heads are likely to be erroneous. This does not, however, rule out the possibility that spatial variability in aquifer properties or inaccurate estimation of recharge may be responsible for head differences. In the region near the coast, discrepancies may in part be due to inaccurate tidal correction to measured data.

This steady state run is independent of the storage coefficient, but can be used to calibrate hydraulic conductivity. Re-running the model with differing hydraulic conductivities and using the mean square prediction error as a measure of goodness of fit suggests a hydraulic conductivity of 145 m/day in the Dammam. This calibration assumes the no-flow boundaries are accurately located, that recharges are correctly specified, and that the aquifer geometry is as assumed. Calibration of the hydraulic conductivity of sabkha and hydraulic fill did not indicate significant differences from the values suggested by field tests. The initial estimates of aquifer properties are summarised in Table 7.1

Table 7.1 Aquifer properties

	Hydraulic Conductivity m/d	Storage Coefficient %
Dammam	145	
Sabkha	25	
Hydraulic fill	35	4

7.4.2 Transient runs with tidal effects

Sequential head measurements from boreholes close to the coast confirmed the presence of tidal effects on groundwater levels, as described in Chapter 4. These were used to calibrate storage in the sabkha and hydraulic fill. In these model runs the heads along the shore were given fixed values at each new time step. Calibration of the storage coefficient gave values shown in Table 7.1. This used combined information from transient runs with tidal effects and with rainfall.

7.4.3 Transient runs with rainfall

Floods may last for several weeks after heavy rain. In the short term this may be due in part to surface flow, but flooding after the cessation of rainfall is sustained by raised groundwater levels.

Rainfall is included in the model as increased recharge (section 7.3.3), with no further changes. Two measured periods of heavy rainfall, February 1988 and December 1989, have been used to assess model performance in simulating flooding. The first storm had a return period of 17 years, and the second of 27 years (FAO,1982). Both produced extensive flooding in low lying areas which lasted several weeks. For the February 1988 rainfall this was clearly shown on aerial photographs.

Figure 7.4 shows the hyetographs for the February 1988 storm, with simulated heads at four nodes adjacent to boreholes 2339.750, 2239.231 and 2239.232 for which time series of water level measurements were available. The location of these nodes is indicated in Figure 7.1. Model runs for this storm give simulated flooding as shown in Figures 7.5 to 7.7. The flooded locations correspond with those observed, but the simulated depth of flooding cannot be checked against observed depths as measurements are not available. Since it is likely that flooding after rainfall has a significant surface runoff component, simulations of the depth and precise locations of flooding must be regarded as approximate.

7.4.4 Summary

These steady state and transient runs for a variety of conditions where the model simulations can be compared with measurements suggest that the model is a reasonable representation of the groundwater processes although flooding after intense rain may have a significant surface water component which is not modelled. Most simulated heads in the absence of rainfall are within 20 cm of interpolated measured heads. Following rainfall, the model simulates flooding in approximately the locations where it is observed, although simulated depths cannot be checked.

7.5 MODEL RUNS FOR INCREASED DEVELOPMENT

Further residential and other development of reclaimed land will result in recharge from irrigation, leakage from water pipes and other sources in the areas concerned. To assess the likely effect of this two stages of development have been included; firstly, the development already underway both on the West Bay peninsula and in an area in the northern part of the model area, and, secondly, maximum development to cover the whole of the West Bay peninsula. Recharge on an equivalent area basis is assumed similar to that for parts of the West Bay area already developed. The areas concerned are indicated in Figure 7.2.

The model has been used to examine whether increased recharge will by itself cause an unacceptable rise in groundwater levels, and also the extent to which increased recharge will exacerbate flooding whose primary cause is heavy rainfall.

To investigate the first of these concerns the model was run steady state with recharges assumed to be as for the existing area of development. This run suggested that, for development already underway, there will be a groundwater rise of up to about 40cm over the northern area. However, as water levels will still be at least 4m below ground surface there will be no risk of flooding despite a fairly large rise in the water table. A rise of only 10cm is expected in the area of the peninsula, which is due to the proximity of the sea and the relatively permeable nature of the sabkha and hydraulic fill such that large head differences cannot be sustained so close to the coast even with the anticipated increase in recharge. Heads over most of the peninsula will remain around 2m below the surface (1m along parts of the former coastline). With maximum development of the West Bay peninsula, the rise in water table, shown in Figure 7.8, is still only expected to be 20cm in the absence of rain.

The area of flooding likely to result from the planned maximum development when heavy rainfall occurs (represented by the February 1988 storm) are shown in Figures 7.10 to 7.12. The corresponding water level hydrographs for representative model nodes are shown in Figure 7.9. (The comparable results for the present development are shown in Figures 7.5 to 7.7 and 7.4, respectively). These model runs indicate that the area of flooding would become more extensive but would still be restricted to a narrow, low lying zone some 3km long situated just inland from the original coastline where flooding already occurs rather than in areas of the new development.

Figures 7.13 and 7.14 show the water table depth if "pumping" was carried out at the nodes shown in order to contain this flooding to maintain water levels at 0.5m or more below ground level with the "worst case" scenario described above. A discharge rate of 21000 m3/d would be required for a short period during and following the storm, although the discharge required to cope with the effects of urbanisation alone need only be about 1300 m3/d to maintain water levels at a depth of 1m.

7.6 IMPLICATIONS OF MODEL RESULTS

The West Bay district of Doha was considered to face two major hydrological problems at the start of this study, namely short-term, local flooding from infrequent storms and a more permanent and widespread flooding associated with a possible long-term rise in groundwater levels due to urban development.

The model was used to examine the water level changes resulting from the proposed development assuming that the estimated present rates and different sources of recharge and discharge (see Table 5.2) would remain proportionally the same. The additional response caused by a major rainfall event, as represented by that which occured in February 1988, was then superimposed.

The main conclusions from the various model runs undertaken during this study are twofold:

• The urban development itself is unlikely to directly result in surface flooding. Whilst water levels are expected to rise by 20cm on the West Bay peninsula and by about 40cm to the north of the present area of development the depth to water level will still be 1m or more even in the low lying areas.

• When the future development has taken place, heavy rainfall can be expected to cause an increase in the extent and duration of flooding compared to the present development. However, this flooding would still be limited to the low-lying area along the old shoreline where floods already occur rather than in new areas.

Hence, the model suggests that the long term rise in water levels will not cause a more widespread permanent flooding and that the short-term flooding would still be limited to a relatively small area of West Bay district following periods of heavy rainfall. These results have the following implications:

1. A widespread network of drains throughout the whole area would not be required as the long-term rise in water level from the urban development would not have the consequences originally anticipated.

2. The pilot drainage scheme study foreseen at the inception of the study is no longer justified.

A combined surface and groundwater drainage network within the low lying area subject to short-term flooding would be sufficient to alleviate the local flooding in this particular area following the planned urban development. An efficient network of surface drains to rapidly remove surface water would reduce the amount of infiltration and the severity of the groundwater problem. The model suggests that the groundwater drains in the low lying area should be capable of removing 21000 m3/d.

It is recommended that:

(a) A more detailed model, which should also take into account the accumulation of surface run-off, would be required to assist the design of a drainage network for this low lying area. This model could be used to evaluate the impact and duration of flooding following storms of different intensity.

(b) The existing West Bay regional model could be used to examine different recharge and discharge scenarios asociated with the urban development.

(c) The water table response to the urban development should be monitored by incorporating selected piezometers drilled during this study in the Doha observation well network.

Following heavy rain our simulations indicate that flooding will be more extensive following planned and potential development, but that this flooding will occur close to regions already subject to flooding rather than at the location of the new development. The extent of additional flooding is indicated in Figures 7.10 to 7.12, which may be compared with Figures 7.5 to 7.7. The water level rise for specific nodes is presented in Figure 7.9.

References

Akili, W. and Torrance, J.K.: 1981. The development and geotechnical problems of sabkha, with preliminary experiments on the static penetration resistance of cemented sands. QJ Eng. Geol. London 14, 59-73.

ASCO, 1983. Rising Water Table Project. (for Ministry of Electricity and Water).

Bouwer, H. & Rice, R.C. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Res. 12(3) 423-428

Cooper H.H. Jr, Bredehoeft, J.D. & Papadopulos, I.S. 1967. Response of a finite diameter well to an instantaneous charge of water. Water Resources Res. 3(1) 263-269

Evans, G., Schmidt, V., Bush, P. and Nelson, H. 1969. Stratigraphy and Geologic History of the Sabkha, Abu Dhasi, Persian Gulf. Sedimentology, 12 (1969) pp 145-159.

Ferris, J. G. 1951.. Cyclical fluctuations of water level as a basis for determining aquifer transmissivity. Asoc. Int. Hydrol. Sci. (33).

Fookes, P.G., French, W.J. and Rice, S.M.M. 1985. The influence of ground and groundwater geochemistry on construction in the Middle East. QJ Eng Geol.London 18, No.2, 101-129

JICA, 1987. The study of drainage improvement plan, Doha City

Pike. J.G: 1971. Evaporation of groundwater from coastal playas (sabkha) in the Arabian Gulf. J.Hydrol. 11, pp79- 88.

Topography (m.QND)

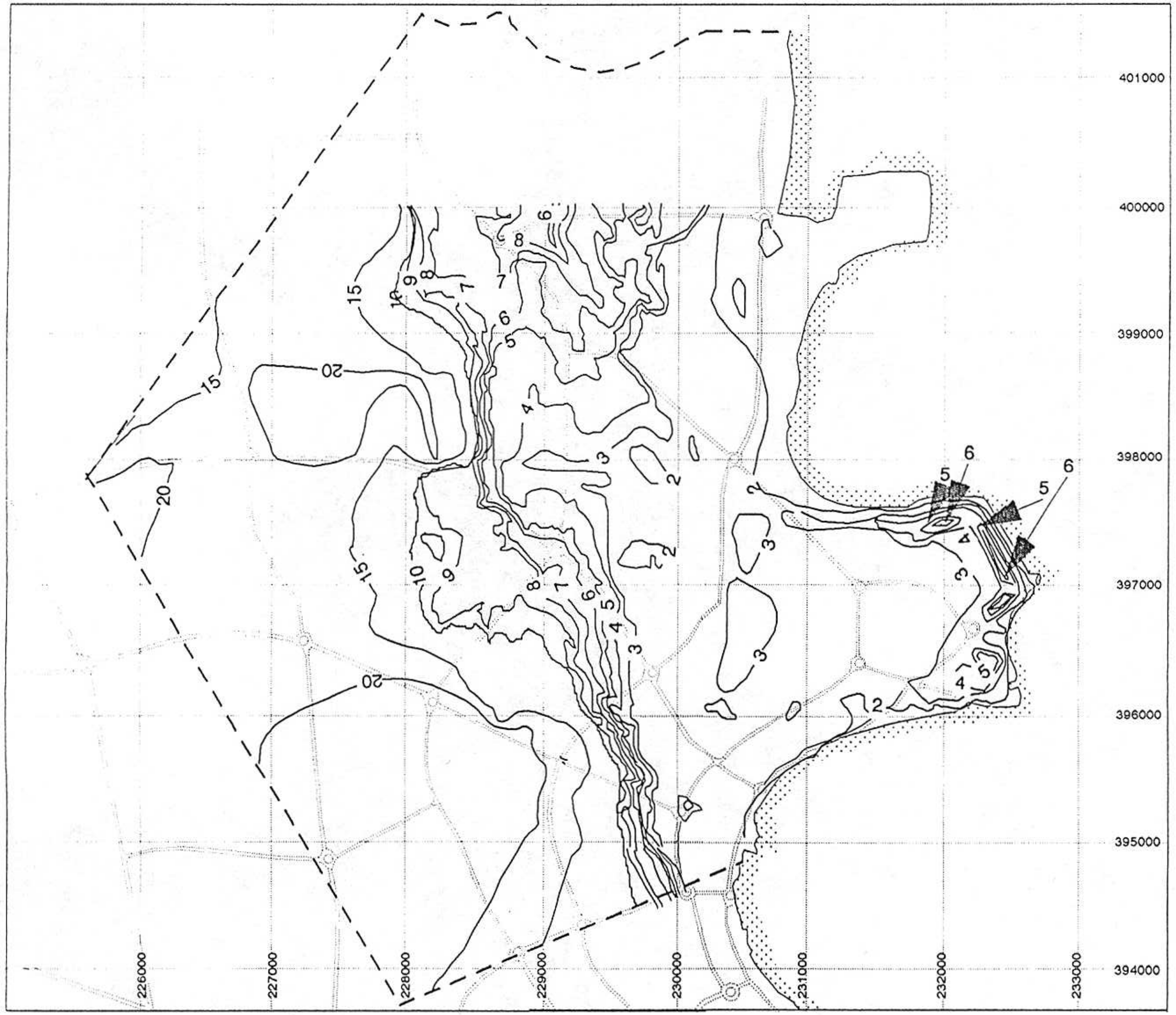


Figure 1.1

Areas of Existing Development

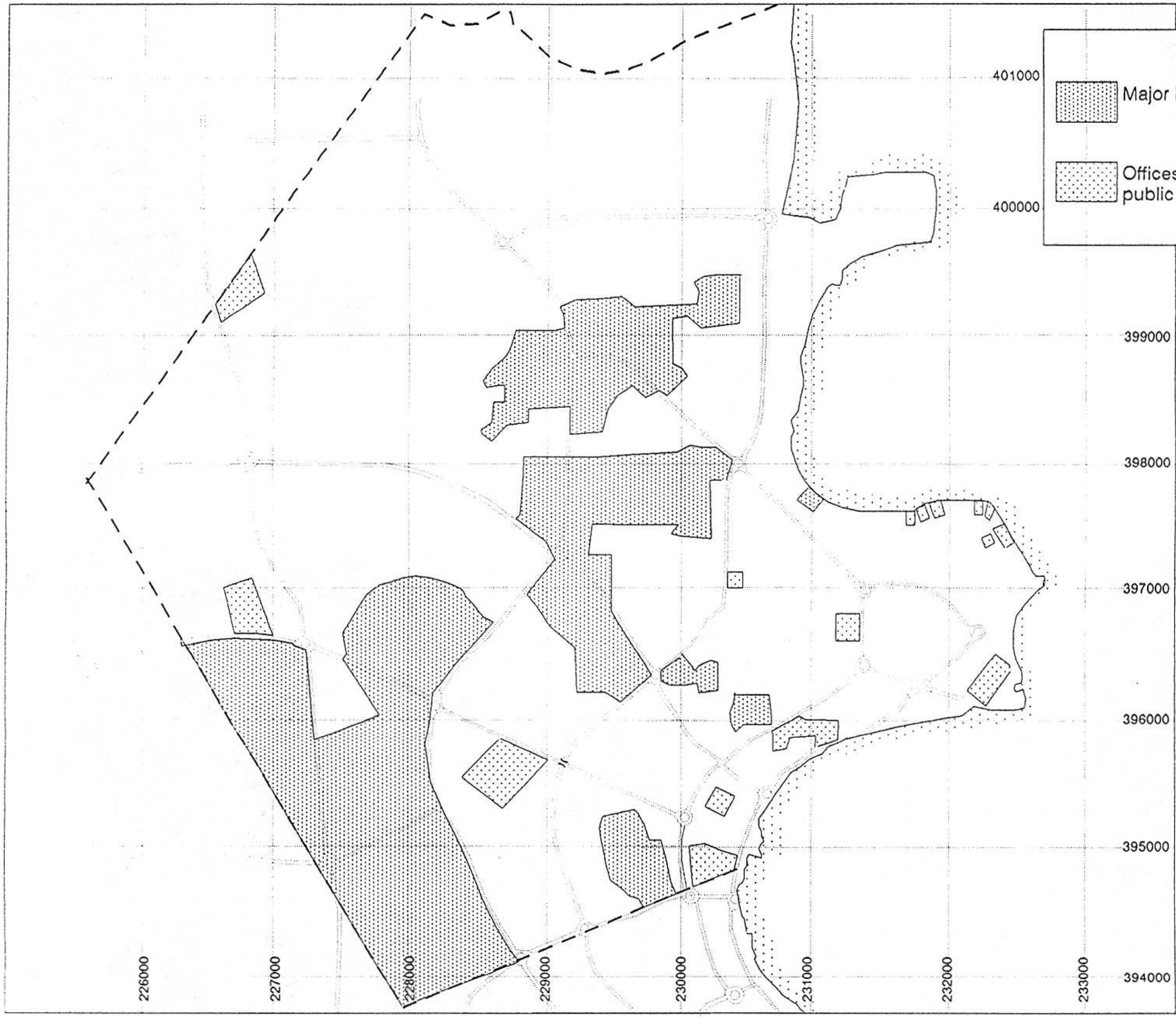


Figure 1.2

Location of Project Boreholes

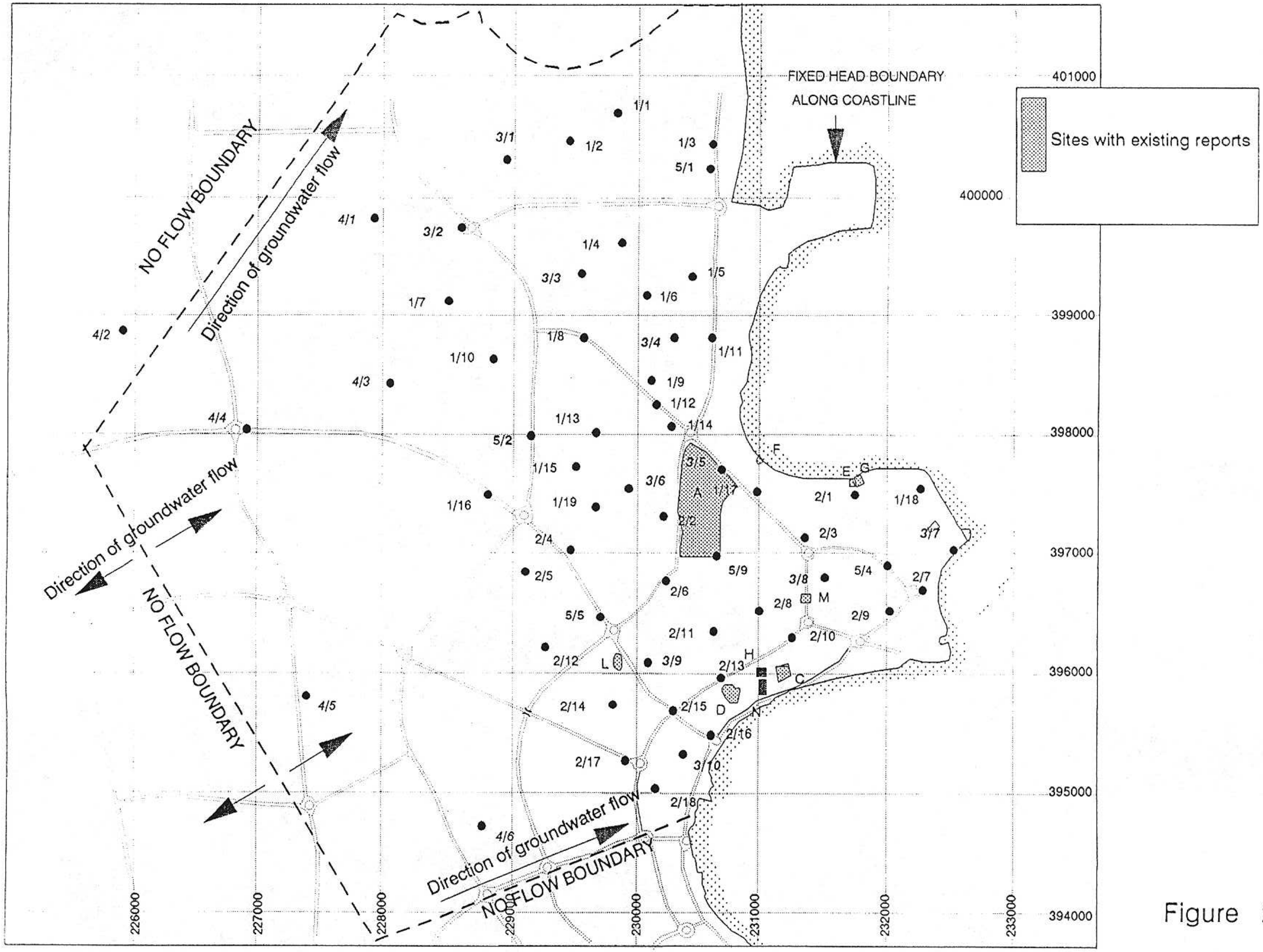


Figure 2.1

Outcrop Geology

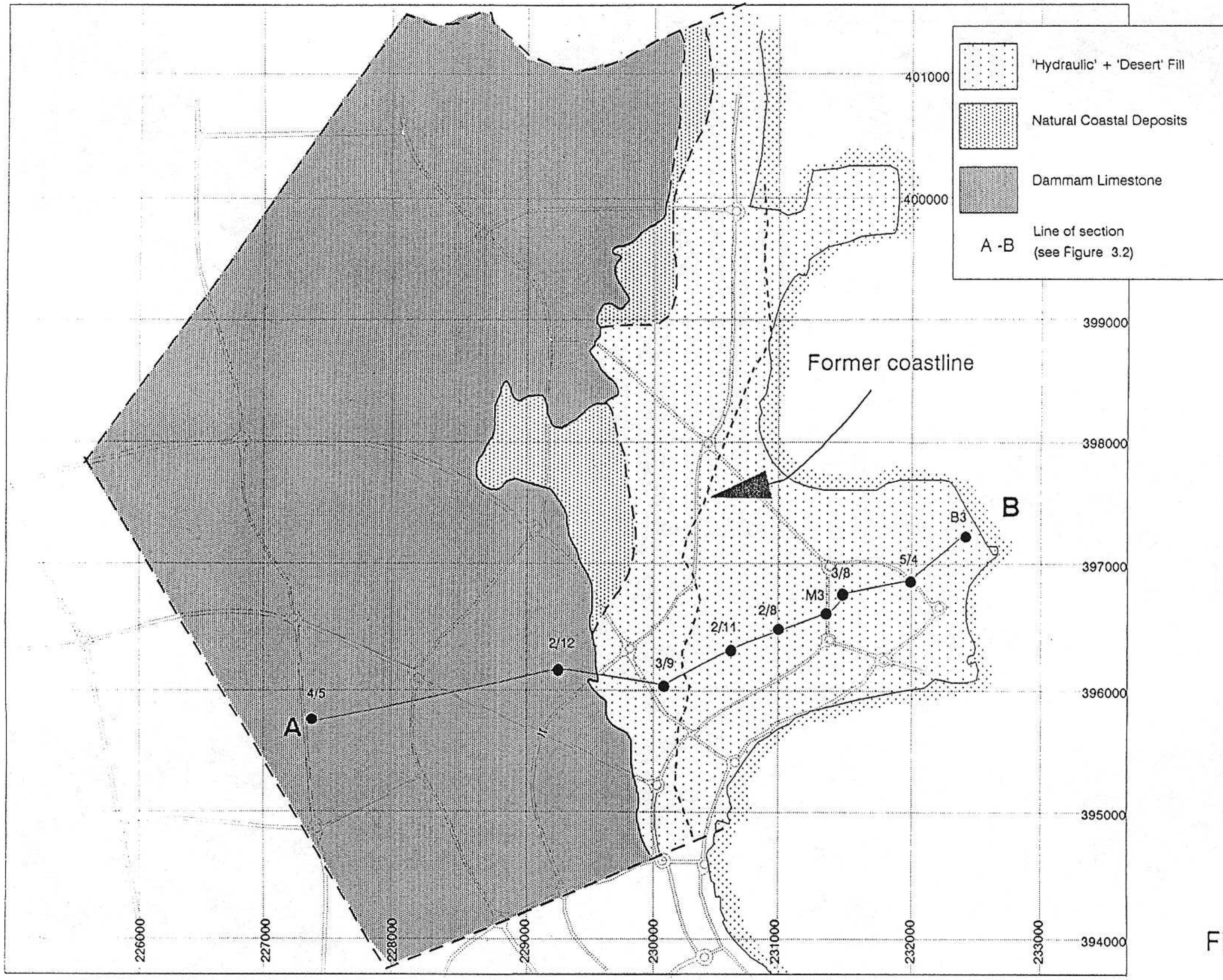


Figure 3.1

Geological Cross Section (See Figure 3.1)

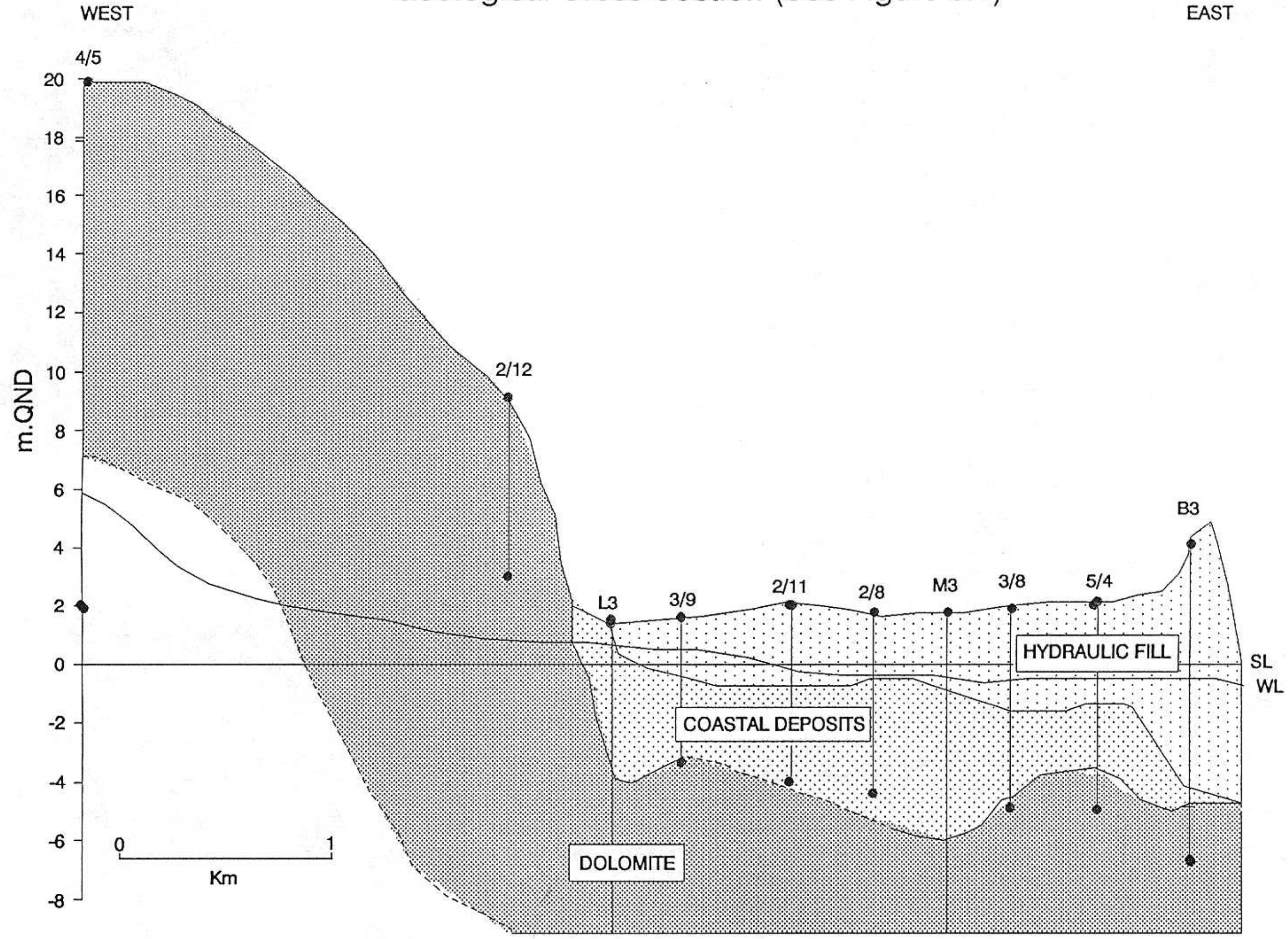


Figure 3.2

Elevation of top surface of Damman Formation (m)QMD

Figure 3.3

Elevation of top surface of Midra shale (m)QMD

Figure 3.4

Areas of Sabkha along original coastline

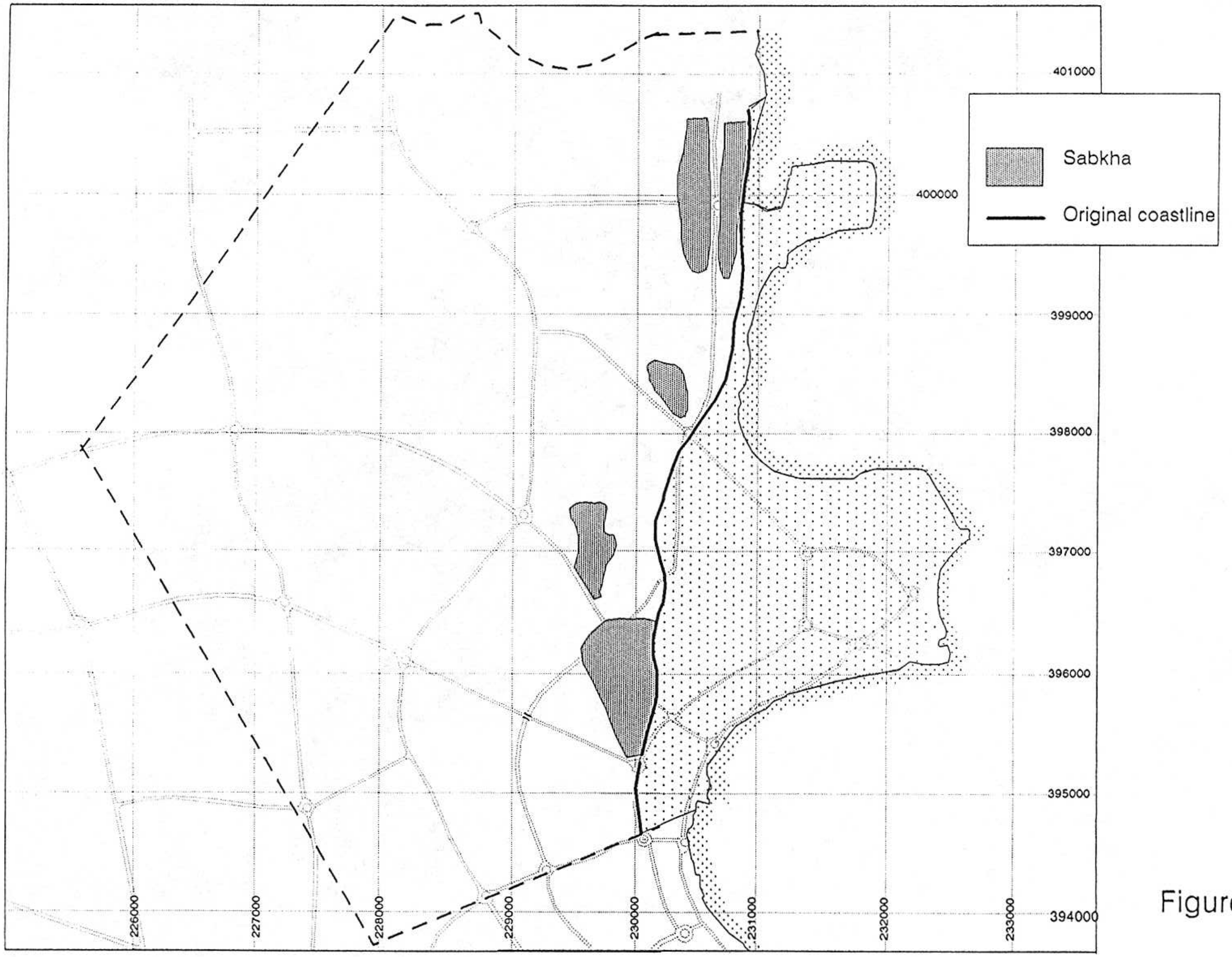


Figure 3.5

Cross section at Sports Stadium illustrating variability of coastal deposits

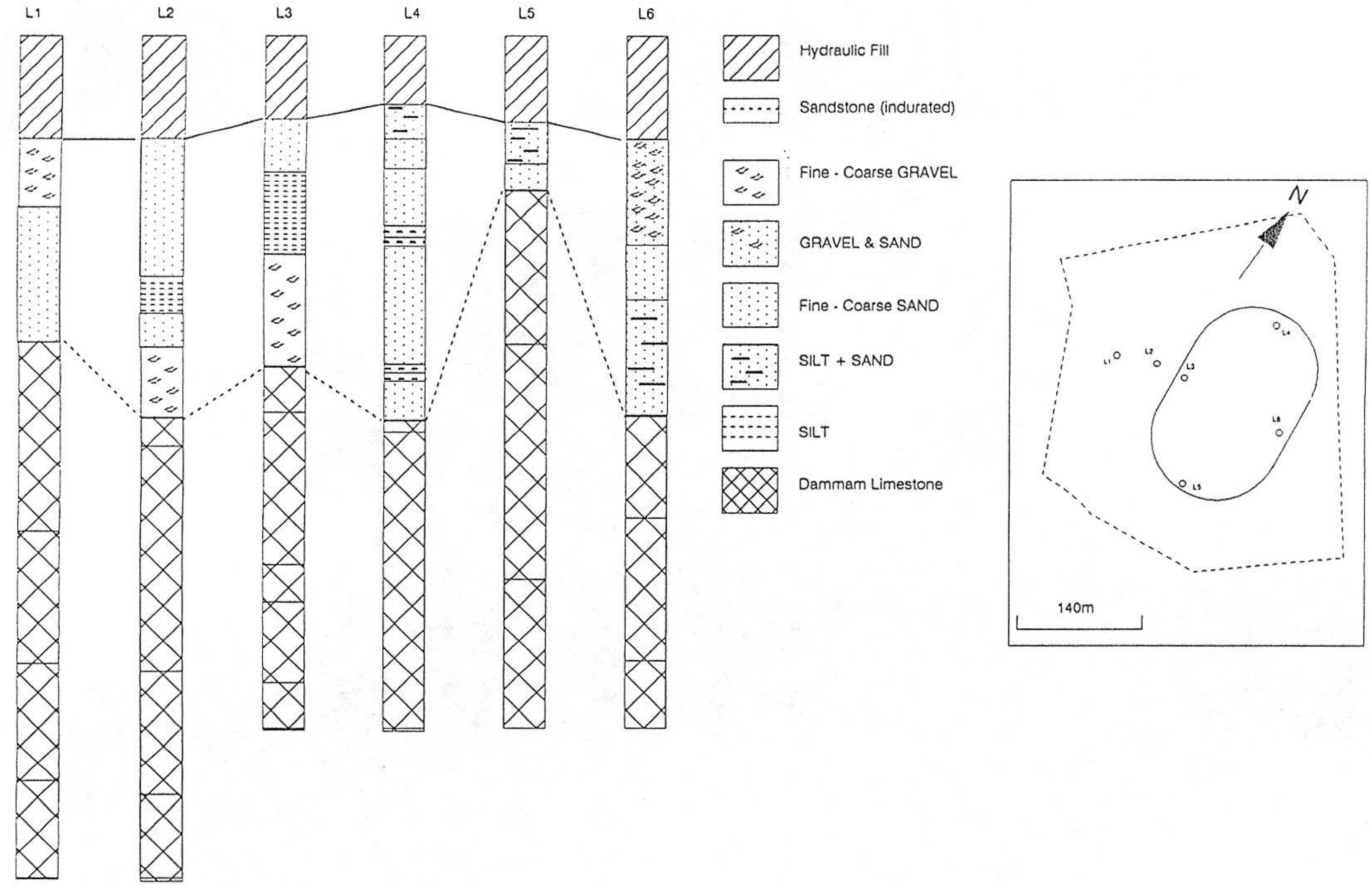


Figure 3.6

Thickness of Coastal Deposits (m)

Figure 3.7

Elevation of base of Hydraulic Fill (m)QMD

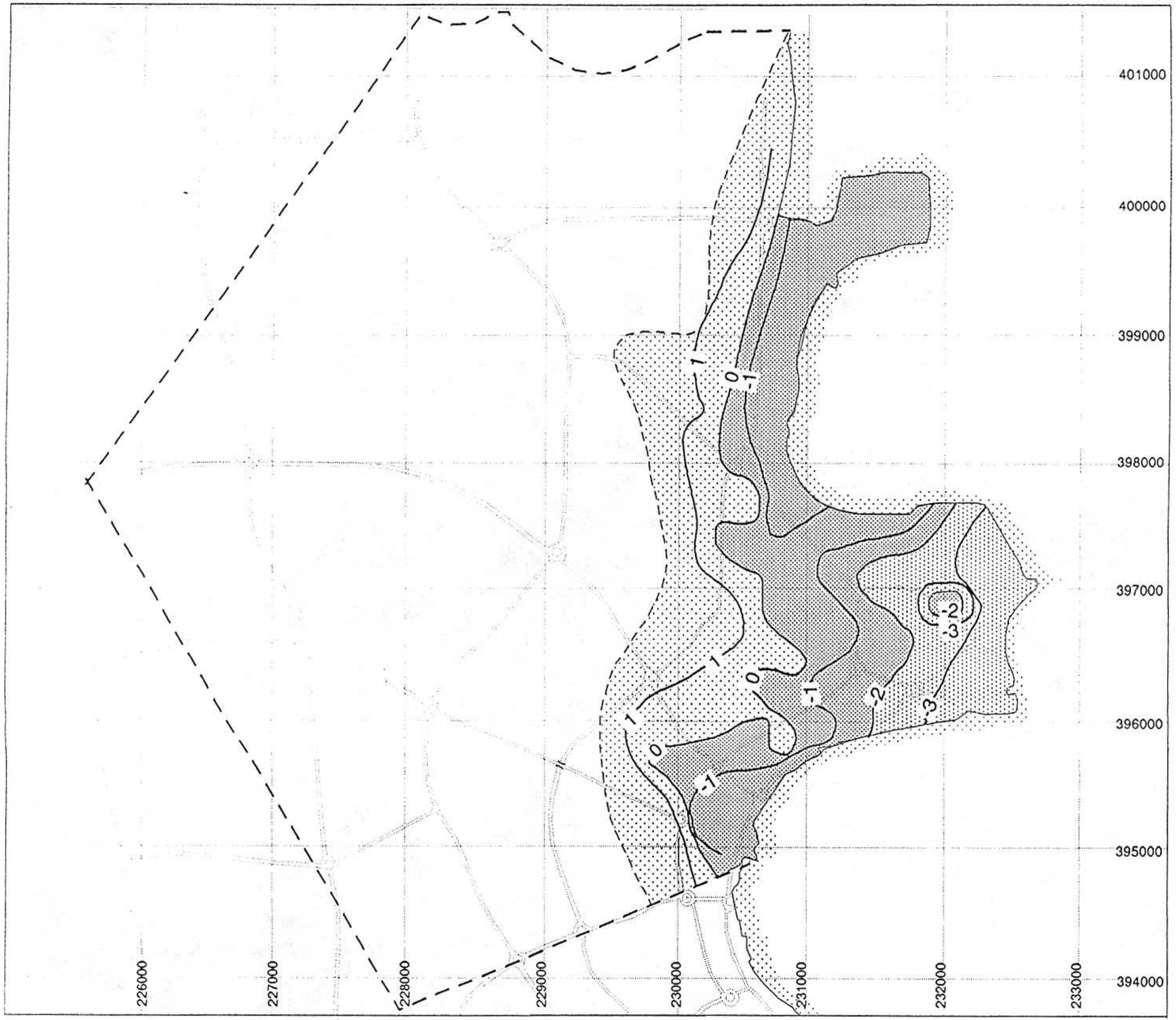


Figure 3.8

Thickness of Hydraulic Fill (m)

Figure 3.9

Elevation of Water Table (high tide 6/9/89)(m)

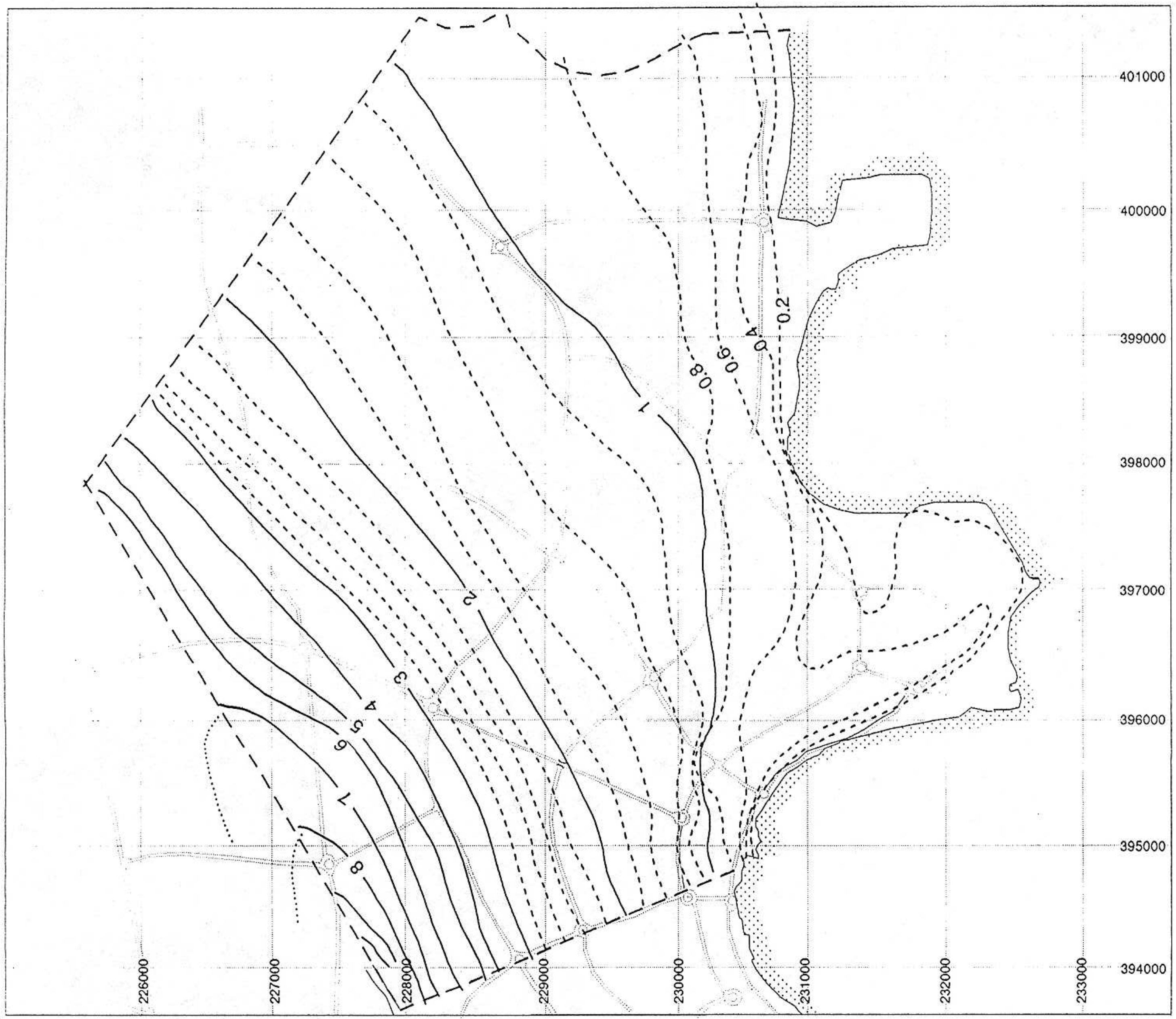


Figure 4.1

Depth to Water Table (high tide 6/9/89)(m)

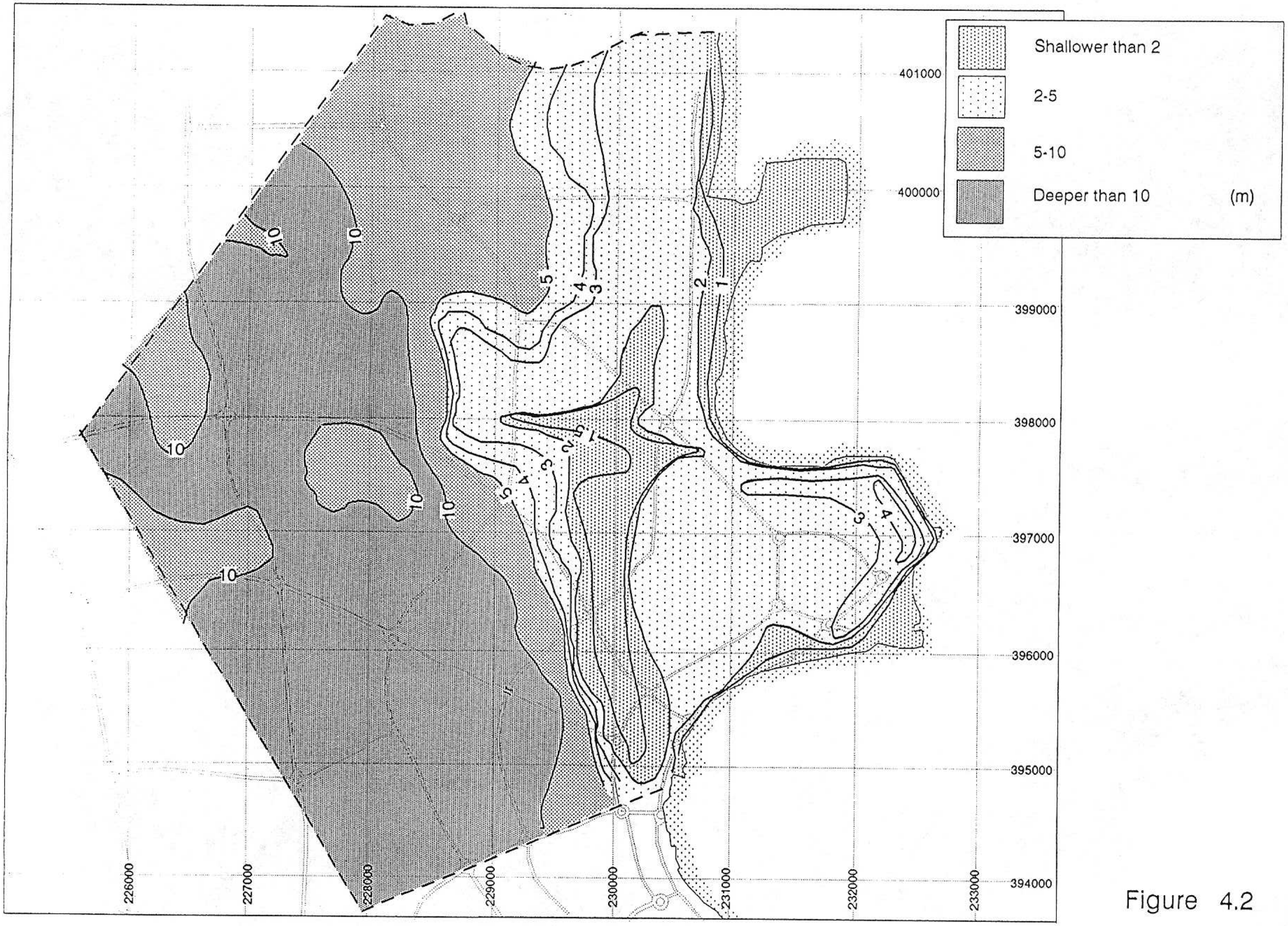


Figure 4.2

Observed changes of water level : 13 - 17th Dec 1989

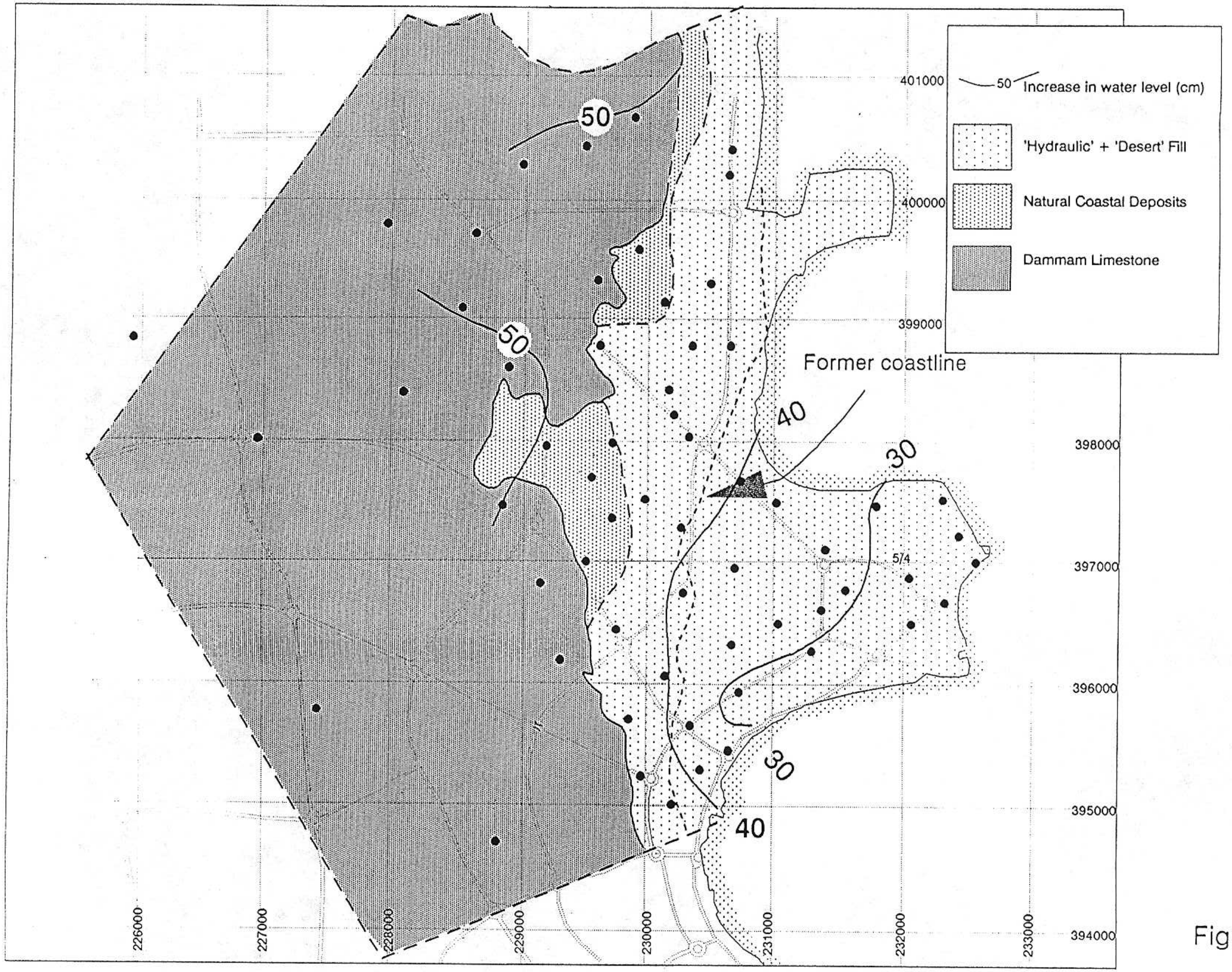
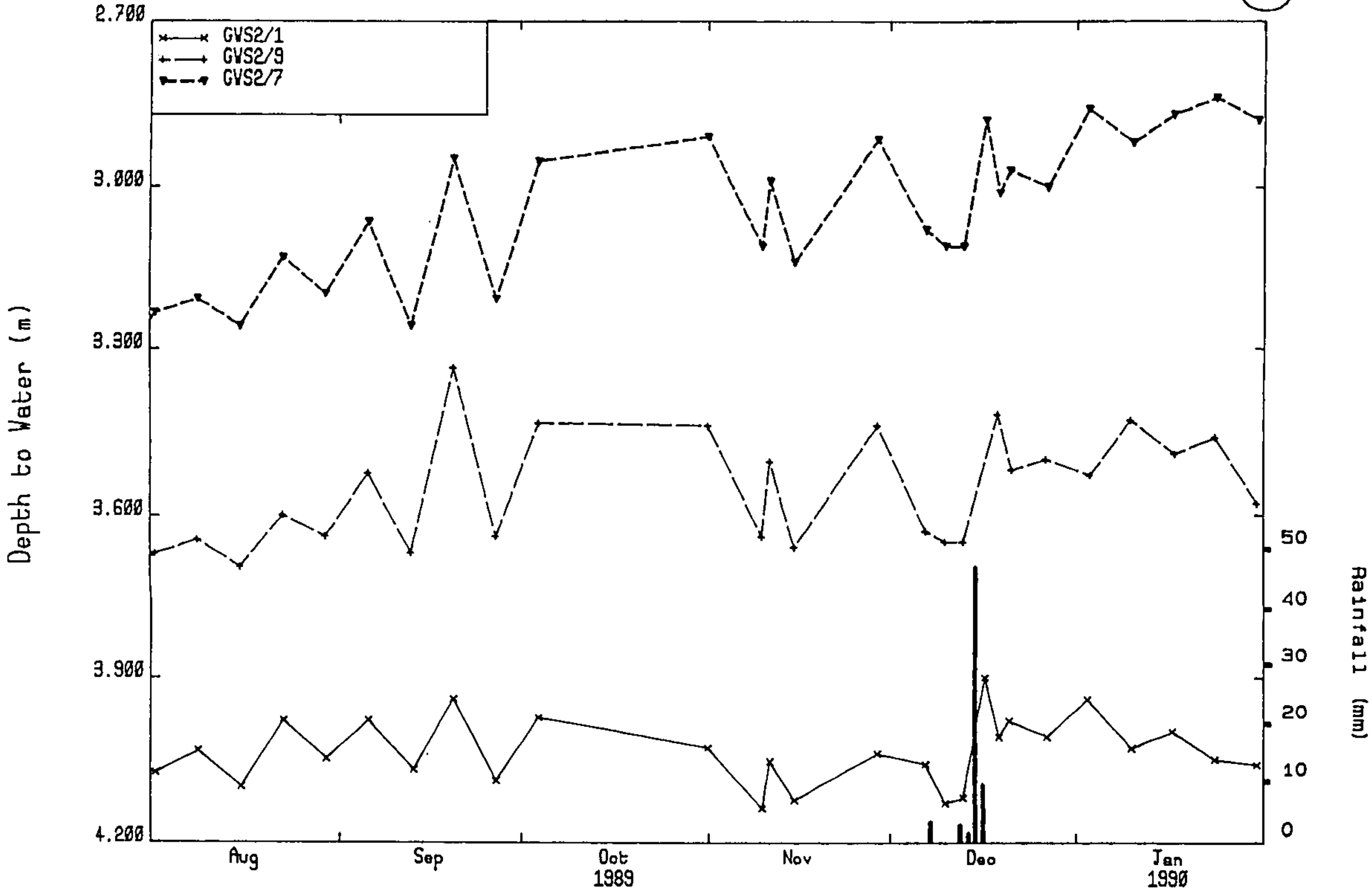


Figure 4.3

Response of boreholes in Hydraulic Fill to the December 1989 rainfall event



Hydrograph

Figure 4.4

Response of boreholes in Coastal Deposit & Dolomite
to the December 1989 rainfall event

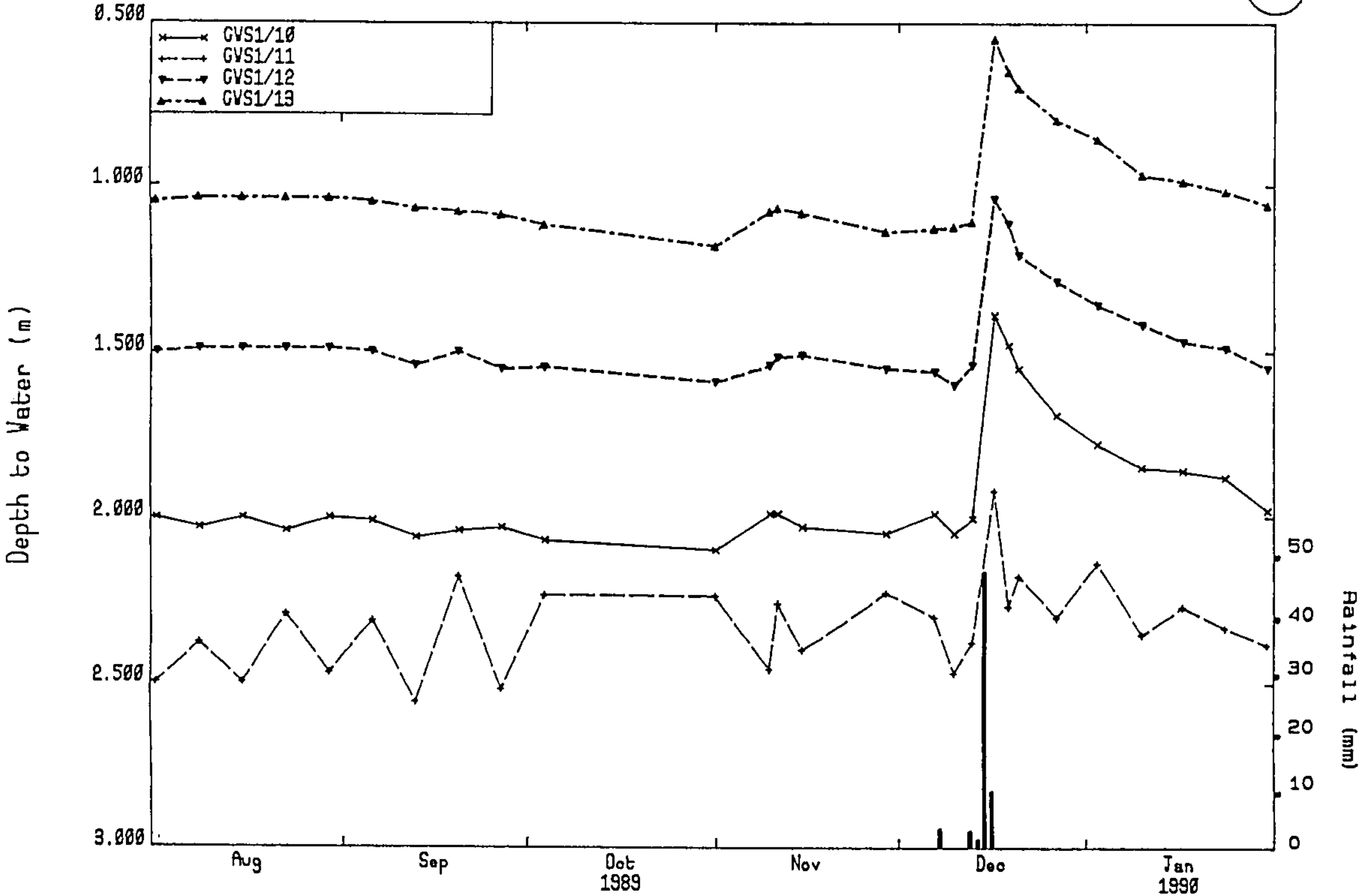


Figure 4.5

Storativity by tidal influence

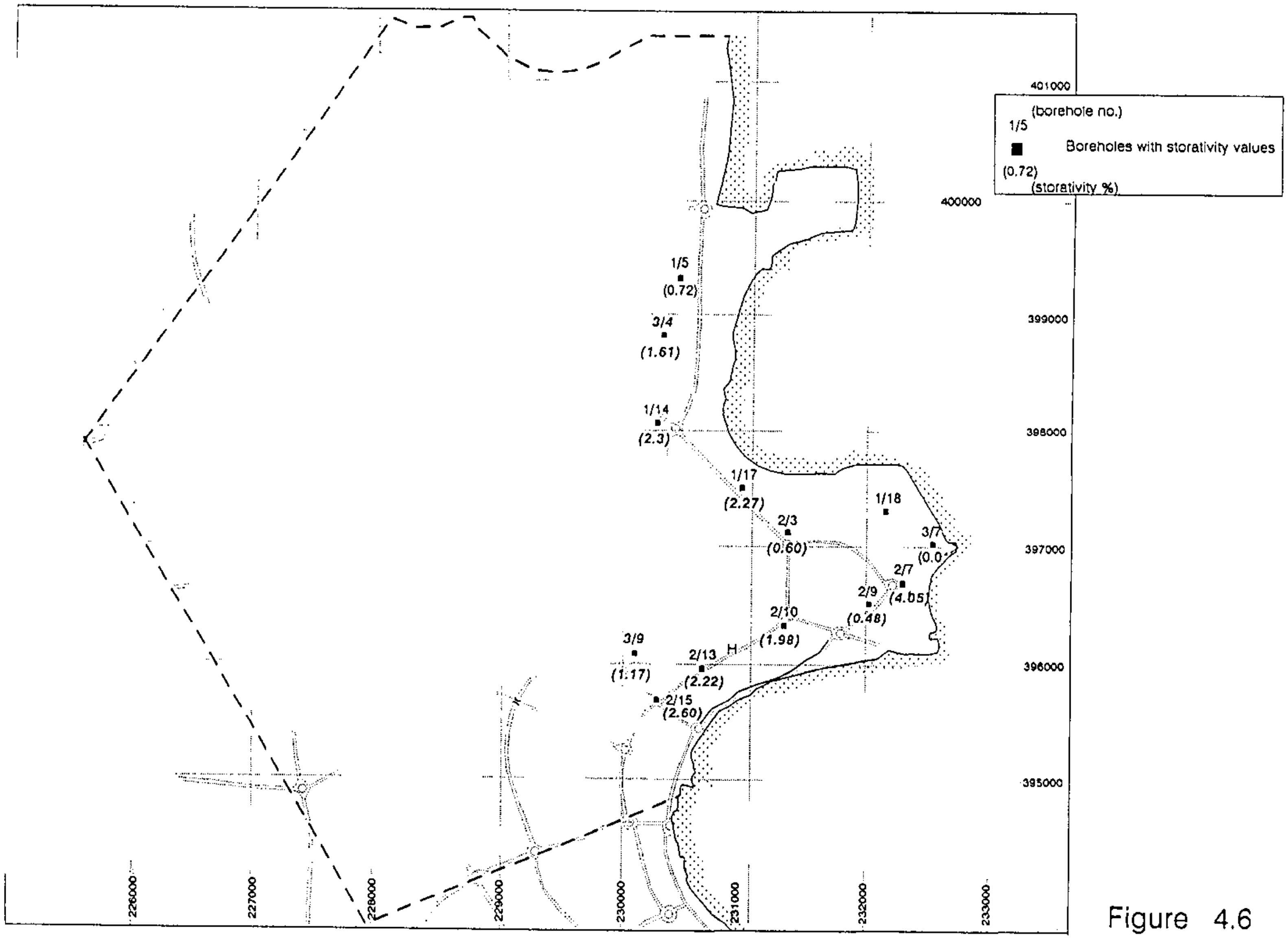
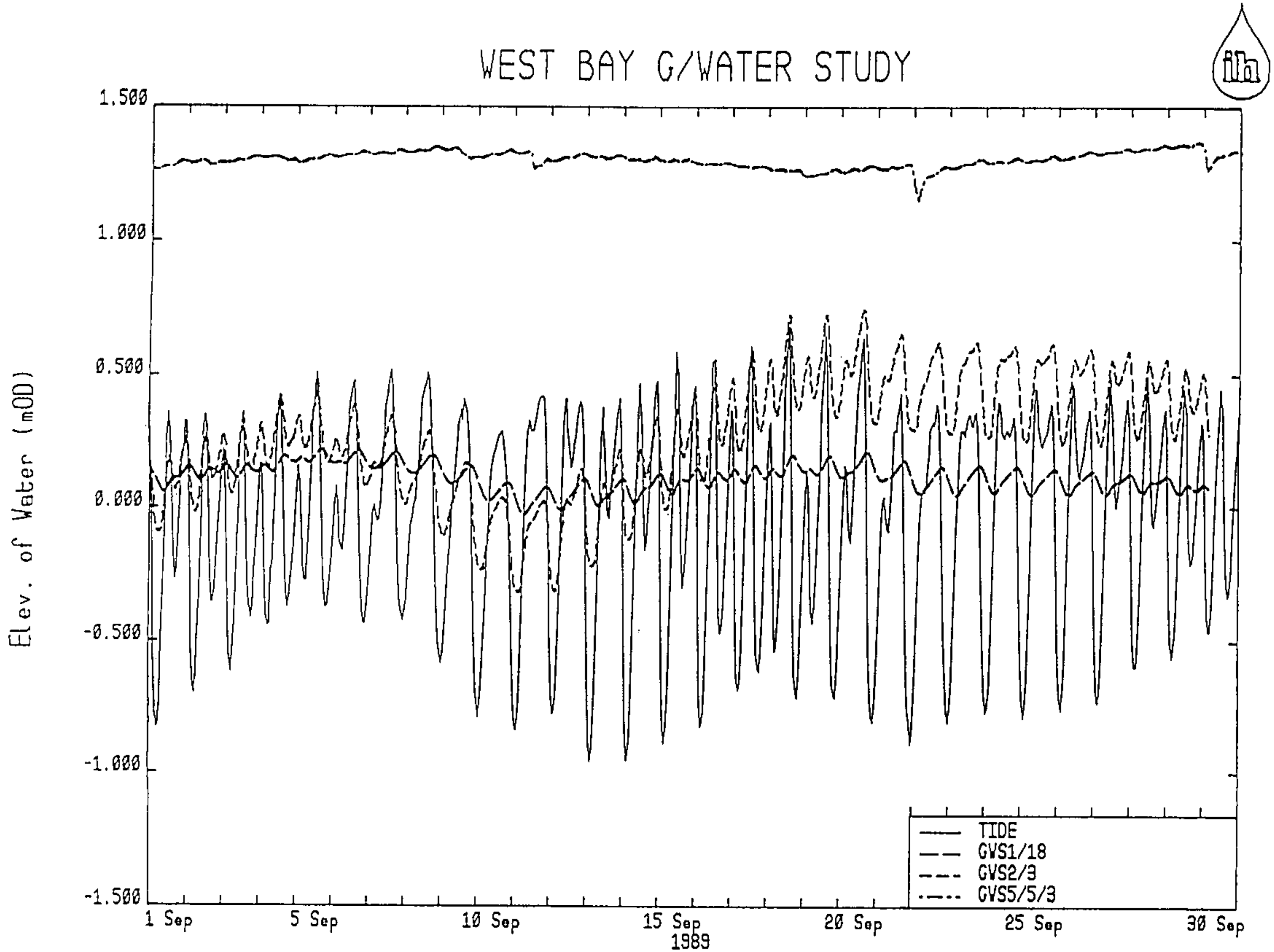


Figure 4.6



Tidal Responses in Boreholes

Figure 4.7

Plot of Amplitude ratio v. Distance from coast

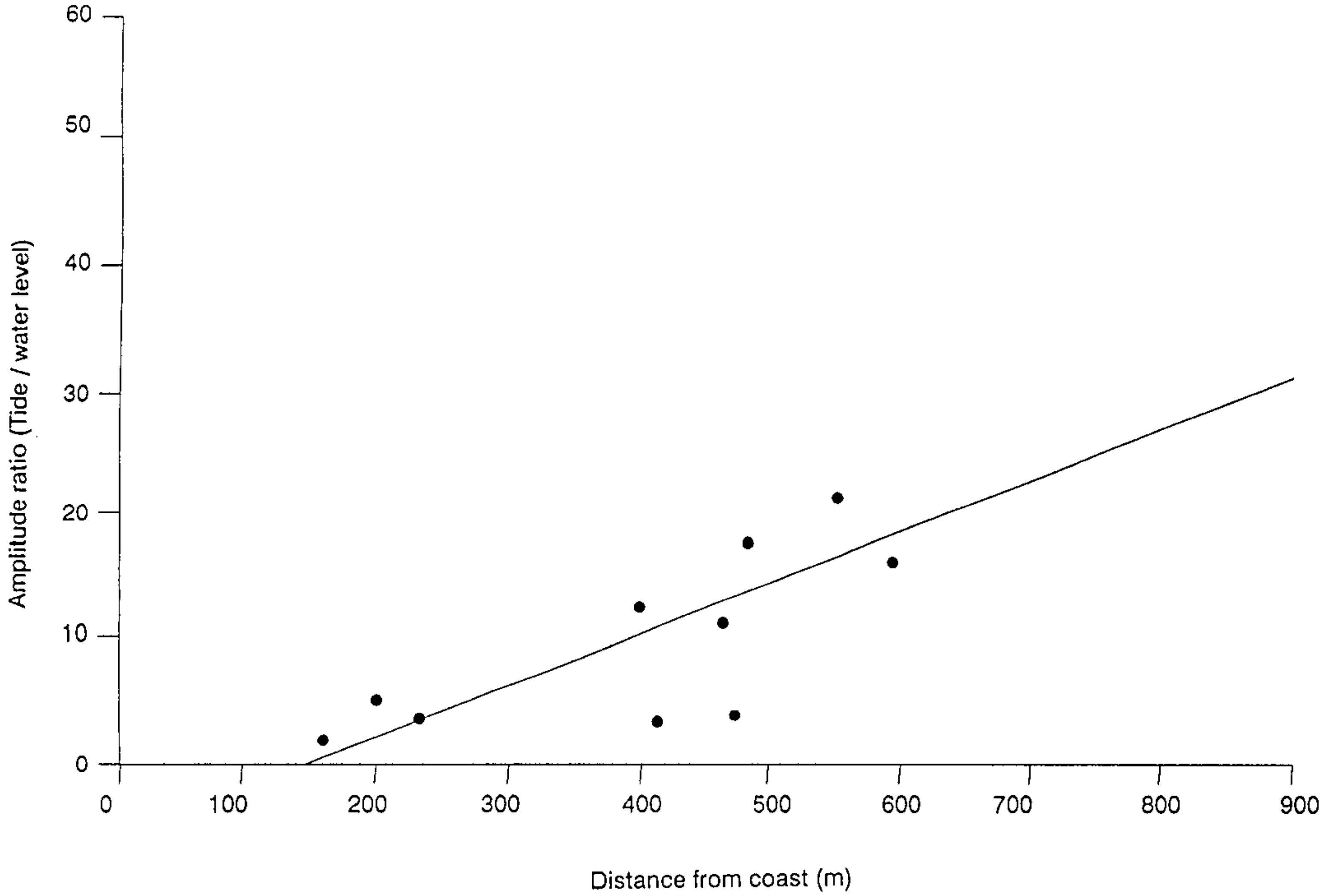


Figure 4.8

DOHA AIRPORT

Annual Rainfall

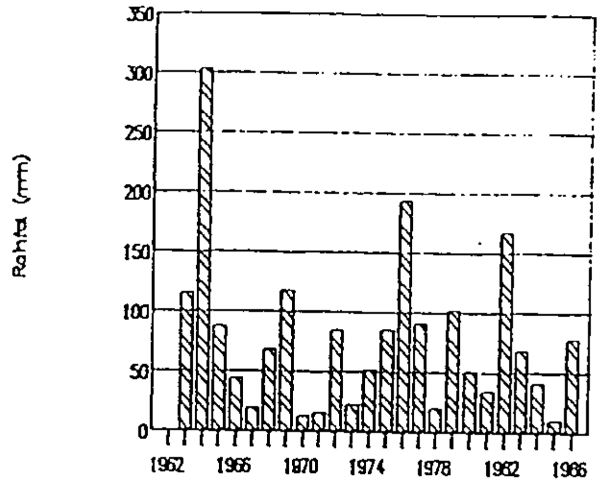


Figure 5.1

Mean Monthly Rainfall (1962 - 1988)

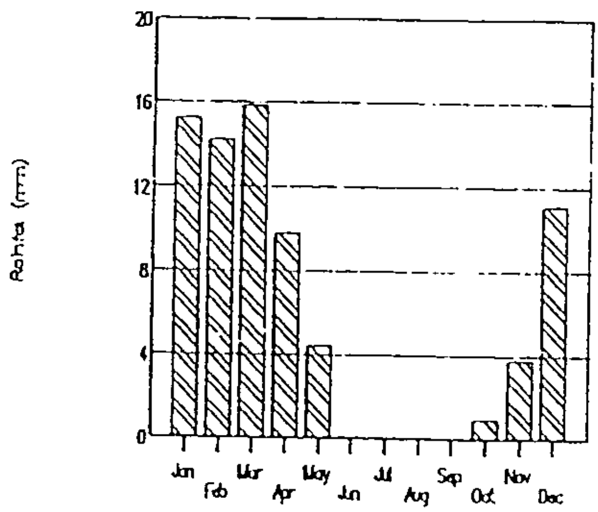


Figure 5.2

Permeability Frequency Diagram

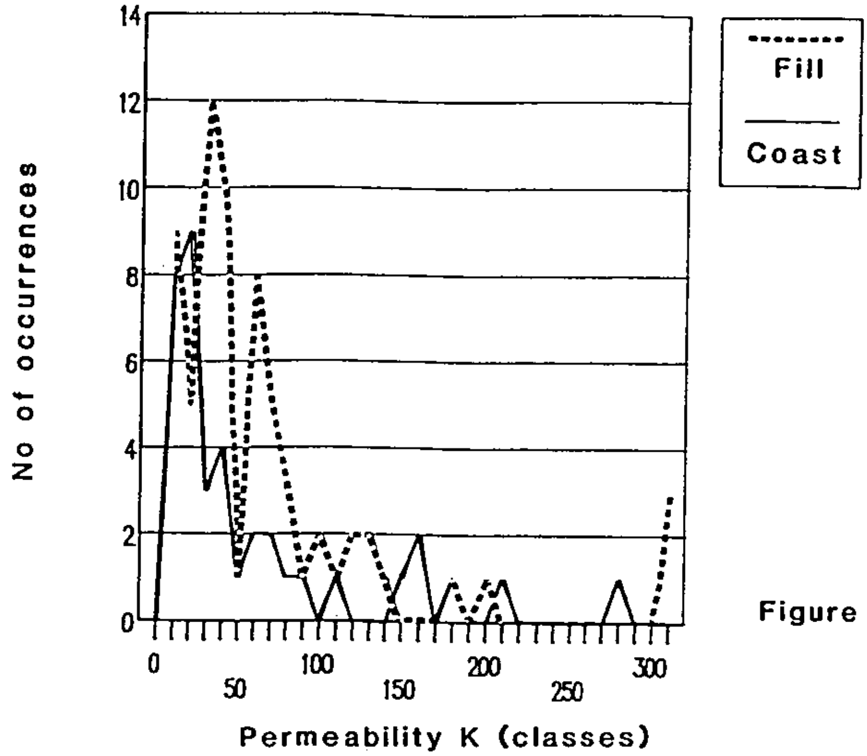


Figure 6.1

Log Premeability Frequency Diagram

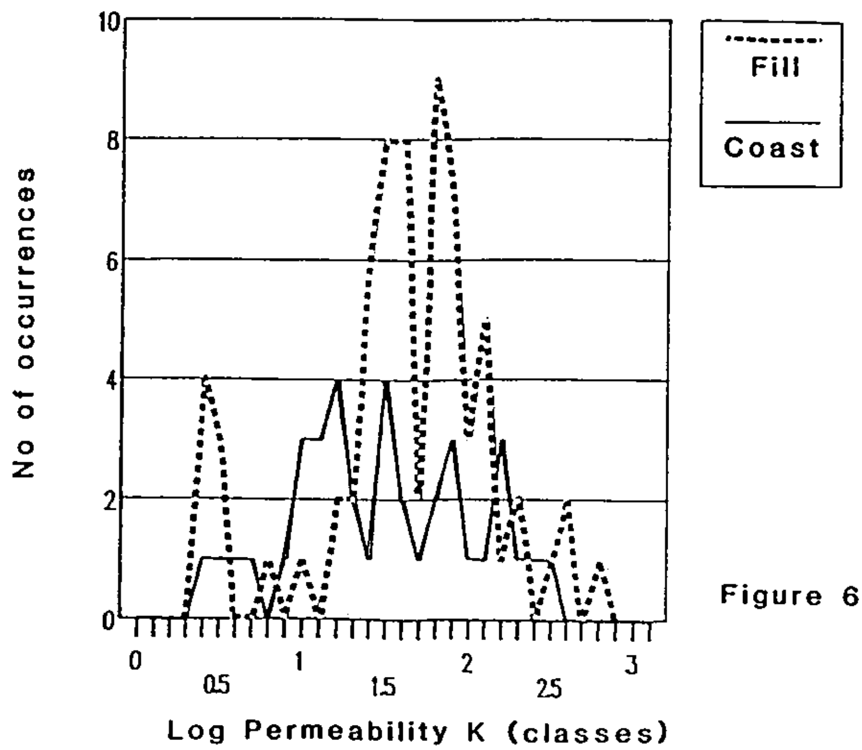


Figure 6.2

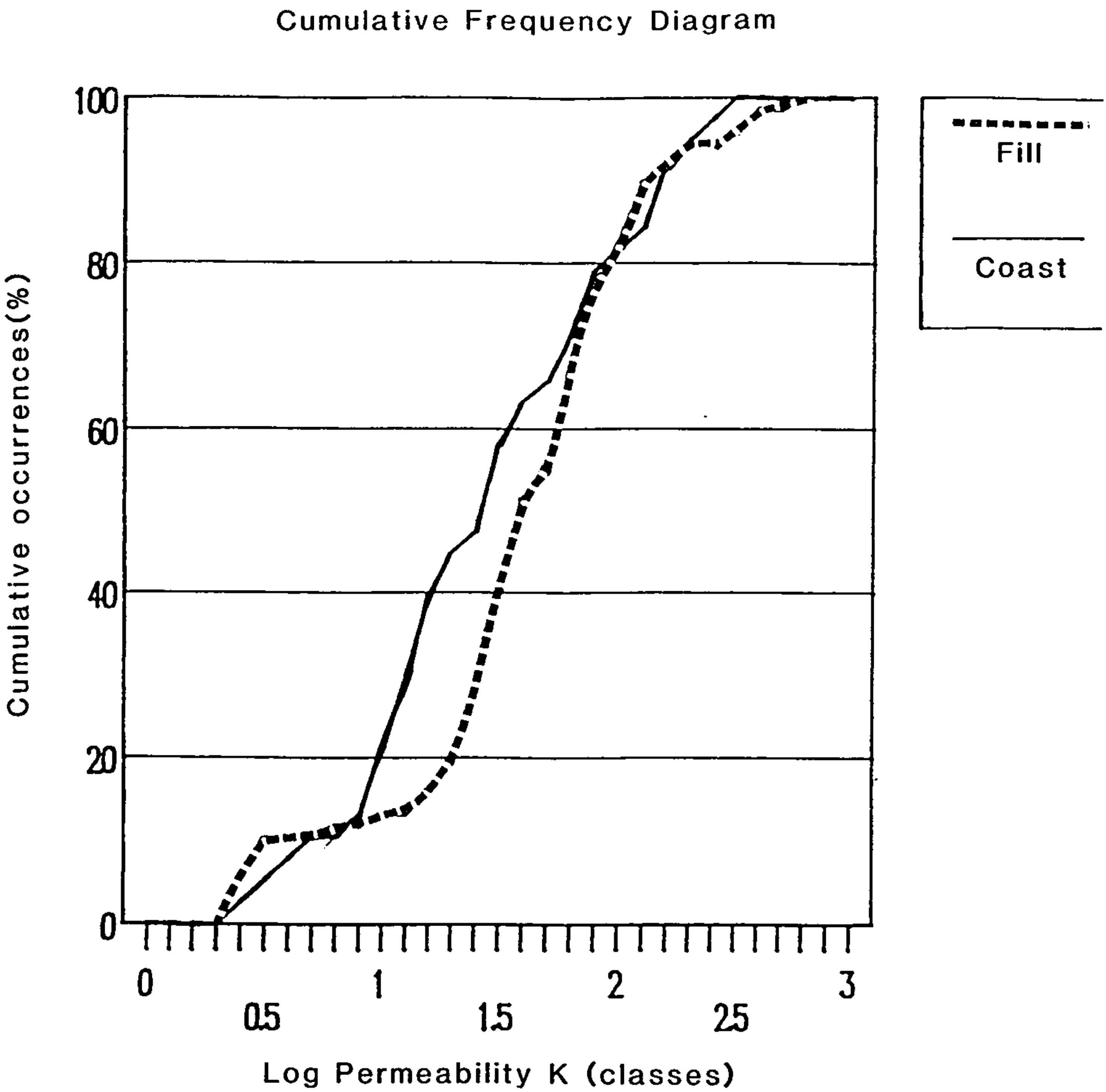
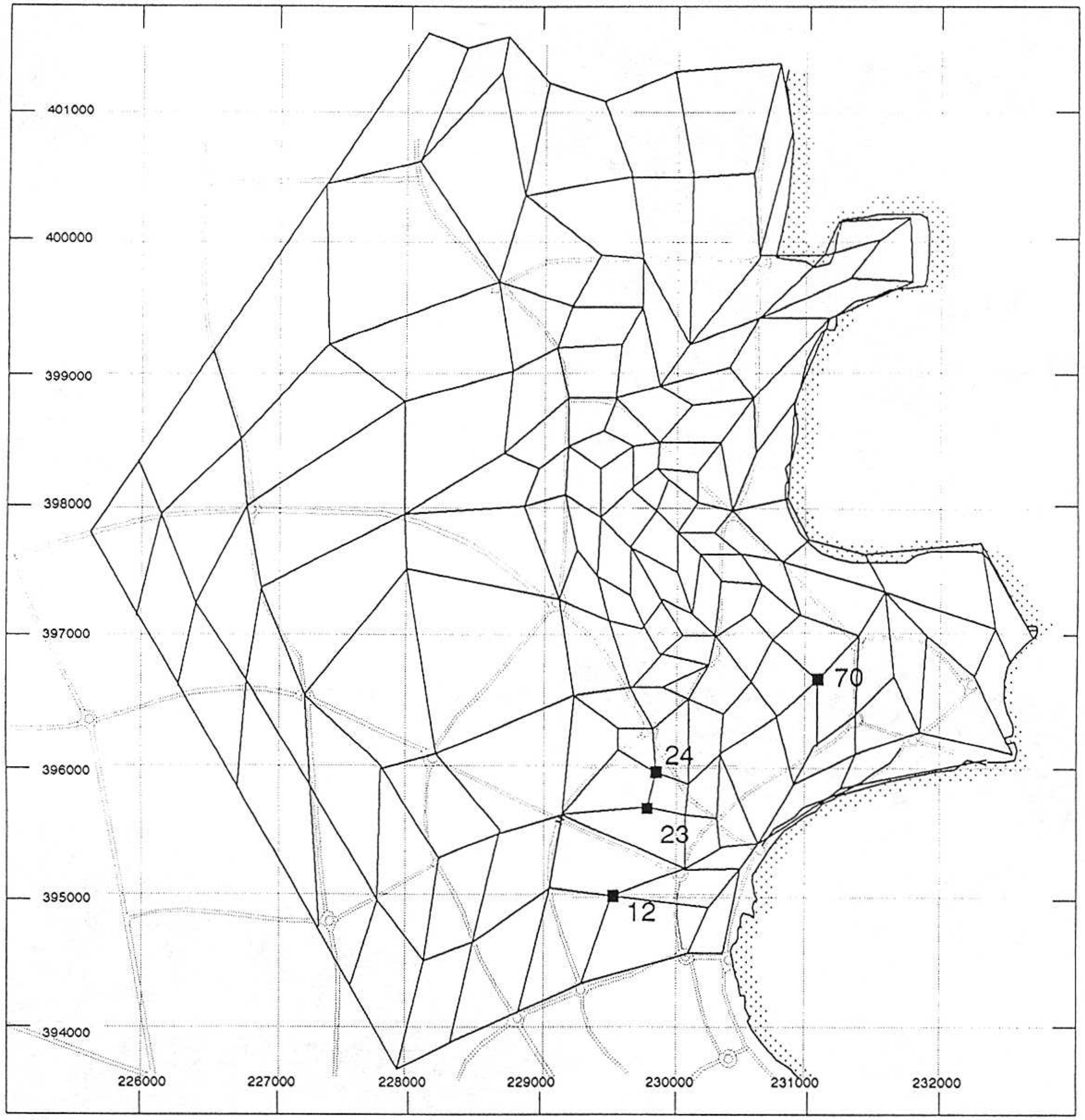

Cumulative Frequency Diagram
Cumulative occurrences(%)
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Log Permeability K (classes)
Fill
Coast

Figure 6.3

Nodal network for West Bay area



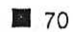

Node numbers referred to in Figures 7.4 and 7.9

Figure 7.1

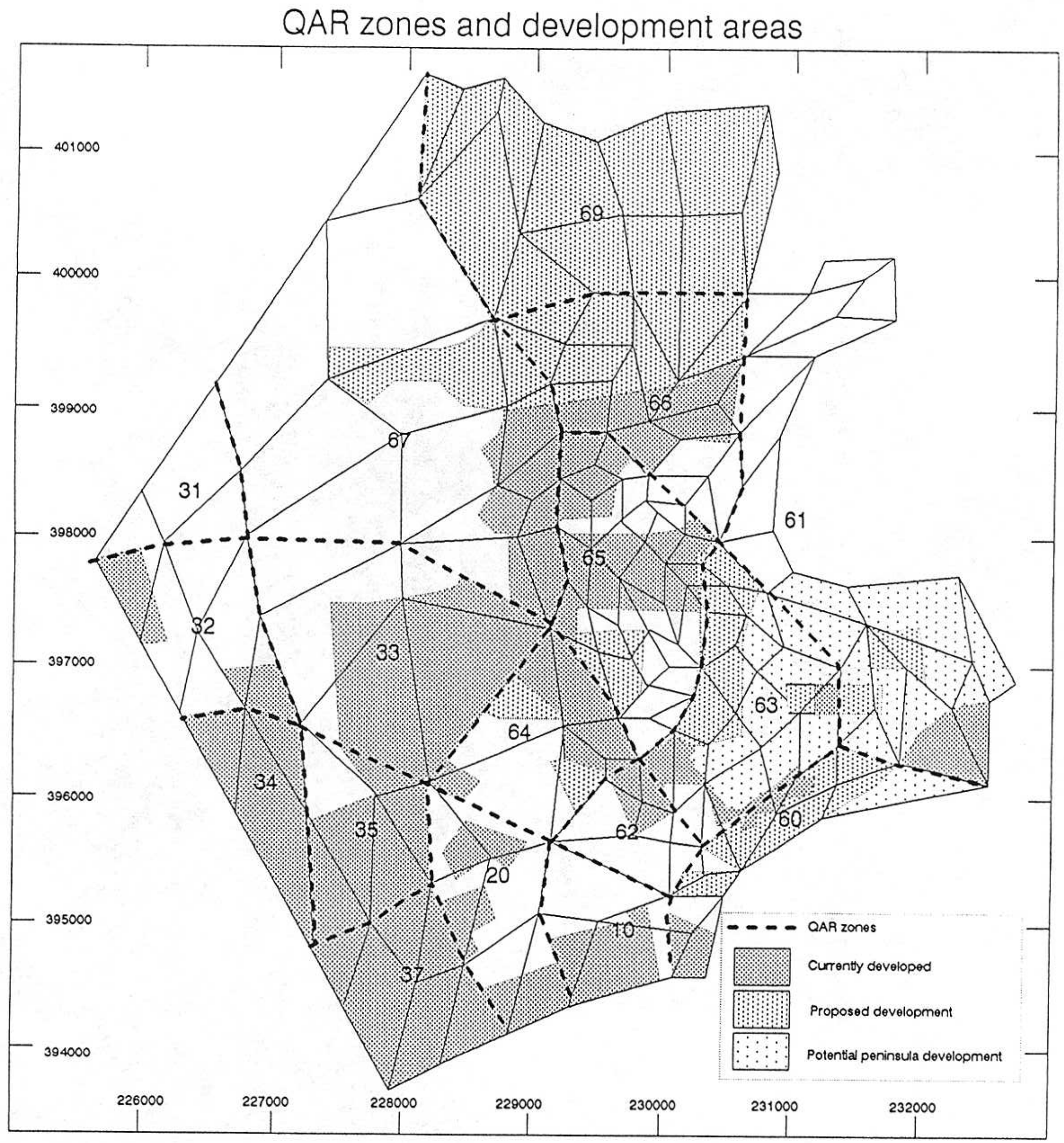

QAR zones and development areas
401000
400000
399000
398000
397000
396000
395000
394000
226000
227000
228000
229000
230000
231000
232000
31
32
33
34
35
37
20
10
62
64
65
66
67
69
61
63
60
QAR zones
Currently developed
Proposed development
Potential peninsula development

Figure 7.2

Differences between observed and steady-state water levels (m)

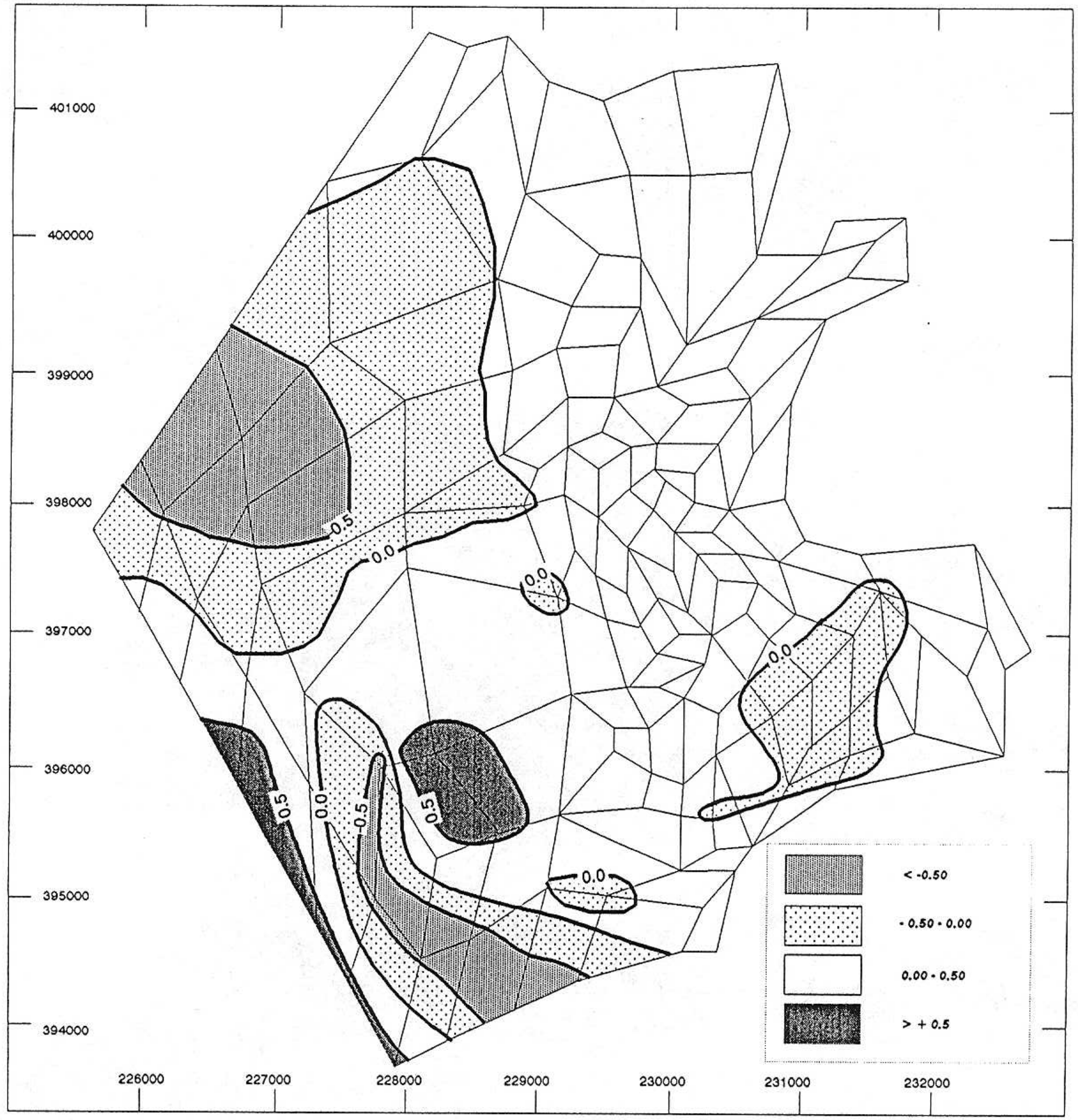


Figure 7.3

Response of boreholes in Hydraulic Fill to the December 1989 rainfall event

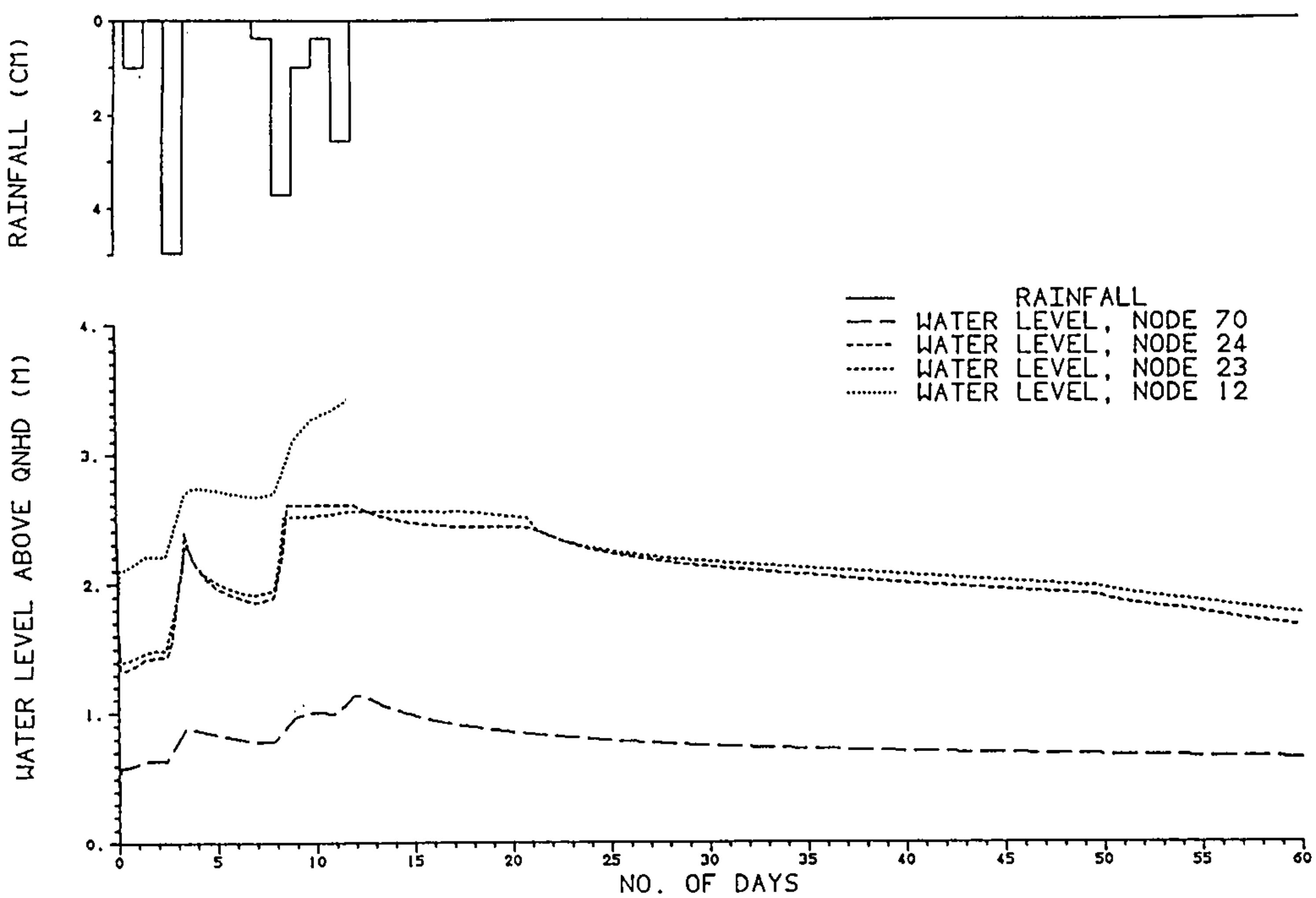


Figure 7.4
(see also 7.9)

Depth to water for February 1988 storm for present development (m)
17 February 1988

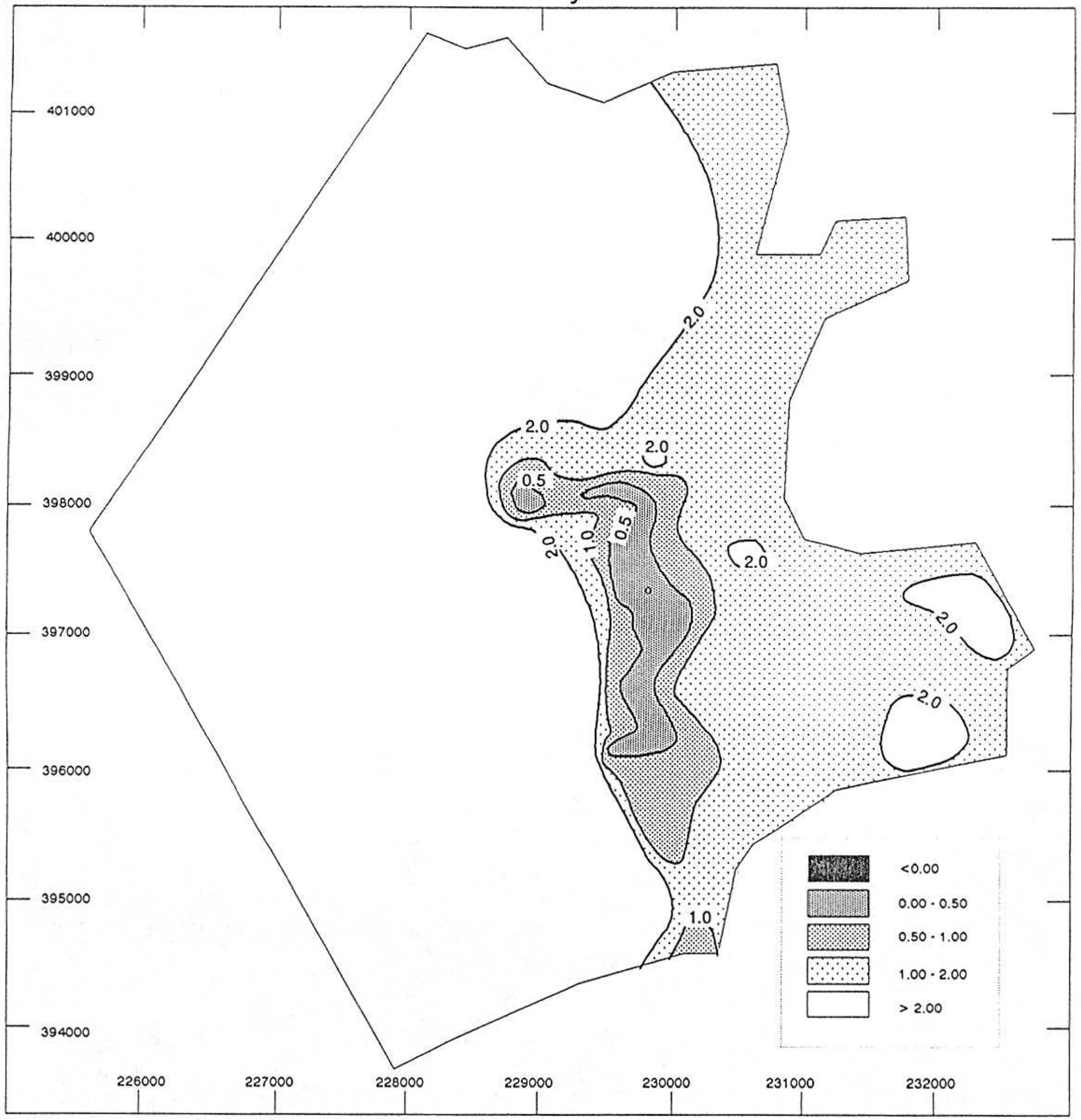


Figure 7.5

Depth to water for February 1988 storm for present development(m)
24 February 1988

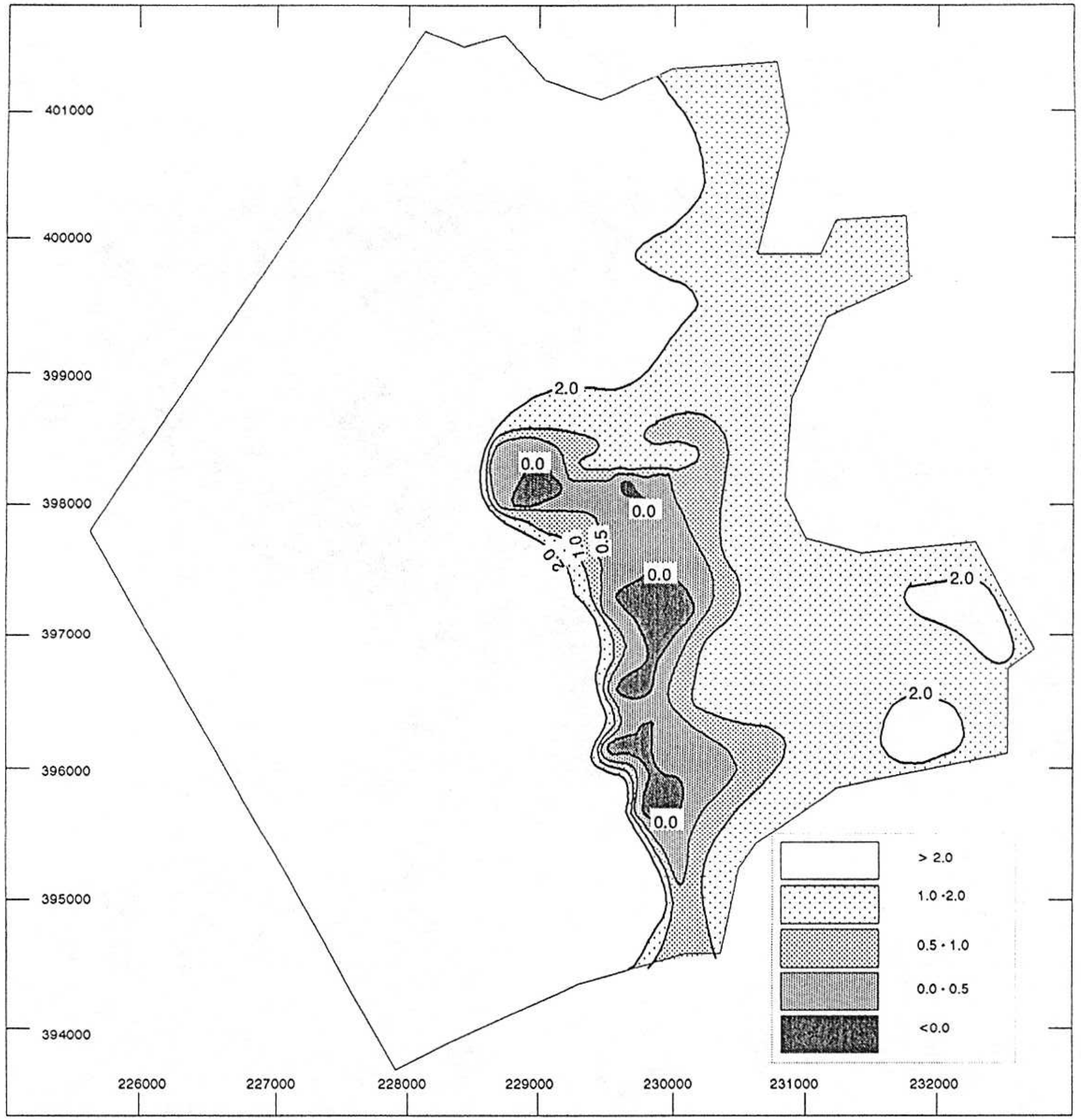


Figure 7.6

Depth to water for February 1988 storm for present development(m)
24 March 1988

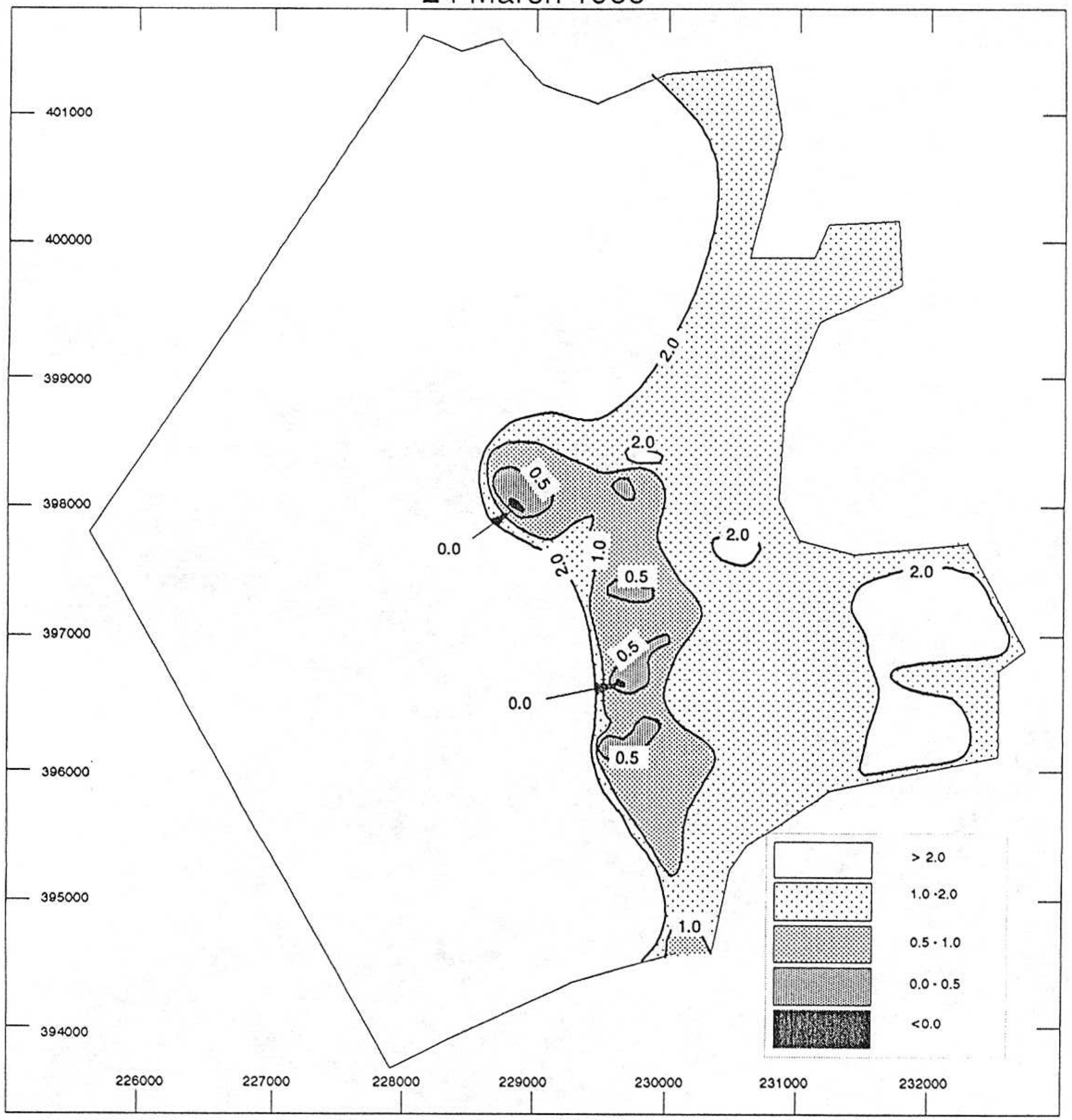


Figure 7.7

Rise in groundwater at steady state with maximum development (cm)

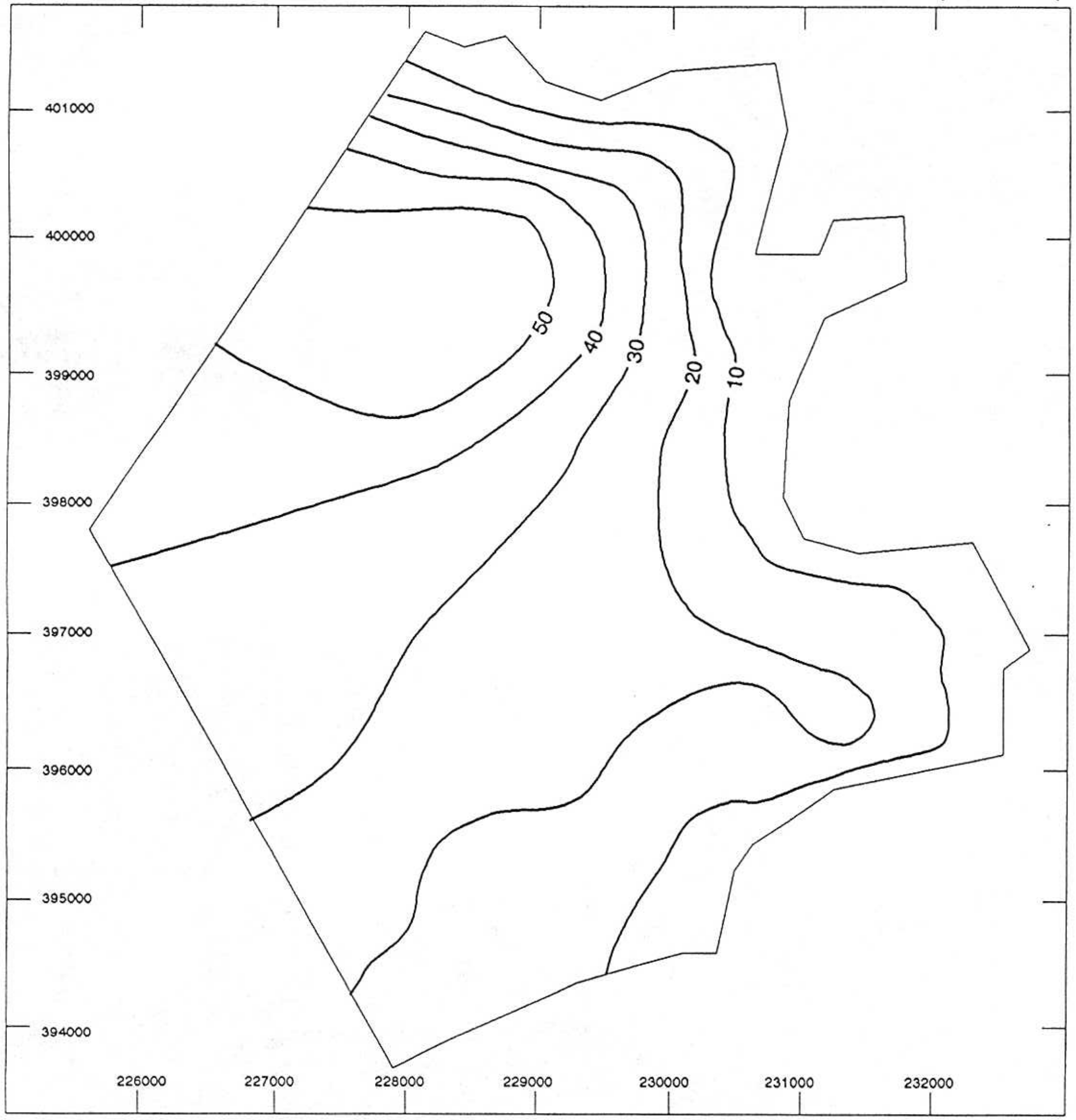


Figure 7.8

Hydrograph and hyetograph of February 1988 storm for specific nodes, for maximum development

13 Feb - 12 Apr 1988

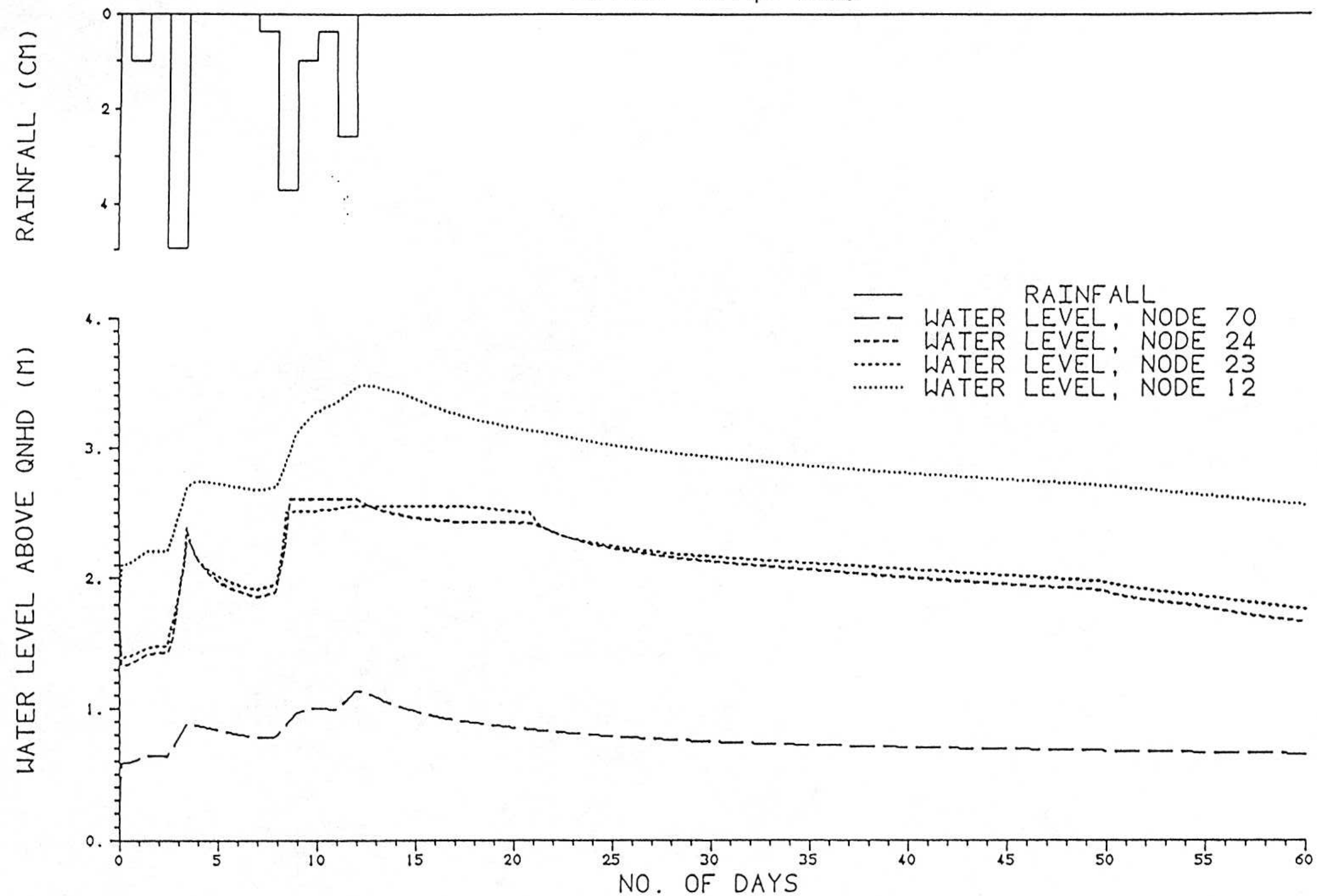


Figure 7.9

Depth to water for February 1988 storm for maximum development (m)
17 February 1988

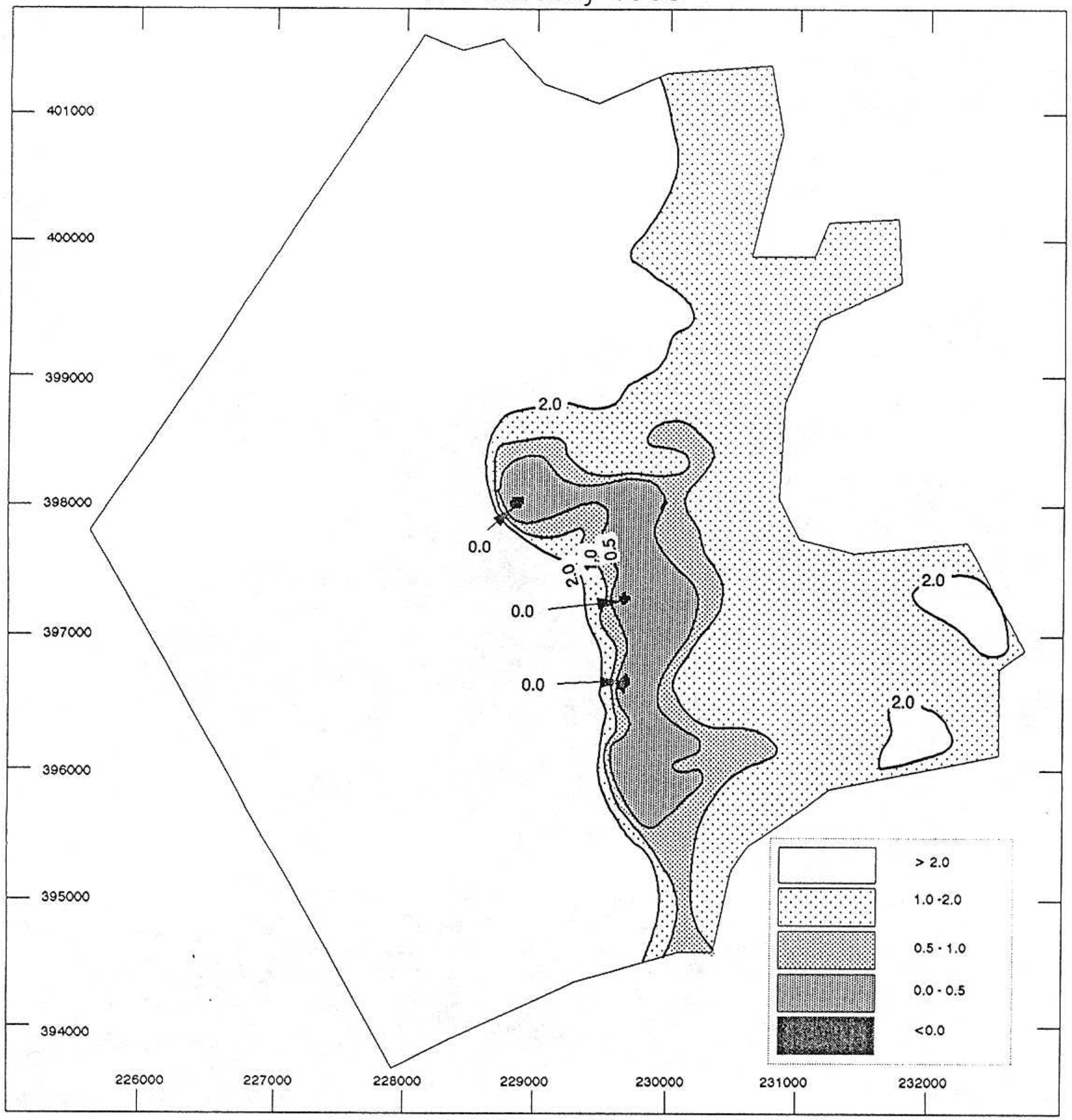


Figure 7.10

Depth to water for February 1988 storm for maximum development (m)
24 February 1988

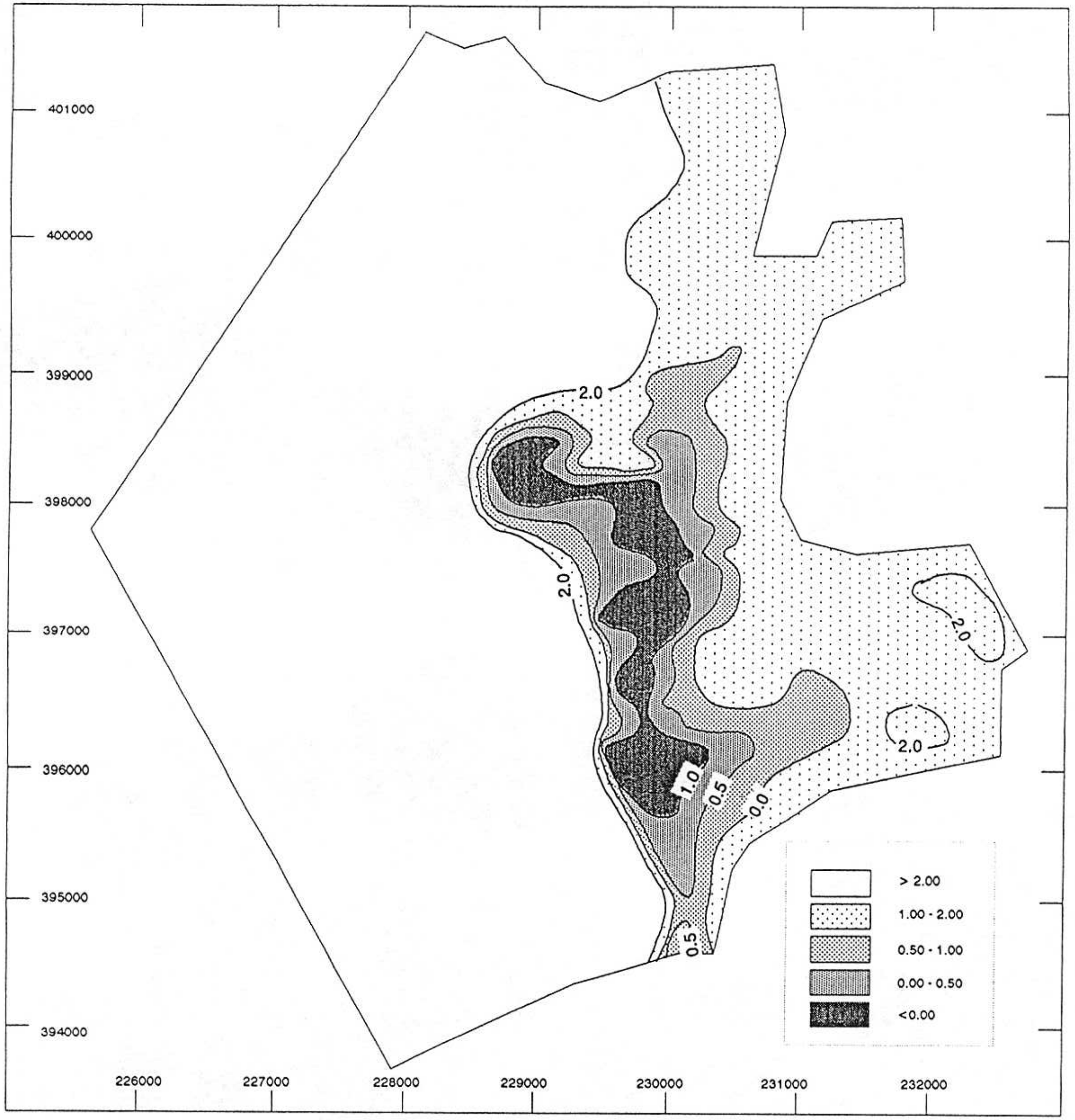


Figure 7.11

Depth to water for February 1988 storm for maximum development (m)
24 March 1988

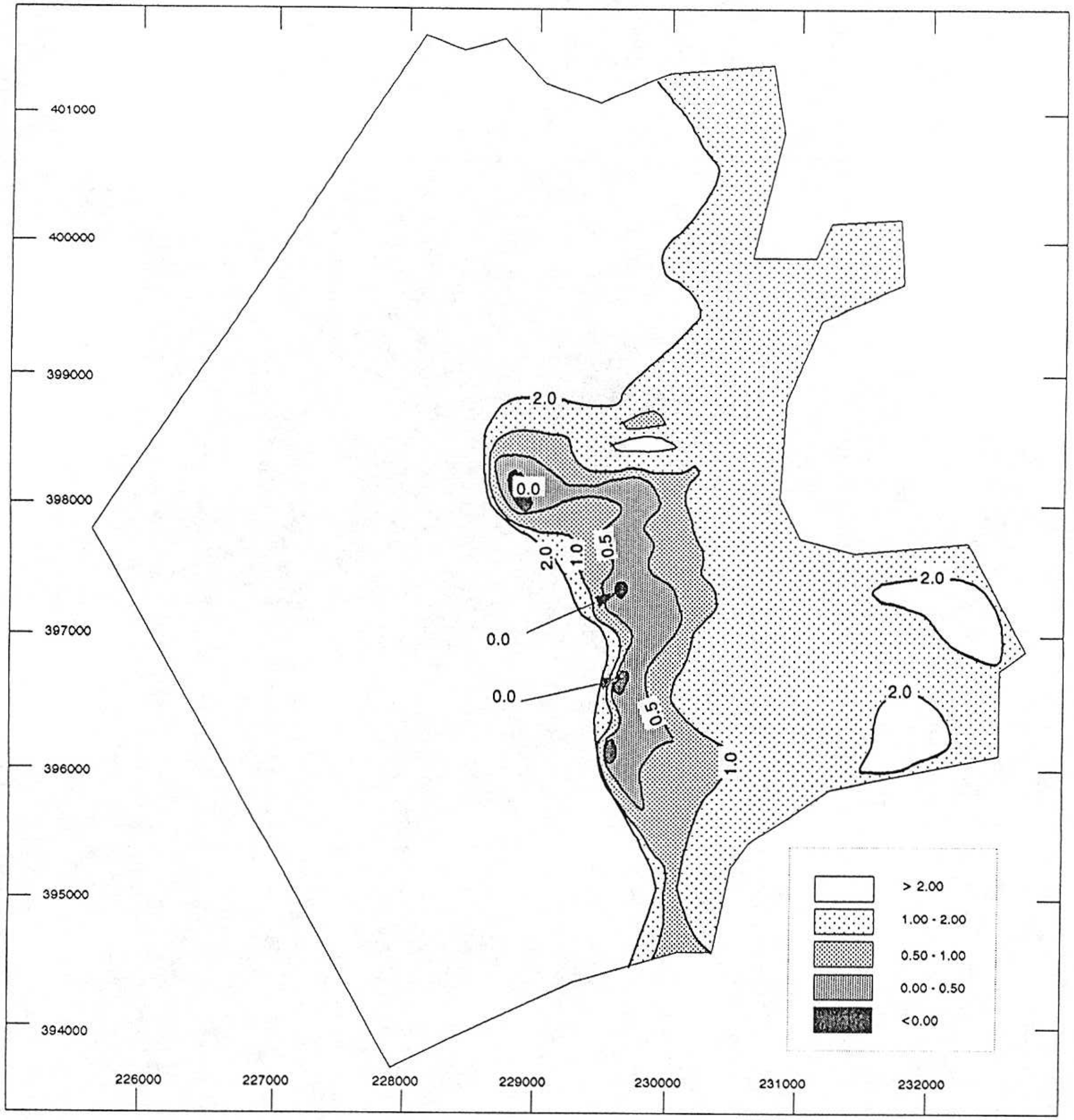


Figure 7.12

Depth to water for February 1988 storm for present development and pumping (m)
17 March 1988

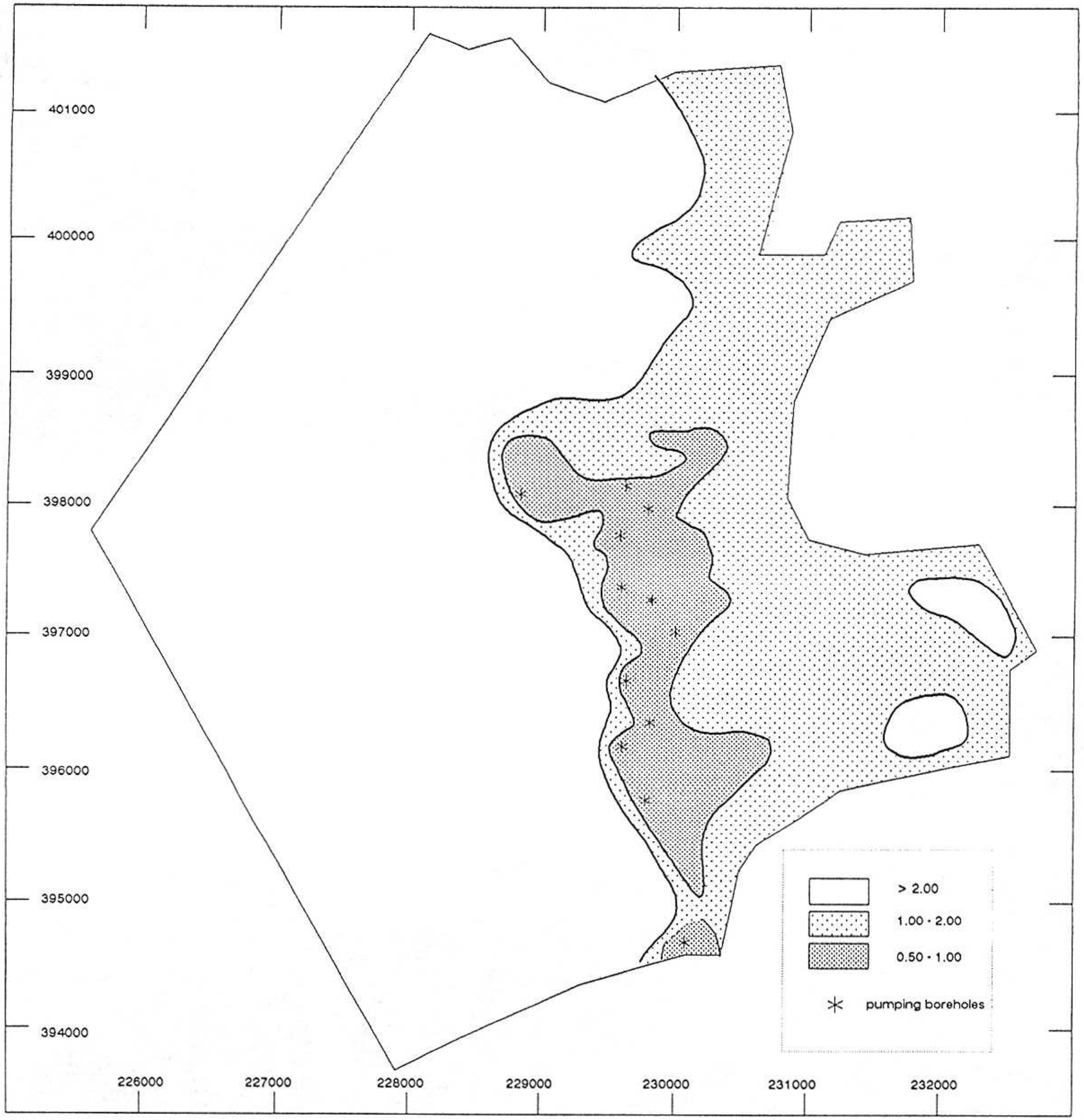


Figure 7.13

Depth to water for February storm for maximum development and pumping(m)
24 March 1988

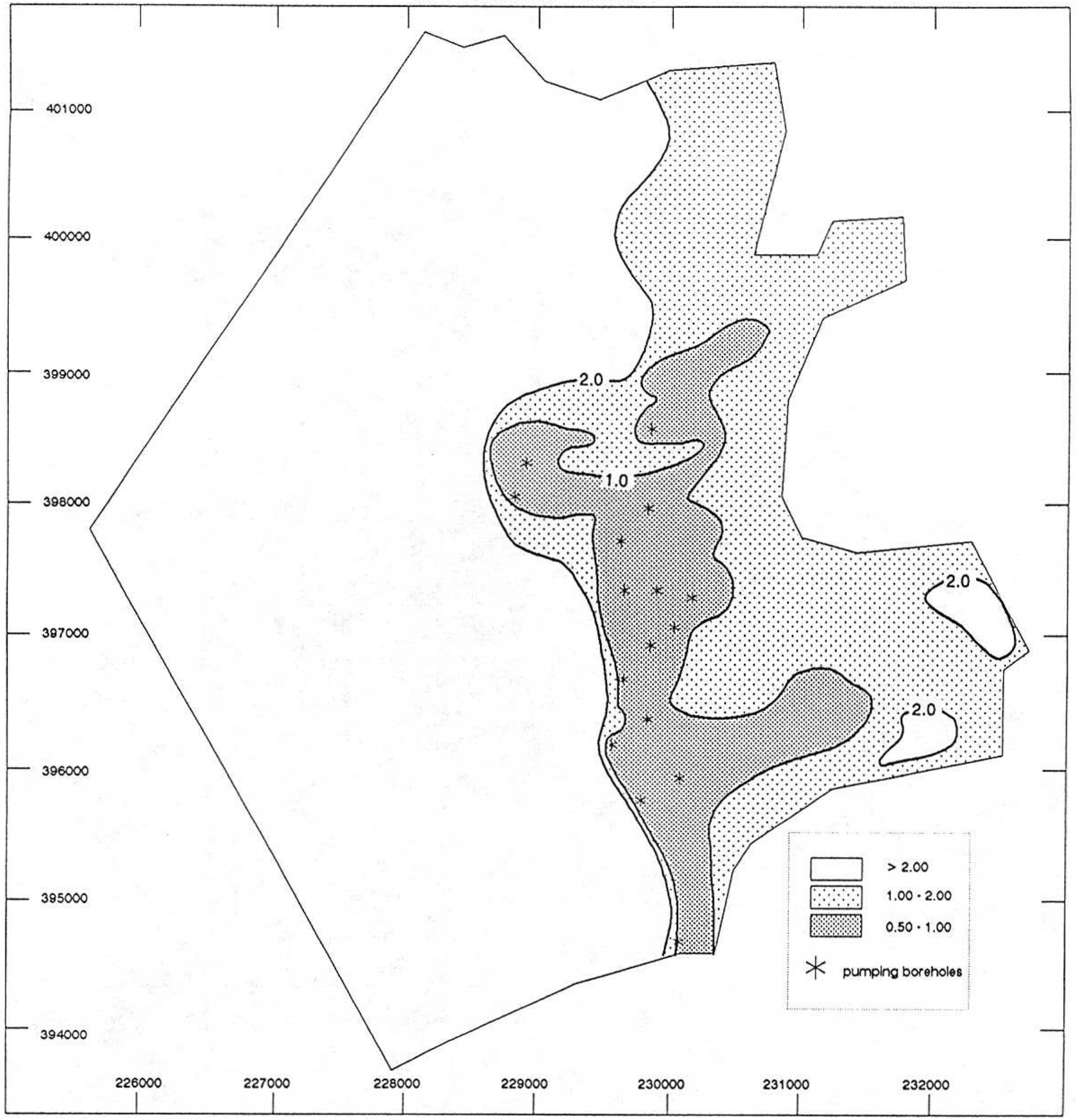


Figure 7.14

APPENDIX 1

List of Engineering Reports for West Bay

REPORT A: July 1989, Gulf Laboratories. Senior staff housing project, sub-surface site investigation. No. GD/199/I.

REPORT B: January 1983, Wimpey Laboratories. Govt. of Iraq. Proposed new embassy in the new district of Doha. No. S/19872.

REPORT C: January 1982, Wimpey Laboratories. Gulf Organization Consulting Doha, Report on site investigation. No. S/18659.

REPORT D: May 1981, Wimpey Laboratories. Qatar General Petroleum Corporation. Proposed extension to headquarters building at new Doha. Report on site investigations. No.S/18003.

REPORT E: March 1983, Wimpey Laboratories. Proposed villa for H.E. Issa Al Kawari, New District of Doha. Report on site investigations. S/19931.

REPORT F: January 1983,Wimpey Laboratories. Government of Pakistan. Proposed new embassy of Pakistan in the New District of Doha. Report on site investigation. No. S/19673.

REPORT G: June 1984, Wimpey Laboratories. Islamic Republic of Iran. Proposed new embassy in the New District of Doha. Report on site investigation. No. S/21210.

REPORT H: February 1983, Wimpey Laboratories. Qatar General Insurance and Reinsurance Company. Proposed multi- storey office building in the New District of Doha. Report on site investigations. o. S/19923.

REPORT J: October 1982, Wimpey Laboratories. Qatar National Cement Company. Proposed headquarters building in the New District of Doha. Report on site investigation. No.S/19287.

REPORT K: September 1981, Wimpey Laboratories. Ministry of Works (ESD). Proposed offices for Ministry of Education, New District of Doha. Report on site investigation. No. S/18204.

REPORT L: April 1985, Wimpey Laboratories. Ministry of Public works. Qatar Sports Club. Site investigation report. No. S/16987/2.

REPORT M: October 1982, Wimpey Laboratories. Mannai Trading. Proposed Office and commercial Centre in the New district of Doha.Report on site investigation. No. S/19496.

REPORT N: March 1989, Gulf Laboratories. Qatar National Navigation and Transport Company. Proposed NNTC HQ - West Bay. Report on site investigation. No. GD/188/SI.

APPENDIX 2

Summary of Borehole Data

BOREHOLE NO.	G.ELEV. (m)	DATUM ELEV. (m)	CO-ORDINATES	TEST DEPTH (m)	DEPTH HYDRAULIC FILL (m)	DEPTH NATURAL MATERIAL (m)	ELEV TOP NATURAL MATERIAL (m)	ELEV TOP DAMMAN (m)
GWS 1/1	3.37	3.71	22985 40071			0.0 - 0.25	G.SURFACE	3.12
GWS 1/2	3.9	4.38	22947 40048			0.0 - 0.5	G.SURFACE	3.4
GWS 1/3	2.15	2.52	23061 40044	6	0 - 0.5	0.5 - EOH	1.65	
GWS 1/4	3.33	3.54	22989 39963			0.0 - 1.0	G.SURFACE	2.3
GWS 1/5	1.78	1.99	23009 39917	6	0 - 1.0	1.0 - EOH	0.78	
GWS 1/6	2.68	2.9	23009 39917			0.0 - EOH	G.SURFACE	
GWS 1/7	6.82	7.05	22848 39913			0.0 - 0.5	G.SURFACE	6.32
GWS 1/8	3.54	3.62	22959 39882	6	0 - 1.0	1.0 - 5.0	2.54	1.4
GWS 1/9	2.42	2.58	23003 39866	6	0 - 0.5	0.5 - EOH	1.92	
GWS 1/10*			22886 39863			0.0 - 2.0	G.SURFACE	
GWS 1/11	2.61	2.79	23062 39880	6	0 - 3.75	3.75 - EOH	1.15	
GWS 1/12	2.13	2.38	23017 39825	6	0 - 1.5	1.5 - EOH	0.7	
GWS 1/13	1.93	2.19	22970 39802			0.0 - 1.0	G.SURFACE	0.9
GWS 1/14	2.52	2.86	23030 39806	6	0 - 2.52	2.52 - EOH	0	
GWS 1/15	3.13	3.4	22950 39772		0.5	0.5 - 4.5	2.63	1.37
GWS 1/16*	6.31	6.5	22882 39750		0	0.0 - EOH	G SURFACE	
GWS 1/17	3.13	3.44	23099 39752	6	0 - 4.0	4.0 - 6.0	-0.87	
GWS 1/18	5.36	5.53	23228 39753	6	0 - EOH		-0.6	
GWS 1/19	2.1	2.36	22970 39742			0.0 - EOH	G.SURFACE	
GWS 1/20*	3.24	3.56	23211 39748					
GWS 2/1	4.06	4.25	23179 39750	6	0 - EOH		1.9	
GWS 2/2	2.13	2.45	23025 39733	6	0 - 2.13	2.13 - EOH	0	
GWS 2/3	2.11	2.25	23139 39712	6	0 - 4.5?	4.5 - EOH	-2.4	
GWS 2/4	4.06	4.37	22948 39702	6	0 - 1.2?	1.2 - EOH	2.86	
GWS 2/5	7.36	7.57	22912 39685			0.0 0.5	G.SURFACE	6.86

BOREHOLE NO.	G.ELEV. (m)	DATUM ELEV. (m)	CO-ORDINATES	TEST DEPTH (m)	DEPTH HYDRAULIC FILL (m)	DEPTH NATURAL MATERIAL (m)	ELEV TOP NATURAL MATERIAL (m)	ELEV TOP DAMMAN (m)
GWS 2/6	2.97	3.13	23027 39676	6		0.0 - 0.5	G.SURFACE	2.47
GWS 2/7	3.28	3.47	23231	6	0 - EOH		- 2.7	
GWS 2/8	2.02	2.34	23101 39654	6	0 - 2.0	2.0 - EOH	0	
GWS 2/9*	3.84	4.02	23206 39651	5	0 - EOH		- 1.2	
GWS 2/10	2.38	2.56	23128 39631	6	0 - 4.0?	4.0 - EOH	1.6(?)	
GWS 2/11	2.55	2.89	23062 39635	6	0 - 3.5	3.5 - EOH	- 0.95	
GWS 2/12*	9.58	9.88	22928 39622			0.5	G.SURFACE	
GWS 2/13	2.32	2.63	23068 39595	6	0 - 3.0	3.0 - EOH	- 0.7	
GWS 2/14	2.46	2.76	22981 39572	6	0 - 2.46	2.46 - 4.0		1.54
GWS 2/15	2.31	2.53	23032 39566	6	0 - 2.5	2.5 - EOH	- 0.19	
GWS 2/16	2.2	2.65	23062 39545	6	0 - 4.0?	4.0 - EOH	1.8?	
GWS 2/17	3.23	3.43	22995 39529	6	0 - 1.5?	1.5 - 3.25	- 1.73	- 0.02
GWS 2/18	2.39	2.5	23017 39503	6	0 - 4.5	4.5 - EOH	2.1	
GWS 2/19								
GWS 3/1	5.8	6.29	22895 40032					5.8
GWS 3/2	6.43	6.88	22858 39974			0.0 - 1.7	G.SURFACE	4.73
GWS 3/3	5.3	5.57	22956 39937			0.0 - 1.4	G.SURFACE	3.9
GWS 3/4	2.05	2.2	23032 39882	5	0 - 1.3	1.3 - 3.4	0.75	1.3
GWS 3/5	1.95	2.12	23071 39772	6.3	0 - 4.0?	4.0 - 4.8	- 2	2.85
GWS 3/6	2.57	2.75	22997 39755	3.4	1 - 1.0	1.0 3.25	1.57	- 0.68
GWS 3/7	4.57	4.71	23255 39701	10	0 - 8.0	8.0 9.5	3.4	- 4.9
GWS 3/8	2.23	2.53	23152 39678	7	0 - 3.45	3.45 - 5.5	1.2	- 3.27
GWS 3/9	2.27	2.41	23011 39608	5.4	0 - 2.0	2.0 - 4.9	0.27	- 2.63
GWS 3/10*	2.33	2.51	23039 39531	6.6	0 - 4.0?	4.0 - 5.0	1.7	- 2.67

BOREHOLE NO.	G.ELEV. (m)	DATUM ELEV. (m)	CO-ORDINATES	TEST DEPTH (m)	DEPTH HYDRAULIC FILL (m)	DEPTH NATURAL MATERIAL (m)	ELEV TOP NATURAL MATERIAL (m)	ELEV TOP DAMMAN (m)
GWS 4/1	9.87	10.16	22788 39982	18				9.87
GWS 4/2	8.05	8.18	22588 39884	35				8.05
GWS 4/3	18.93	19.17	22803 39844	18.8				18.93
GWS 4/4	18.46	18.55	22686 39804	25				18.46
GWS 4/5	20.82	20.98	22732 39580	16.5				20.82
GWS 4/6	16.5	16.67	22875	18				16.5

* Some Information not available

APPENDIX 3

Water Level Data for Project Boreholes

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/1	5 Jul 89	822	3.035	0.675
	12 Jul 89	754	3.065	0.645
	19 Jul 89	832	3.045	0.665
	26 Jul 89	740	3.045	0.665
	2 Aug 89	739	3.025	0.685
	9 Aug 89	732	3.025	0.685
	16 Aug 89	728	3.000	0.710
	23 Aug 89	738	2.990	0.720
	30 Aug 89	721	2.975	0.735
	6 Sep 89	742	2.990	0.720
	13 Sep 89	806	3.000	0.710
	20 Sep 89	759	3.000	0.710
	27 Sep 89	751	3.000	0.710
	4 Oct 89	811	3.050	0.660
	1 Nov 89	837	3.080	0.630
	10 Nov 89	733	3.060	0.650
	11 Nov 89	1524	3.010	0.700
	15 Nov 89	1524	2.990	0.720
	29 Nov 89	840	3.100	0.610
	7 Dec 89	838	3.080	0.630
	10 Dec 89	1516	3.100	0.610
	13 Dec 89	1523	3.055	0.655
	17 Dec 89	750	2.560	1.150
	19 Dec 89	1513	2.620	1.090
	21 Dec 89	808	2.680	1.030
	27 Dec 89	1527	2.780	0.930
	3 Jan 90	828	2.880	0.830
	10 Jan 90	1520	3.010	0.700
	17 Jan 90	825	3.000	0.710
	24 Jan 90	855	3.030	0.680
	31 Jan 90	826	3.040	0.670

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/10	2 Aug 89	903	2.000	*
	9 Aug 89	837	2.030	*
	16 Aug 89	831	2.000	*
	23 Aug 89	845	2.040	*
	30 Aug 89	824	2.000	*
	6 Sep 89	851	2.010	*
	13 Sep 89	915	2.060	*
	20 Sep 89	913	2.040	*
	27 Sep 89	855	2.030	*
	4 Oct 89	919	2.070	*
	1 Nov 89	1003	2.100	*
	10 Nov 89	835	1.990	*
	11 Nov 89	1617	1.990	*
	15 Nov 89	1619	2.030	*
	29 Nov 89	938	2.050	*
	7 Dec 89	933	1.990	*
	10 Dec 89	1603	2.050	*
	13 Dec 89	1612	2.005	*
	17 Dec 89	842	1.390	*
	19 Dec 89	1622	1.480	*
	21 Dec 89	853	1.550	*
	27 Dec 89	1612	1.690	*
	3 Jan 90	923	1.780	*
	10 Jan 90	1406	1.850	*
	17 Jan 90	919	1.860	*
	24 Jan 90	943	1.880	*
	31 Jan 90	915	1.980	*

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/11	5 Jul 89	806	2.455	0.334
	12 Jul 89	738	2.465	0.324
	19 Jul 89	821	2.550	0.239
	26 Jul 89	727	2.485	0.304
	2 Aug 89	727	2.500	0.289
	9 Aug 89	720	2.380	0.409
	16 Aug 89	716	2.500	0.289
	23 Aug 89	725	2.290	0.499
	30 Aug 89	710	2.470	0.319
	6 Sep 89	729	2.310	0.479
	13 Sep 89	753	2.560	0.229
	20 Sep 89	745	2.180	0.609
	27 Sep 89	740	2.520	0.269
	4 Oct 89	759	2.235	0.554
	1 Nov 89	823	2.240	0.549
	10 Nov 89	719	2.460	0.329
	11 Nov 89	1513	2.260	0.529
	15 Nov 89	1513	2.400	0.389
	29 Nov 89	825	2.230	0.559
	7 Dec 89	828	2.300	0.489
	10 Dec 89	1507	2.470	0.319
	13 Dec 89	1513	2.375	0.414
	17 Dec 89	732	1.920	0.869
	19 Dec 89	1520	2.270	0.519
	21 Dec 89	758	2.180	0.609
	27 Dec 89	1517	2.300	0.489
	3 Jan 90	819	2.140	0.649
	10 Jan 90	1510	2.350	0.439
	17 Jan 90	812	2.270	0.519
	24 Jan 90	838	2.330	0.459
	31 Jan 90	816	2.380	0.409

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/12	5 Jul 89	858	1.540	0.840
	12 Jul 89	1006	1.505	0.875
	19 Jul 89	855	1.520	0.860
	26 Jul 89	810	1.515	0.865
	2 Aug 89	816	1.500	0.880
	9 Aug 89	803	1.490	0.890
	16 Aug 89	758	1.490	0.890
	23 Aug 89	807	1.490	0.890
	30 Aug 89	741	1.490	0.890
	6 Sep 89	809	1.500	0.880
	13 Sep 89	832	1.540	0.840
	20 Sep 89	825	1.500	0.880
	27 Sep 89	819	1.550	0.830
	4 Oct 89	836	1.545	0.835
	1 Nov 89	908	1.590	0.790
	10 Nov 89	758	1.540	0.840
	11 Nov 89	1544	1.515	0.865
	15 Nov 89	1547	1.510	0.870
	29 Nov 89	905	1.550	0.830
	7 Dec 89	900	1.560	0.820
	10 Dec 89	1533	1.600	0.780
	13 Dec 89	1541	1.540	0.840
	17 Dec 89	810	1.040	1.340
	19 Dec 89	1552	1.115	1.265
	21 Dec 89	826	1.210	1.170
	27 Dec 89	1544	1.290	1.090
	3 Jan 90	851	1.360	1.020
	10 Jan 90	1538	1.420	0.960
	17 Jan 90	849	1.470	0.910
	24 Jan 90	918	1.490	0.890
	31 Jan 90	846	1.550	0.830

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/13	5 Jul 89	902	1.100	1.090
	12 Jul 89	838	1.080	1.110
	19 Jul 89	857	1.070	1.120
	26 Jul 89	812	1.050	1.140
	2 Aug 89	819	1.050	1.140
	9 Aug 89	805	1.040	1.150
	16 Aug 89	800	1.040	1.150
	23 Aug 89	813	1.040	1.150
	30 Aug 89	747	1.040	1.150
	6 Sep 89	813	1.050	1.140
	13 Sep 89	834	1.070	1.120
	20 Sep 89	827	1.080	1.110
	27 Sep 89	821	1.090	1.100
	4 Oct 89	838	1.120	1.070
	1 Nov 89	910	1.185	1.005
	10 Nov 89	800	1.080	1.110
	11 Nov 89	1546	1.070	1.120
	15 Nov 89	1549	1.085	1.105
	29 Nov 89	906	1.140	1.050
	7 Dec 89	902	1.130	1.060
	10 Dec 89	1535	1.125	1.065
	13 Dec 89	1542	1.110	1.080
	17 Dec 89	813	0.550	1.640
	19 Dec 89	1553	0.650	1.540
	21 Dec 89	829	0.700	1.490
	27 Dec 89	1545	0.800	1.390
	3 Jan 90	853	0.860	1.330
	10 Jan 90	1540	0.970	1.220
	17 Jan 90	851	0.990	1.200
	24 Jan 90	920	1.020	1.170
	31 Jan 90	848	1.060	1.130

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/14	5 Jul 89	802	2.020	0.839
	12 Jul 89	733	2.035	0.824
	19 Jul 89	817	2.040	0.819
	26 Jul 89	724	2.045	0.814
	2 Aug 89	723	2.050	0.809
	9 Aug 89	717	2.030	0.829
	16 Aug 89	713	1.995	0.864
	23 Aug 89	721	2.000	0.859
	30 Aug 89	707	2.040	0.819
	6 Sep 89	725	2.060	0.799
	13 Sep 89	751	2.090	0.769
	20 Sep 89	742	1.700	1.159
	27 Sep 89	737	2.020	0.839
	4 Oct 89	756	1.765	1.094
	1 Nov 89	820	2.100	0.759
	10 Nov 89	715	2.080	0.779
	11 Nov 89	1510	2.050	0.809
	15 Nov 89	1511	2.040	0.819
	29 Nov 89	822	2.070	0.789
	7 Dec 89	825	2.090	0.769
	10 Dec 89	1505	2.100	0.759
	13 Dec 89	1510	2.080	0.779
	17 Dec 89	728	1.600	1.259
	19 Dec 89	1518	1.710	1.149
	21 Dec 89	755	1.770	1.089
	27 Dec 89	1515	1.850	1.009
	3 Jan 90	812	1.900	0.959
	17 Jan 90	809	2.010	0.849
	24 Jan 90	835	2.030	0.829
	31 Jan 90	814	2.100	0.759

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/15	5 Jul 89	906	2.220	1.180
	12 Jul 89	843	2.190	1.210
	19 Jul 89	901	2.180	1.220
	26 Jul 89	814	2.155	1.245
	2 Aug 89	822	2.150	1.250
	9 Aug 89	807	2.150	1.250
	16 Aug 89	802	2.150	1.250
	23 Aug 89	815	2.150	1.250
	30 Aug 89	750	2.160	1.240
	6 Sep 89	815	2.165	1.235
	13 Sep 89	836	2.180	1.220
	20 Sep 89	831	2.180	1.220
	27 Sep 89	824	2.200	1.200
	4 Oct 89	840	2.230	1.170
	1 Nov 89	912	2.290	1.110
	10 Nov 89	803	2.190	1.210
	11 Nov 89	1548	2.175	1.225
	15 Nov 89	1551	2.190	1.210
	29 Nov 89	908	2.250	1.150
	7 Dec 89	904	2.225	1.175
	10 Dec 89	1536	2.220	1.180
	13 Dec 89	1544	2.210	1.190
	17 Dec 89	815	1.660	1.740
	19 Dec 89	1556	1.740	1.660
	21 Dec 89	830	1.790	1.610
	27 Dec 89	1548	1.890	1.510
	3 Jan 90	854	1.950	1.450
	10 Jan 90	1542	2.050	1.350
	17 Jan 90	853	2.070	1.330
	24 Jan 90	922	2.100	1.300
	31 Jan 90	849	2.150	1.250

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/16	5 Jul 89	942	5.160	1.340
	12 Jul 89	922	5.125	1.375
	19 Jul 89	942	5.110	1.390
	26 Jul 89	844	5.095	1.405
	2 Aug 89	859	5.090	1.410
	9 Aug 89	834	5.080	1.420
	16 Aug 89	828	5.080	1.420
	23 Aug 89	842	5.080	1.420
	30 Aug 89	818	5.080	1.420
	6 Sep 89	847	5.075	1.425
	13 Sep 89	909	5.090	1.410
	20 Sep 89	906	5.100	1.400
	27 Sep 89	850	5.110	1.390
	4 Oct 89	913	5.135	1.365
	1 Nov 89	944	5.200	1.300
	10 Nov 89	830	5.150	1.350
	11 Nov 89	1611	5.115	1.385
	15 Nov 89	1613	5.115	1.385
	29 Nov 89	931	5.170	1.330
	7 Dec 89	928	5.160	1.340
	10 Dec 89	1558	5.195	1.305
	13 Dec 89	1607	5.145	1.355
	17 Dec 89	837	4.650	1.850
	19 Dec 89	1616	4.670	1.830
	21 Dec 89	849	4.670	1.830
	27 Dec 89	1607	4.740	1.760
	3 Jan 90	917	4.850	1.650
	10 Jan 90	1601	4.900	1.600
	17 Jan 90	913	4.950	1.550
	24 Jan 90	938	5.020	1.480
	31 Jan 90	910	5.060	1.440

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/17	5 Jul 89	754	3.065	0.375
	12 Jul 89	726	3.090	0.350
	19 Jul 89	811	3.180	0.260
	26 Jul 89	718	3.150	0.290
	2 Aug 89	716	3.110	0.330
	9 Aug 89	710	3.020	0.420
	16 Aug 89	707	3.130	0.310
	23 Aug 89	716	2.930	0.510
	30 Aug 89	659	3.070	0.370
	6 Sep 89	719	2.920	0.520
	13 Sep 89	745	3.160	0.280
	20 Sep 89	735	2.820	0.620
	27 Sep 89	731	3.120	0.320
	4 Oct 89	749	2.850	0.590
	1 Nov 89	812	2.860	0.580
	10 Nov 89	708	3.050	0.390
	11 Nov 89	1504	2.895	0.545
	15 Nov 89	1505	3.055	0.385
	29 Nov 89	816	2.840	0.600
	7 Dec 89	819	2.935	0.505
	10 Dec 89	1500	3.050	0.390
	13 Dec 89	1505	3.030	0.410
	17 Dec 89	722	2.680	0.760
	19 Dec 89	1511	2.870	0.570
	21 Dec 89	750	2.790	0.650
	27 Dec 89	1509	2.880	0.560
	3 Jan 90	806	2.760	0.680
	17 Jan 90	803	2.850	0.590
	24 Jan 90	825	2.860	0.580
	31 Jan 90	810	2.930	0.510
GWS1/18	10 Jan 90	1502	5.390	0.140
	17 Jan 90	750	5.500	0.030
	24 Jan 90	815	5.500	0.030
	31 Jan 90	753	5.600	-0.070

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/19	5 Jul 89	918	1.180	1.179
	12 Jul 89	858	1.145	1.214
	19 Jul 89	909	1.130	1.229
	26 Jul 89	823	1.120	1.239
	2 Aug 89	833	1.150	1.209
	9 Aug 89	816	1.111	1.248
	16 Aug 89	811	1.110	1.249
	23 Aug 89	824	1.095	1.264
	30 Aug 89	758	1.100	1.259
	6 Sep 89	824	1.100	1.259
	13 Sep 89	845	1.130	1.229
	20 Sep 89	839	1.140	1.219
	27 Sep 89	832	1.150	1.209
	4 Oct 89	849	1.180	1.179
	1 Nov 89	920	1.240	1.119
	10 Nov 89	813	1.150	1.209
	11 Nov 89	1556	1.135	1.224
	15 Nov 89	1559	1.145	1.214
	29 Nov 89	917	1.210	1.149
	7 Dec 89	912	1.190	1.169
	10 Dec 89	1544	1.210	1.149
	13 Dec 89	1550	1.175	1.184
	17 Dec 89	822	0.650	1.709
	19 Dec 89	1603	0.720	1.639
	21 Dec 89	836	0.760	1.599
	27 Dec 89	1554	0.830	1.529
	3 Jan 90	901	0.910	1.449
	10 Jan 90	1549	1.000	1.359
	17 Jan 90	900	1.030	1.329
	24 Jan 90	926	1.070	1.289
	31 Jan 90	855	1.120	1.239

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/2	5 Jul 89	826	3.660	0.720
	12 Jul 89	757	3.670	0.710
	19 Jul 89	834	3.655	0.725
	26 Jul 89	742	3.650	0.730
	2 Aug 89	741	3.630	0.750
	9 Aug 89	734	3.620	0.760
	16 Aug 89	729	3.610	0.770
	23 Aug 89	740	3.600	0.780
	30 Aug 89	722	3.580	0.800
	6 Sep 89	744	3.580	0.800
	13 Sep 89	809	3.590	0.790
	20 Sep 89	800	3.590	0.790
	27 Sep 89	753	3.600	0.780
	4 Oct 89	813	3.635	0.745
	1 Nov 89	839	3.670	0.710
	10 Nov 89	735	3.660	0.720
	11 Nov 89	1526	3.615	0.765
	15 Nov 89	1526	3.590	0.790
	29 Nov 89	842	3.700	0.680
	7 Dec 89	840	3.670	0.710
	10 Dec 89	1518	3.680	0.700
	13 Dec 89	1524	3.665	0.715
	17 Dec 89	752	3.200	1.180
	19 Dec 89	1533	3.190	1.190
	21 Dec 89	809	3.230	1.150
	27 Dec 89	1528	3.370	1.010
	3 Jan 90	829	3.450	0.930
	10 Jan 90	1522	3.600	0.780
	17 Jan 90	827	3.580	0.800
	24 Jan 90	857	3.600	0.780
	31 Jan 90	829	3.620	0.760

WEST BAY G/WATER STUDY   Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/20	5 Jul 89	746	3.310	0.249
	12 Jul 89	716	3.300	0.259
	19 Jul 89	806	3.350	0.209
	26 Jul 89	712	3.350	0.209
	2 Aug 89	710	3.380	0.179
	9 Aug 89	706	3.365	0.194
	16 Aug 89	701	3.360	0.199
	23 Aug 89	711	3.350	0.209
	30 Aug 89	654	3.370	0.189
	6 Sep 89	714	3.370	0.189
	13 Sep 89	740	3.415	0.144
	20 Sep 89	728	3.395	0.164
	27 Sep 89	726	3.410	0.149
	4 Oct 89	742	3.440	0.119
	1 Nov 89	804	3.490	0.069
	15 Nov 89	1459	3.450	0.109
	29 Nov 89	1817	3.480	0.079
	7 Dec 89	814	3.460	0.099
	17 Dec 89	717	3.390	0.169
	21 Dec 89	745	3.400	0.159
	3 Jan 90	801	3.420	0.139
	17 Jan 90	752	3.460	0.099
	31 Jan 90	800	3.520	0.039

WEST BAY G/WATER STUDY Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/3	5 Jul 89	818	1.965	0.554
	12 Jul 89	749	2.085	0.434
	19 Jul 89	828	2.075	0.444
	26 Jul 89	736	2.100	0.419
	2 Aug 89	735	2.060	0.459
	9 Aug 89	727	2.075	0.444
	16 Aug 89	723	2.050	0.469
	23 Aug 89	734	2.020	0.499
	30 Aug 89	717	2.040	0.479
	6 Sep 89	738	2.060	0.459
	13 Sep 89	801	2.120	0.399
	20 Sep 89	755	1.980	0.539
	27 Sep 89	747	2.110	0.409
	4 Oct 89	808	2.040	0.479
	1 Nov 89	833	2.020	0.499
	10 Nov 89	730	2.110	0.409
	11 Nov 89	1521	2.025	0.494
	15 Nov 89	1521	2.005	0.514
	29 Nov 89	834	2.010	0.509
	7 Dec 89	835	2.070	0.449
	10 Dec 89	1513	2.180	0.339
	13 Dec 89	1520	2.040	0.479
	17 Dec 89	747	1.660	0.859
	19 Dec 89	1528	1.900	0.619
	21 Dec 89	805	1.950	0.569
	27 Dec 89	1523	1.980	0.539
	3 Jan 90	825	1.990	0.529
	10 Jan 90	1518	2.100	0.419
	17 Jan 90	822	2.070	0.449
	24 Jan 90	852	2.060	0.459
	31 Jan 90	824	2.150	0.369

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/4	5 Jul 89	838	2.980	0.559
	12 Jul 89	807	3.000	0.539
	19 Jul 89	841	2.950	0.589
	26 Jul 89	748	2.890	0.649
	2 Aug 89	747	2.865	0.674
	9 Aug 89	739	2.840	0.699
	16 Aug 89	735	2.810	0.729
	23 Aug 89	746	2.750	0.789
	30 Aug 89	728	2.750	0.789
	6 Sep 89	750	2.720	0.819
	13 Sep 89	819	2.720	0.819
	20 Sep 89	812	2.720	0.819
	27 Sep 89	806	2.730	0.809
	4 Oct 89	818	2.785	0.754
	1 Nov 89	846	2.750	0.789
	10 Nov 89	743	2.710	0.829
	11 Nov 89	1531	2.910	0.629
	15 Nov 89	1533	2.850	0.689
	29 Nov 89	851	3.060	0.479
	7 Dec 89	846	2.950	0.589
	10 Dec 89	1522	3.000	0.539
	13 Dec 89	1529	2.750	0.789
	17 Dec 89	1757	2.360	1.179
	19 Dec 89	1537	2.610	0.929
	21 Dec 89	814	2.660	0.879
	27 Dec 89	1532	2.830	0.709
	3 Jan 90	838	2.880	0.659
	10 Jan 90	1526	3.300	0.239
	17 Jan 90	832	2.920	0.619
	24 Jan 90	904	2.980	0.559
	31 Jan 90	832	2.920	0.619

WEST BAY G/WATER STUDY

Water levels

Station No.	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/5	5 Jul 89	814	2.520	-0.530
	12 Jul 89	744	2.555	-0.565
	19 Jul 89	825	2.585	-0.595
	26 Jul 89	733	2.585	-0.595
	2 Aug 89	732	2.575	-0.585
	9 Aug 89	725	2.530	-0.540
	16 Aug 89	720	2.550	-0.560
	23 Aug 89	732	2.480	-0.490
	30 Aug 89	714	2.545	-0.555
	6 Sep 89	733	2.520	-0.530
	13 Sep 89	757	2.630	-0.640
	20 Sep 89	750	2.465	-0.475
	27 Sep 89	744	2.620	-0.630
	4 Oct 89	803	2.510	-0.520
	1 Nov 89	828	2.520	-0.530
	10 Nov 89	725	2.590	-0.600
	11 Nov 89	1517	2.490	-0.500
	15 Nov 89	1518	2.520	-0.530
	29 Nov 89	830	2.510	-0.520
	7 Dec 89	832	2.540	-0.550
	10 Dec 89	1511	2.630	-0.640
	13 Dec 89	1517	2.540	-0.550
	17 Dec 89	744	2.110	-0.120
	19 Dec 89	1525	2.330	-0.340
	21 Dec 89	802	2.360	-0.370
	27 Dec 89	1521	2.440	-0.450
	3 Jan 90	822	2.440	-0.450
	10 Jan 90	1514	2.560	-0.570
	17 Jan 90	818	2.530	-0.540
	31 Jan 90	820	2.600	-0.610

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/6	5 Jul 89	842	2.155	0.745
	12 Jul 89	811	2.150	0.750
	19 Jul 89	844	2.140	0.760
	26 Jul 89	750	2.120	0.780
	2 Aug 89	750	2.115	0.785
	9 Aug 89	741	2.100	0.800
	16 Aug 89	737	2.110	0.790
	23 Aug 89	749	2.110	0.790
	30 Aug 89	730	2.110	0.790
	6 Sep 89	752	2.100	0.800
	13 Sep 89	821	2.125	0.775
	20 Sep 89	814	2.100	0.800
	27 Sep 89	808	2.110	0.790
	4 Oct 89	825	2.150	0.750
	1 Nov 89	848	2.180	0.720
	10 Nov 89	745	2.110	0.790
	11 Nov 89	1533	2.085	0.815
	15 Nov 89	1534	2.080	0.820
	29 Nov 89	853	2.190	0.710
	7 Dec 89	848	2.170	0.730
	10 Dec 89	1524	2.160	0.740
	13 Dec 89	1531	2.130	0.770
	17 Dec 89	758	1.700	1.200
	19 Dec 89	1539	1.720	1.180
	21 Dec 89	815	1.780	1.120
	27 Dec 89	1533	1.900	1.000
	3 Jan 90	840	2.000	0.900
	10 Jan 90	1527	2.110	0.790
	17 Jan 90	834	2.140	0.760
	24 Jan 90	906	2.140	0.760
	31 Jan 90	835	2.160	0.740

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/7	5 Jul 89	951	5.880	1.170
	12 Jul 89	935	5.854	1.196
	19 Jul 89	951	5.850	1.200
	26 Jul 89	851	5.845	1.205
	2 Aug 89	906	5.840	1.210
	9 Aug 89	840	5.830	1.220
	16 Aug 89	834	5.830	1.220
	23 Aug 89	847	5.820	1.230
	30 Aug 89	828	5.820	1.230
	6 Sep 89	854	5.810	1.240
	13 Sep 89	917	5.830	1.220
	20 Sep 89	916	5.820	1.230
	27 Sep 89	858	5.835	1.215
	4 Oct 89	922	5.850	1.200
	1 Nov 89	1006	5.885	1.165
	10 Nov 89	838	5.875	1.175
	11 Nov 89	1620	5.840	1.210
	15 Nov 89	1622	5.830	1.220
	29 Nov 89	941	5.870	1.180
	7 Dec 89	937	5.870	1.180
	10 Dec 89	1605	5.870	1.180
	13 Dec 89	1616	5.855	1.195
	17 Dec 89	846	5.400	1.650
	19 Dec 89	1625	5.310	1.740
	21 Dec 89	855	5.330	1.720
	27 Dec 89	1615	5.420	1.630
	3 Jan 90	925	5.530	1.520
	10 Jan 90	1609	5.600	1.450
	17 Jan 90	922	2.650	4.400
	24 Jan 90	946	5.690	1.360
	31 Jan 90	916	5.730	1.320

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/8	5 Jul 89	851	2.750	0.869
	12 Jul 89	819	2.735	0.884
	19 Jul 89	849	2.720	0.899
	26 Jul 89	804	2.685	0.934
	2 Aug 89	809	2.680	0.939
	9 Aug 89	757	2.675	0.944
	16 Aug 89	753	2.670	0.949
	23 Aug 89	801	2.660	0.959
	30 Aug 89	735	2.670	0.949
	6 Sep 89	803	2.660	0.959
	13 Sep 89	826	2.700	0.919
	20 Sep 89	819	2.700	0.919
	27 Sep 89	813	2.700	0.919
	4 Oct 89	830	2.735	0.884
	1 Nov 89	900	2.780	0.839
	10 Nov 89	751	2.700	0.919
	11 Nov 89	1538	2.680	0.939
	15 Nov 89	1541	2.680	0.939
	29 Nov 89	858	2.780	0.839
	7 Dec 89	853	2.735	0.884
	10 Dec 89	1528	2.750	0.869
	13 Dec 89	1535	2.725	0.894
	17 Dec 89	804	2.190	1.429
	19 Dec 89	1545	2.260	1.359
	21 Dec 89	820	2.310	1.309
	27 Dec 89	1538	2.430	1.189
	3 Jan 90	845	2.540	1.079
	10 Jan 90	1533	2.660	0.959
	17 Jan 90	842	2.660	0.959
	24 Jan 90	912	2.680	0.939
	31 Jan 90	840	2.710	0.909

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS1/9	5 Jul 89	854	1.765	0.814
	12 Jul 89	823	1.755	0.824
	19 Jul 89	852	1.760	0.819
	26 Jul 89	808	1.755	0.824
	2 Aug 89	813	1.750	0.829
	9 Aug 89	801	1.730	0.849
	16 Aug 89	756	1.730	0.849
	23 Aug 89	804	1.730	0.849
	30 Aug 89	738	1.730	0.849
	6 Sep 89	806	1.745	0.834
	13 Sep 89	830	1.775	0.804
	20 Sep 89	823	1.760	0.819
	27 Sep 89	816	1.780	0.799
	4 Oct 89	833	1.800	0.779
	1 Nov 89	905	1.850	0.729
	10 Nov 89	755	1.780	0.799
	11 Nov 89	1541	1.760	0.819
	15 Nov 89	1545	1.750	0.829
	29 Nov 89	902	1.820	0.759
	7 Dec 89	857	1.810	0.769
	10 Dec 89	1538	1.790	0.789
	17 Dec 89	807	1.270	1.309
	19 Dec 89	1549	1.365	1.214
	21 Dec 89	824	1.430	1.149
	27 Dec 89	1542	1.510	1.069
	3 Jan 90	848	1.610	0.969
	10 Jan 90	1537	1.690	0.889
	17 Jan 90	846	1.730	0.849
	24 Jan 90	916	1.750	0.829
	31 Jan 90	844	1.800	0.779

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/1	5 Jul 89	751	4.090	0.160
	12 Jul 89	721	4.055	0.195
	19 Jul 89	809	4.090	0.160
	26 Jul 89	714	4.050	0.200
	2 Aug 89	713	4.075	0.175
	9 Aug 89	708	4.035	0.215
	16 Aug 89	704	4.100	0.150
	23 Aug 89	713	3.980	0.270
	30 Aug 89	656	4.050	0.200
	6 Sep 89	716	3.980	0.270
	13 Sep 89	1742	4.070	0.180
	20 Sep 89	730	3.940	0.310
	27 Sep 89	728	4.090	0.160
	4 Oct 89	744	3.975	0.275
	1 Nov 89	809	4.030	0.220
	10 Nov 89	703	4.140	0.110
	11 Nov 89	1459	4.055	0.195
	15 Nov 89	1501	4.125	0.125
	29 Nov 89	810	4.040	0.210
	7 Dec 89	816	4.060	0.190
	10 Dec 89	1457	4.130	0.120
	13 Dec 89	1502	4.120	0.130
	17 Dec 89	720	3.900	0.350
	19 Dec 89	1508	4.010	0.240
	21 Dec 89	747	3.980	0.270
	27 Dec 89	1505	4.010	0.240
	3 Jan 90	803	3.940	0.310
	10 Jan 90	1505	4.030	0.220
	17 Jan 90	755	4.000	0.250
	24 Jan 90	817	4.050	0.200
	31 Jan 90	802	4.060	0.190

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/10	5 Jul 89	726	1.980	0.579
	12 Jul 89	658	1.985	0.574
	19 Jul 89	752	2.070	0.489
	26 Jul 89	657	2.085	0.474
	2 Aug 89	656	2.080	0.479
	9 Aug 89	652	2.029	0.530
	16 Aug 89	648	2.020	0.539
	23 Aug 89	658	2.030	0.529
	30 Aug 89	641	2.010	0.549
	6 Sep 89	653	2.020	0.539
	13 Sep 89	723	2.060	0.499
	20 Sep 89	711	2.000	0.559
	27 Sep 89	710	2.065	0.494
	4 Oct 89	727	2.015	0.544
	1 Nov 89	747	2.000	0.559
	10 Nov 89	644	2.070	0.489
	11 Nov 89	1445	2.040	0.519
	15 Nov 89	1444	2.060	0.499
	29 Nov 89	748	2.060	0.499
	7 Dec 89	800	2.150	0.409
	10 Dec 89	1444	2.120	0.439
	13 Dec 89	1448	2.110	0.449
	19 Dec 89	705	1.870	0.689
	21 Dec 89	1455	1.905	0.654
	27 Dec 89	734	1.950	0.609
	3 Jan 90	1456	1.950	0.609
	10 Jan 90	748	1.995	0.564
	17 Jan 90	1448	2.000	0.559
	24 Jan 90	801	2.020	0.539
	31 Jan 90	745	2.160	0.399

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/11	5 Jul 89	718	2.295	0.595
	12 Jul 89	651	2.285	0.605
	19 Jul 89	748	2.300	0.590
	26 Jul 89	653	2.295	0.595
	2 Aug 89	651	2.300	0.590
	9 Aug 89	648	2.295	0.595
	16 Aug 89	644	2.280	0.610
	23 Aug 89	654	2.280	0.610
	30 Aug 89	637	2.280	0.610
	6 Sep 89	649	2.290	0.600
	13 Sep 89	719	2.300	0.590
	20 Sep 89	707	2.300	0.590
	27 Sep 89	707	2.310	0.580
	4 Oct 89	723	2.320	0.570
	1 Nov 89	742	2.320	0.570
	10 Nov 89	638	2.340	0.550
	11 Nov 89	1441	2.310	0.580
	15 Nov 89	1440	2.320	0.570
	29 Nov 89	744	2.370	0.520
	7 Dec 89	757	2.380	0.510
	10 Dec 89	1441	2.365	0.525
	13 Dec 89	1445	2.340	0.550
	17 Dec 89	701	1.950	0.940
	19 Dec 89	1451	1.980	0.910
	21 Dec 89	731	2.020	0.870
	27 Dec 89	1452	2.040	0.850
	3 Jan 90	745	2.100	0.790
	10 Jan 90	1444	2.120	0.770
	17 Jan 90	734	2.160	0.730
	24 Jan 90	757	2.200	0.690
	31 Jan 90	741	2.260	0.630

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/13	5 Jul 89	714	2.130	0.500
	12 Jul 89	647	2.165	0.465
	19 Jul 89	745	2.220	0.410
	26 Jul 89	650	2.225	0.405
	2 Aug 89	648	2.210	0.420
	9 Aug 89	646	2.200	0.430
	16 Aug 89	642	2.190	0.440
	23 Aug 89	652	2.190	0.440
	30 Aug 89	635	2.180	0.450
	6 Sep 89	647	2.200	0.430
	13 Sep 89	716	2.240	0.390
	20 Sep 89	705	2.200	0.430
	27 Sep 89	705	2.255	0.375
	4 Oct 89	721	2.225	0.405
	1 Nov 89	739	2.260	0.370
	10 Nov 89	635	2.270	0.360
	11 Nov 89	1439	2.235	0.395
	15 Nov 89	1439	2.230	0.400
	29 Nov 89	742	2.260	0.370
	7 Dec 89	754	2.310	0.320
	10 Dec 89	1439	2.300	0.330
	13 Dec 89	1443	2.260	0.370
	17 Dec 89	658	1.990	0.640
	19 Dec 89	1449	1.980	0.650
	21 Dec 89	729	2.010	0.620
	27 Dec 89	1450	2.010	0.620
	3 Jan 90	743	2.085	0.545
	10 Jan 90	1442	2.080	0.550
	24 Jan 90	755	2.150	0.480
	31 Jan 90	738	2.260	0.370

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/14	5 Jul 89	931	1.265	1.494
	12 Jul 89	633	1.265	1.494
	19 Jul 89	737	1.270	1.489
	26 Jul 89	640	1.265	1.494
	2 Aug 89	634	1.260	1.499
	9 Aug 89	636	1.245	1.514
	16 Aug 89	633	1.245	1.514
	23 Aug 89	646	1.240	1.519
	30 Aug 89	628	1.240	1.519
	6 Sep 89	641	1.245	1.514
	13 Sep 89	709	1.270	1.489
	20 Sep 89	659	1.255	1.504
	27 Sep 89	700	1.285	1.474
	4 Oct 89	714	1.285	1.474
	1 Nov 89	732	1.330	1.429
	10 Nov 89	623	1.305	1.454
	11 Nov 89	1428	1.270	1.489
	15 Nov 89	1428	1.270	1.489
	29 Nov 89	729	1.310	1.449
	7 Dec 89	750	1.320	1.439
	10 Dec 89	1435	1.325	1.434
	13 Dec 89	1438	1.300	1.459
	17 Dec 89	652	0.890	1.869
	19 Dec 89	1439	0.850	1.909
	21 Dec 89	717	0.840	1.919
	27 Dec 89	1441	0.880	1.879
	3 Jan 90	737	0.955	1.804
	10 Jan 90	1432	1.030	1.729
	17 Jan 90	722	1.060	1.699
	24 Jan 90	744	1.120	1.639
	31 Jan 90	730	1.180	1.579

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/15	5 Jul 89	706	1.790	0.739
	12 Jul 89	639	1.795	0.734
	19 Jul 89	731	1.800	0.729
	26 Jul 89	644	1.835	0.694
	2 Aug 89	640	1.820	0.709
	9 Aug 89	640	1.820	0.709
	16 Aug 89	637	1.800	0.729
	23 Aug 89	640	1.815	0.714
	30 Aug 89	622	1.775	0.754
	6 Sep 89	635	1.790	0.739
	13 Sep 89	703	1.820	0.709
	20 Sep 89	653	1.800	0.729
	27 Sep 89	653	1.850	0.679
	4 Oct 89	708	1.850	0.679
	1 Nov 89	726	1.900	0.629
	10 Nov 89	616	1.860	0.669
	11 Nov 89	1422	1.840	0.689
	15 Nov 89	1423	1.840	0.689
	29 Nov 89	722	1.870	0.659
	7 Dec 89	744	1.890	0.639
	10 Dec 89	1429	1.885	0.644
	13 Dec 89	1433	1.840	0.689
	17 Dec 89	642	1.470	1.059
	19 Dec 89	1430	1.450	1.079
	21 Dec 89	709	1.490	1.039
	27 Dec 89	1435	1.500	1.029
	3 Jan 90	731	1.600	0.929
	10 Jan 90	1425	1.600	0.929
	17 Jan 90	716	1.680	0.849
	24 Jan 90	738	1.670	0.859
	31 Jan 90	724	1.800	0.729

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/16	5 Jul 89	702	2.120	0.530
	12 Jul 89	621	2.220	0.430
	19 Jul 89	719	2.270	0.380
	26 Jul 89	633	2.355	0.295
	2 Aug 89	626	2.180	0.470
	9 Aug 89	630	2.200	0.450
	16 Aug 89	626	2.235	0.415
	23 Aug 89	638	2.140	0.510
	30 Aug 89	620	2.160	0.490
	6 Sep 89	632	2.070	0.580
	13 Sep 89	700	2.285	0.365
	20 Sep 89	650	1.935	0.715
	27 Sep 89	651	2.260	0.390
	4 Oct 89	704	1.920	0.730
	1 Nov 89	723	1.885	0.765
	10 Nov 89	614	2.110	0.540
	11 Nov 89	1420	1.990	0.660
	15 Nov 89	1421	2.190	0.460
	29 Nov 89	720	1.840	0.810
	7 Dec 89	741	2.120	0.530
	10 Dec 89	1427	2.140	0.510
	13 Dec 89	1431	2.150	0.500
	17 Dec 89	639	1.780	0.870
	19 Dec 89	1427	1.945	0.705
	21 Dec 89	706	1.940	0.710
	27 Dec 89	1433	2.040	0.610
	3 Jan 90	728	1.880	0.770
	10 Jan 90	1423	2.060	0.590
	17 Jan 90	713	2.000	0.650
	24 Jan 90	737	1.880	0.770
	31 Jan 90	721	2.080	0.570

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/17	5 Jul 89	658	1.980	1.450
	12 Jul 89	627	1.975	1.455
	19 Jul 89	734	1.990	1.440
	26 Jul 89	636	2.000	1.430
	2 Aug 89	630	2.100	1.330
	9 Aug 89	633	2.000	1.430
	16 Aug 89	629	1.980	1.450
	23 Aug 89	643	1.990	1.440
	30 Aug 89	625	1.990	1.440
	6 Sep 89	638	2.000	1.430
	13 Sep 89	706	2.020	1.410
	20 Sep 89	656	2.000	1.430
	27 Sep 89	656	2.020	1.410
	4 Oct 89	711	2.035	1.395
	1 Nov 89	728	2.080	1.350
	10 Nov 89	619	2.020	1.410
	11 Nov 89	1425	2.010	1.420
	15 Nov 89	1425	2.010	1.420
	29 Nov 89	726	2.060	1.370
	7 Dec 89	746	2.060	1.370
	10 Dec 89	1432	2.055	1.375
	13 Dec 89	1436	2.030	1.400
	17 Dec 89	645	1.530	1.900
	19 Dec 89	1432	1.550	1.880
	21 Dec 89	711	1.600	1.830
	27 Dec 89	1436	1.640	1.790
	3 Jan 90	733	1.745	1.685
	10 Jan 90	1428	1.770	1.660
	17 Jan 90	719	1.830	1.600
	24 Jan 90	741	1.870	1.560
	31 Jan 90	728	1.930	1.500

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/18	5 Jul 89	654	1.300	1.200
	12 Jul 89	615	1.310	1.190
	19 Jul 89	728	1.350	1.150
	26 Jul 89	629	1.375	1.125
	2 Aug 89	623	1.340	1.160
	9 Aug 89	627	1.360	1.140
	16 Aug 89	623	1.330	1.170
	23 Aug 89	634	1.365	1.135
	30 Aug 89	617	1.325	1.175
	6 Sep 89	628	1.370	1.130
	13 Sep 89	657	1.380	1.120
	20 Sep 89	646	1.375	1.125
	27 Sep 89	648	1.385	1.115
	4 Oct 89	700	1.365	1.135
	1 Nov 89	720	1.360	1.140
	10 Nov 89	610	1.340	1.160
	11 Nov 89	1417	1.330	1.170
	15 Nov 89	1418	1.290	1.210
	29 Nov 89	716	1.310	1.190
	7 Dec 89	738	1.410	1.090
	10 Dec 89	1425	1.365	1.135
	13 Dec 89	1429	1.330	1.170
	17 Dec 89	636	0.880	1.620
	19 Dec 89	1424	0.830	1.670
	21 Dec 89	702	0.920	1.580
	27 Dec 89	1430	1.000	1.500
	3 Jan 90	725	1.150	1.350
	10 Jan 90	1421	1.150	1.350
	17 Jan 90	710	1.250	1.250
	24 Jan 90	733	1.200	1.300
	31 Jan 90	718	1.370	1.130

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/2	5 Jul 89	914	1.490	0.960
	12 Jul 89	854	1.475	0.975
	19 Jul 89	906	1.480	0.970
	26 Jul 89	820	1.475	0.975
	2 Aug 89	829	1.480	0.970
	9 Aug 89	813	1.470	0.980
	16 Aug 89	808	1.460	0.990
	23 Aug 89	821	1.450	1.000
	30 Aug 89	755	1.460	0.990
	6 Sep 89	821	1.460	0.990
	13 Sep 89	842	1.480	0.970
	20 Sep 89	836	1.485	0.965
	27 Sep 89	828	1.490	0.960
	4 Oct 89	846	1.515	0.935
	1 Nov 89	918	1.580	0.870
	10 Nov 89	810	1.570	0.880
	11 Nov 89	1553	1.540	0.910
	15 Nov 89	1556	1.510	0.940
	29 Nov 89	914	1.540	0.910
	7 Dec 89	910	1.540	0.910
	10 Dec 89	1541	1.530	0.920
	13 Dec 89	1548	1.530	0.920
	17 Dec 89	819	0.570	1.880
	19 Dec 89	1601	0.690	1.760
	21 Dec 89	833	0.750	1.700
	27 Dec 89	1552	1.030	1.420
	3 Jan 90	859	1.150	1.300
	10 Jan 90	1547	1.240	1.210
	17 Jan 90	858	1.310	1.140
	31 Jan 90	853	1.400	1.050
GWS2/3	17 Jan 90	759	1.990	0.260
	24 Jan 90	821	1.990	0.260
	31 Jan 90	806	2.080	0.170

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/5	26 Jul 89	840	6.100	1.470
	2 Aug 89	856	6.085	1.485
	9 Aug 89	831	6.085	1.485
	16 Aug 89	825	6.085	1.485
	23 Aug 89	839	6.080	1.490
	30 Aug 89	815	6.090	1.480
	6 Sep 89	844	6.075	1.495
	13 Sep 89	906	6.090	1.480
	20 Sep 89	903	6.100	1.470
	27 Sep 89	847	6.100	1.470
	11 Nov 89	1608	6.110	1.460
	17 Dec 89	834	5.630	1.940
	19 Dec 89	1614	5.660	1.910
	21 Dec 89	846	5.680	1.890
	27 Dec 89	1604	5.750	1.820
	3 Jan 90	915	5.850	1.720
	10 Jan 90	1559	5.920	1.650
	17 Jan 90	910	5.950	1.620
	24 Jan 90	935	6.010	1.560
	31 Jan 90	906	6.060	1.510

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/6	5 Jul 89	726	2.190	0.940
	12 Jul 89	911	2.175	0.955
	19 Jul 89	931	2.170	0.960
	26 Jul 89	834	2.165	0.965
	2 Aug 89	843	2.155	0.975
	9 Aug 89	826	2.150	0.980
	16 Aug 89	819	2.140	0.990
	23 Aug 89	834	2.150	0.980
	30 Aug 89	809	2.140	0.990
	6 Sep 89	835	2.145	0.985
	13 Sep 89	853	2.165	0.965
	20 Sep 89	846	2.160	0.970
	27 Sep 89	840	2.170	0.960
	4 Oct 89	859	2.190	0.940
	1 Nov 89	930	2.240	0.890
	10 Nov 89	626	2.210	0.920
	11 Nov 89	1431	2.180	0.950
	15 Nov 89	1431	2.170	0.960
	29 Nov 89	732	2.220	0.910
	7 Dec 89	918	2.220	0.910
	10 Dec 89	1549	2.220	0.910
	13 Dec 89	1559	2.200	0.930
	17 Dec 89	828	1.870	1.260
	19 Dec 89	1442	1.800	1.330
	21 Dec 89	720	1.800	1.330
	27 Dec 89	1444	1.855	1.275
	3 Jan 90	909	1.930	1.200
	10 Jan 90	1435	1.990	1.140
	17 Jan 90	725	2.030	1.100
	24 Jan 90	747	2.070	1.060
	31 Jan 90	733	2.100	1.030

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/7	5 Jul 89	738	3.180	0.290
	12 Jul 89	708	3.300	0.170
	19 Jul 89	801	3.350	0.120
	26 Jul 89	706	3.355	0.115
	2 Aug 89	704	3.235	0.235
	9 Aug 89	701	3.210	0.260
	16 Aug 89	656	3.260	0.210
	23 Aug 89	706	3.130	0.340
	30 Aug 89	649	3.200	0.270
	6 Sep 89	708	3.065	0.405
	13 Sep 89	734	3.260	0.210
	20 Sep 89	722	2.950	0.520
	27 Sep 89	721	3.210	0.260
	4 Oct 89	737	2.955	0.515
	1 Nov 89	759	2.910	0.560
	10 Nov 89	655	3.110	0.360
	11 Nov 89	1453	2.990	0.480
	15 Nov 89	1453	3.140	0.330
	29 Nov 89	802	2.915	0.555
	7 Dec 89	809	3.080	0.390
	10 Dec 89	1452	3.110	0.360
	13 Dec 89	1457	3.110	0.360
	17 Dec 89	713	2.880	0.590
	19 Dec 89	1502	3.010	0.460
	21 Dec 89	741	2.970	0.500
	27 Dec 89	1502	3.000	0.470
	3 Jan 90	756	2.860	0.610
	10 Jan 90	1456	2.920	0.550
	17 Jan 90	744	2.870	0.600
	24 Jan 90	810	2.840	0.630
	31 Jan 90	754	2.880	0.590

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/8	5 Jul 89	722	2.325	0.014
	12 Jul 89	655	2.365	-0.026
	19 Jul 89	749	2.410	-0.071
	26 Jul 89	655	2.435	-0.096
	2 Aug 89	653	2.390	-0.051
	9 Aug 89	650	2.370	-0.031
	16 Aug 89	646	2.385	-0.046
	23 Aug 89	656	2.350	-0.011
	30 Aug 89	639	2.360	-0.021
	6 Sep 89	651	2.350	-0.011
	13 Sep 89	721	2.440	-0.101
	20 Sep 89	709	2.290	0.049
	27 Sep 89	709	2.425	-0.086
	4 Oct 89	725	2.300	0.039
	1 Nov 89	744	2.310	0.029
	10 Nov 89	641	2.400	-0.061
	11 Nov 89	1442	2.325	0.014
	15 Nov 89	1442	2.390	-0.051
	29 Nov 89	746	2.310	0.029
	7 Dec 89	758	2.405	-0.066
	10 Dec 89	1442	2.410	-0.071
	13 Dec 89	1446	2.400	-0.061
	17 Dec 89	702	2.080	0.259
	19 Dec 89	1453	2.150	0.189
	21 Dec 89	732	2.170	0.169
	27 Dec 89	1454	2.200	0.139
	3 Jan 90	747	2.205	0.134
	10 Jan 90	1445	2.240	0.099
	17 Jan 90	736	2.270	0.069
	24 Jan 90	759	2.260	0.079
	31 Jan 90	742	2.370	-0.031

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS2/9	5 Jul 89	734	3.560	0.459
	12 Jul 89	704	3.660	0.359
	19 Jul 89	757	3.730	0.289
	26 Jul 89	703	3.755	0.264
	2 Aug 89	702	3.670	0.349
	9 Aug 89	658	3.645	0.374
	16 Aug 89	653	3.695	0.324
	23 Aug 89	703	3.600	0.419
	30 Aug 89	646	3.640	0.379
	6 Sep 89	706	3.525	0.494
	13 Sep 89	731	3.670	0.349
	20 Sep 89	719	3.335	0.684
	27 Sep 89	719	3.640	0.379
	4 Oct 89	735	3.435	0.584
	1 Nov 89	756	3.440	0.579
	10 Nov 89	653	3.640	0.379
	11 Nov 89	1451	3.505	0.514
	15 Nov 89	1451	3.660	0.359
	29 Nov 89	759	3.440	0.579
	7 Dec 89	807	3.630	0.389
	10 Dec 89	1450	3.650	0.369
	13 Dec 89	1455	3.650	0.369
	19 Dec 89	711	3.420	0.599
	21 Dec 89	1500	3.520	0.499
	27 Dec 89	739	3.500	0.519
	3 Jan 90	1500	3.530	0.489
	10 Jan 90	754	3.430	0.589
	17 Jan 90	1454	3.490	0.529
	24 Jan 90	808	3.460	0.559
	31 Jan 90	752	3.580	0.439
GWS3/1	6 Sep 89	746	5.435	0.854
	13 Sep 89	812	5.450	0.839
	20 Sep 89	802	5.455	0.834
	27 Sep 89	755	5.450	0.839
	4 Oct 89	815	5.475	0.814
	1 Nov 89	841	5.510	0.779
	10 Nov 89	739	5.520	0.769
	11 Nov 89	1528	5.460	0.829
	15 Nov 89	1529	5.440	0.849
	29 Nov 89	846	5.550	0.739

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS3/10	5 Jul 89	651	1.580	0.929
	12 Jul 89	611	1.655	0.854
	19 Jul 89	726	1.700	0.809
	26 Jul 89	626	1.770	0.739
	2 Aug 89	620	1.660	0.849
	9 Aug 89	625	1.690	0.819
	16 Aug 89	621	1.685	0.824
	23 Aug 89	632	1.670	0.839
	30 Aug 89	615	1.635	0.874
	6 Sep 89	626	1.630	0.879
	13 Sep 89	655	1.740	0.769
	20 Sep 89	643	1.575	0.934
	27 Sep 89	646	1.720	0.789
	4 Oct 89	659	1.530	0.979
	1 Nov 89	718	1.500	1.009
	10 Nov 89	608	1.560	0.949
	11 Nov 89	1415	1.550	0.959
	15 Nov 89	1417	1.640	0.869
GWS3/2	6 Sep 89	857	5.870	1.010
	13 Sep 89	922	5.875	1.005
	20 Sep 89	919	5.885	0.995
	27 Sep 89	901	5.875	1.005
	4 Oct 89	925	5.900	0.980
	1 Nov 89	1008	5.940	0.940
	10 Nov 89	841	5.940	0.940
	11 Nov 89	1623	5.900	0.980
	15 Nov 89	1625	5.880	1.000
	29 Nov 89	943	5.950	0.930
GWS3/3	6 Sep 89	754	4.680	0.890
	13 Sep 89	824	4.700	0.870
	20 Sep 89	815	4.675	0.895
	27 Sep 89	811	4.700	0.870
	4 Oct 89	827	4.730	0.840
	1 Nov 89	851	4.760	0.810
	10 Nov 89	748	4.735	0.835
	11 Nov 89	1536	4.700	0.870
	15 Nov 89	1537	4.695	0.875
	29 Nov 89	856	4.820	0.750

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS3/4	5 Jul 89	811	1.610	0.590
	12 Jul 89	741	1.610	0.590
	19 Jul 89	822	1.630	0.570
	26 Jul 89	731	1.625	0.575
	2 Aug 89	729	1.615	0.585
	9 Aug 89	722	1.590	0.610
	16 Aug 89	718	1.600	0.600
	23 Aug 89	727	1.575	0.625
	30 Aug 89	712	1.600	0.600
	6 Sep 89	731	1.600	0.600
	13 Sep 89	755	1.650	0.550
	20 Sep 89	746	1.575	0.625
	27 Sep 89	742	1.680	0.520
	4 Oct 89	801	1.620	0.580
	1 Nov 89	825	1.660	0.540
	10 Nov 89	721	1.640	0.560
	11 Nov 89	1514	1.600	0.600
	15 Nov 89	1515	1.600	0.600
	29 Nov 89	828	1.630	0.570
GWS3/5	5 Jul 89	758	1.590	0.529
	12 Jul 89	729	1.585	0.534
	19 Jul 89	813	1.700	0.419
	26 Jul 89	721	1.610	0.509
	2 Aug 89	719	1.620	0.499
	9 Aug 89	713	1.495	0.624
	16 Aug 89	709	1.630	0.489
	23 Aug 89	718	1.400	0.719
	30 Aug 89	703	1.580	0.539
	6 Sep 89	721	1.410	0.709
	13 Sep 89	747	1.675	0.444
	20 Sep 89	737	1.285	0.834
	27 Sep 89	734	1.640	0.479
	4 Oct 89	753	1.340	0.779
	1 Nov 89	815	1.360	0.759
	10 Nov 89	710	1.570	0.549
	11 Nov 89	1506	1.380	0.739
	15 Nov 89	1507	1.530	0.589

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS3/6	5 Jul 89	911	1.665	1.085
	12 Jul 89	848	1.645	1.105
	19 Jul 89	903	1.640	1.110
	26 Jul 89	817	1.630	1.120
	2 Aug 89	826	1.630	1.120
	9 Aug 89	811	1.615	1.135
	16 Aug 89	805	1.610	1.140
	23 Aug 89	818	1.610	1.140
	30 Aug 89	753	1.610	1.140
	6 Sep 89	819	1.620	1.130
	13 Sep 89	839	1.640	1.110
	20 Sep 89	832	1.650	1.100
	27 Sep 89	825	1.670	1.080
	4 Oct 89	843	1.700	1.050
	1 Nov 89	915	1.740	1.010
	10 Nov 89	807	1.670	1.080
	11 Nov 89	1551	1.640	1.110
	15 Nov 89	1554	1.650	1.100
GWS3/7	5 Jul 89	742	4.850	-0.140
	12 Jul 89	711	4.875	-0.165
	19 Jul 89	802	5.090	-0.380
	26 Jul 89	708	4.910	-0.200
	2 Aug 89	707	4.910	-0.200
	9 Aug 89	703	4.660	0.050
	16 Aug 89	658	4.980	-0.270
	23 Aug 89	708	4.435	0.275
	30 Aug 89	651	4.830	-0.120
	6 Sep 89	710	4.420	0.290
	13 Sep 89	737	4.990	-0.280
	20 Sep 89	723	4.140	0.570
	27 Sep 89	723	4.910	-0.200
	4 Oct 89	739	4.185	0.525
	1 Nov 89	801	4.160	0.550
	10 Nov 89	658	4.740	-0.030
	11 Nov 89	1455	4.310	0.400
	15 Nov 89	1455	4.740	-0.030

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS3/8	5 Jul 89	731	2.380	0.149
	12 Jul 89	701	2.445	0.084
	19 Jul 89	755	2.510	0.019
	26 Jul 89	701	2.550	-0.021
	2 Aug 89	658	2.450	0.079
	9 Aug 89	655	2.410	0.119
	16 Aug 89	651	2.470	0.059
	23 Aug 89	701	2.370	0.159
	30 Aug 89	643	2.430	0.099
	6 Sep 89	656	2.340	0.189
	13 Sep 89	726	2.525	0.004
	20 Sep 89	713	2.220	0.309
	27 Sep 89	714	2.500	0.029
	4 Oct 89	730	2.245	0.284
	1 Nov 89	750	2.220	0.309
	10 Nov 89	646	2.430	0.099
	11 Nov 89	1447	2.285	0.244
	15 Nov 89	1447	2.445	0.084
GWS3/9	5 Jul 89	711	1.110	1.300
	12 Jul 89	642	1.090	1.320
	19 Jul 89	741	1.085	1.325
	26 Jul 89	647	1.075	1.335
	2 Aug 89	643	1.089	1.321
	9 Aug 89	643	1.065	1.345
	16 Aug 89	639	1.065	1.345
	23 Aug 89	649	1.060	1.350
	30 Aug 89	631	1.065	1.345
	6 Sep 89	644	1.060	1.350
	13 Sep 89	712	1.080	1.330
	20 Sep 89	702	1.080	1.330
	27 Sep 89	702	1.100	1.310
	4 Oct 89	719	1.110	1.300
	1 Nov 89	736	1.180	1.230
	10 Nov 89	632	1.120	1.290
	11 Nov 89	1436	1.075	1.335
	15 Nov 89	1436	1.095	1.315
GWS4/1	6 Sep 89	902	8.820	1.339
GWS4/2	6 Sep 89	928	5.910	2.270
GWS4/3	6 Sep 89	910	17.570	1.600
GWS4/4	6 Sep 89	923	16.180	2.369
GWS4/5	6 Sep 89	936	14.320	6.639
GWS4/6	6 Sep 89	946	13.700	2.970

WEST BAY G/WATER STUDY

Water levels

Station No	Date	Time	Depth to water (m below datum level)	Elevation of water table (m above sea level)
GWS5/1	6 Sep 89	736	2.855	0.295
GWS5/2	6 Sep 89	909	1.100	1.259
GWS5/3	6 Sep 89	836	2.115	0.724

The demand for long-term scientific capabilities concerning the resources of the land and its freshwaters is rising sharply as the power of man to change his environment is growing, and with it the scale of his impact. Comprehensive research facilities (laboratories, field studies, computer modelling, instrumentation, remote sensing) are needed to provide solutions to the challenging problems of the modern world in its concern for appropriate and sympathetic management of the fragile systems of the land's surface.

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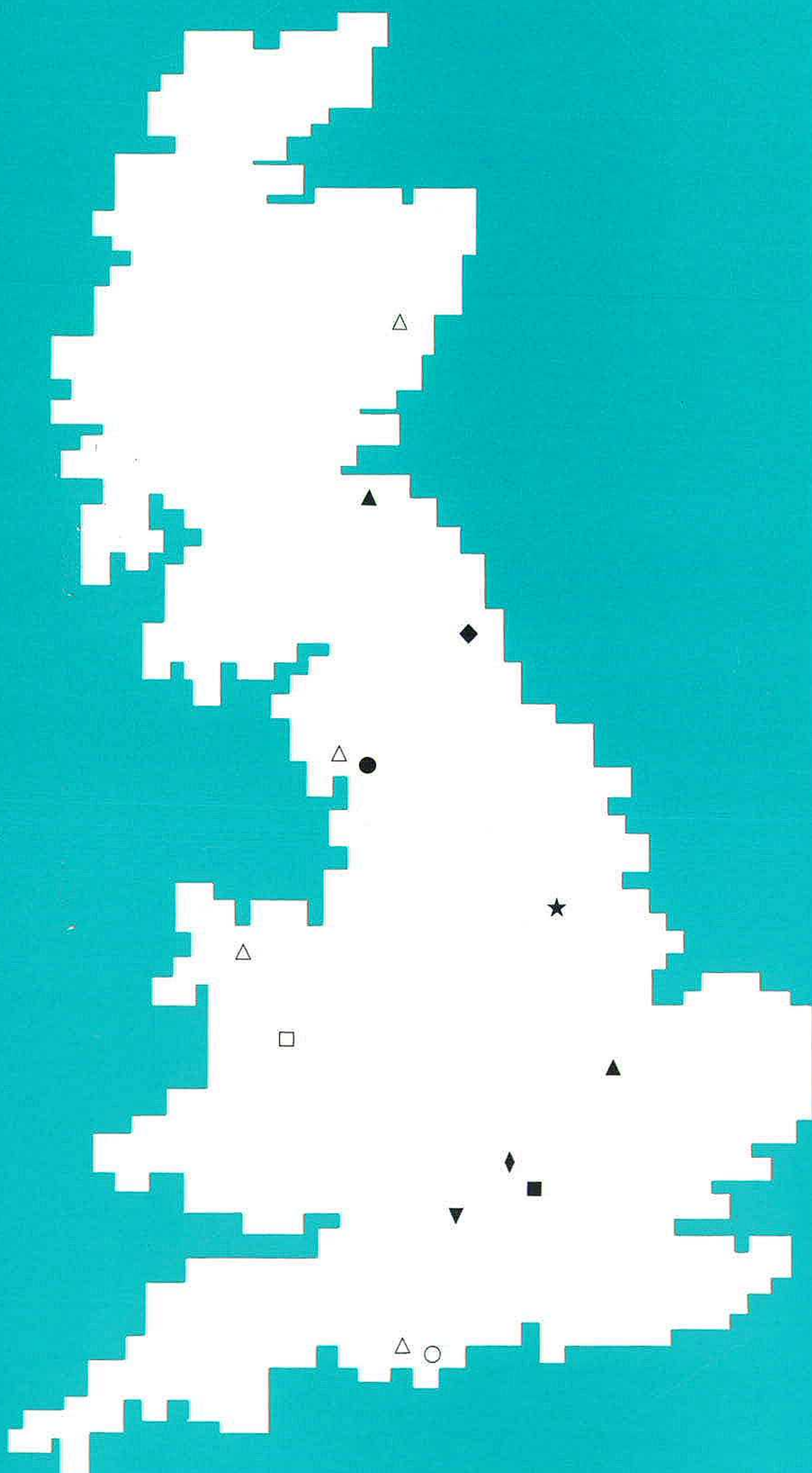

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