MUQDISHO WATER SUPPLY
EXPANSION
STAGE IIA
EXPLORATION AND MODELLING
STUDIES

VOLUME I

This report is prepared for

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SECTION 1

BACKGROUND AND RECONNAISSANCE STUDIES

1. THE WATER RESOURCES STUDY

1.1 INTRODUCTION

The present Muqdisho water supply is derived from a marine and aeolian sand aquifer lying between the sea and the Shebeelle River. Hydrogeological investigations carried out by Sir Alexander Gibb and Partners (Africa) and the Institute of Hydrology between 1977 and 1979 identified groundwater resources of 25 Mm^3/year (million cubic metres) within a limited area of the coastal plain in the close vicinity of the capital. The July 1980 Final Report indicated that additional resources from outside the original study area needed to be located and developed before 1990. Two alternative sources were proposed; groundwater from elsewhere on the coastal plain and/or surface water to be abstracted directly from the Shebeelle in a run of river scheme.

This report concerns the investigations carried out to locate and evaluate resources to satisfy demands in Muqdisho through to the year 2000. Terms of Reference for the study indicated that new sources of about 18 Mm^3/year would need to be commissioned by January 1990 with a further 18 Mm^3/year by January 1996. Implicit in the Terms of Reference was a preference for groundwater although it was recognised that adequate resources may not exist within reasonable distance of Muqdisho. Separate studies of surface water from the Shebeelle for potential supply to Muqdisho have therefore been made.

1.2 GROUNDWATER STUDIES

The 1977-1979 study concerned groundwater within the small area between Muqdisho and the Shebeelle river within the Afgooye and Balcad roads. Geophysics, drilling and pumping tests determined the nature of the aquifer here and led to the design of new wellfields. The hydrogeological evidence showed conclusively that the groundwater was derived mainly by recharge from the Shebeelle River but that the original study area was only part of a large regional hydrological system with important controls beyond the prescribed study boundaries. To assess aquifer recharge in that regional system our previous study made use of data derived from an earlier (1968) investigation of the Shebeelle[1]. Groundwater modelling techniques were employed to infer the quantities of recharge from the water table configuration and an assumed aquifer property distribution across the region.

This present study involves an updating of the hydrogeological information for the regional system covering an area extending from Aw Dheegle to upstream of Jawhar and from the coast inland to Wanleweyne. Our strategy first required the collection of post-1968 geological, water quality and piezometric data from existing sources for a review of the regional groundwater modelling made in the previous study. From this assessment a drilling programme of 14 trial wells and 2 pump test wells was available to support, enhance, or check on important facets of the regional groundwater picture. Our strategy, throughout, was to be based upon the concept of maximum use of sparse data through improved quantitative assessment of groundwater by modelling rather than by water balance. Specific proposals for new wellfield construction and the management of these relative to existing wellfields were then to be developed through more detailed modelling of part of that regional system.

Chapter 2 of this report discusses the preliminary modelling studies of the post-1968 data. This work clearly demonstrated that our understanding of either the regional groundwater configuration or the regional aquifer properties was inadequate. Our drilling and pump testing exploration (described in Chapter 3) was designed specifically to test the assumptions contained in this early analysis. It led directly to the recognition of perched water tables in places along the course of the River Shebeelle which appear to be separated from a deeper regional water table. This small but significant improvement in understanding led directly to successful modelling. Chapters 4 and 5 discuss the regional geology and the hydrogeology which provide the framework for these studies.

Section 3 is concerned with the main groundwater modelling. Chapter 6 deals first with models of the total study area, the

[1]Inter Riverine Agricultural Study, Hunting Technical Services, Nov 1977.

REGIONAL MODEL, in which relationships between the whole aquifer system and recharge are examined. In chapter 7 a more detailed model is presented of a smaller area, the STUDY MODEL, representing the region from which new groundwater supplies might be developed for Muqdisho. Finally a management model examining possible groundwater abstraction strategies is reported in chapter 8.

1.3 SURFACE WATER STUDIES

The broad objectives of these studies may be summarised as follows;

(a) To estimate the historic flows in the Shebeelle river and hence to study the total available surface water resources.

(b) To estimate present and future abstractions by other Shebeelle water users. The principal water abstractions are for irrigation purposes and consequently a study of present and future irrigation requirements was necessary.

(c) To estimate the possible range of future river flows available to the Muqdisho Water Agency after consideration of seasonal variations and the likely effects of upstream works and abstractions by other water users.

(d) To estimate the probable recharge from surface water to the deep aquifer system as an aid to the determination of the safe long term yield of the groundwater resources.

(e) To study the effects of the new offstream storage reservoir at Jawhar on the river regime. This is an extension of the studies described in (b) to (d) above but is considered as a separate topic because of the importance of this scheme on river flows in the lower Shebeelle.

Recharge from the Shebeelle is discussed in Chapter 5 although the main hydrological study is discussed in Section 4. Chapter 9 first summarises the groundwater resources before the main hydrological studies are reported in Chapter 10. Here the surface water potential for Muqdisho is discussed within the important setting of the overall River Shebeelle. Finally Chapter 11 concludes by examining the options offered by both ground and surface waters.

1.4 STUDY SETTING AND REMOTE SENSING

Climate, hydrology and geology combine to produce an unusual and complicated physiographic setting in Southern Somalia. In the vicinity of Muqdisho the annual rainfall is some 525 mm which occurs in two seasons, the 'Gu' from March to May and the 'Der' from September to November. Locally rain falls in isolated storm cells resulting in an extremely irregular distribution from place to place and from year to year. This local rain appears to have no important significance on the major water resources of the area contributing little to either groundwater recharge or to the main surface water of the area.

Our previous study showed that the River Shebeelle controlled by rainfall in the highlands of Ethiopia. This river is the main source of groundwater recharge. However, the river does not drain to the sea but runs parallel to the coast at Muqdisho obstructed by a wide belt of dune sands rising to an elevation of 200 m above sea level. The nature of the wide alluvial floodplain of the Shebeelle inland from the dunes, the position of the river relative to the dune sands along the margin of the floodplain, and processes of flooding and irrigation along the river are the important factors concerning water supply.

Landsat imagery has been used to define the regional setting, examine the physiography of the study area, and determine the extent of irrigation along the Shebeelle River. Cloud cover affects all Landsat data for this area with cumulus over large areas preventing time series analysis or detailed studies of specific flood events. Persistent thin but scattered clouds are present on even the best images obscuring parts of the Shebeelle and the coast. Imagery from 3 relatively cloud-free scenes has been used in the study (12 Feb 1973, 28 Nov 1978 and 7 March 1979). Computer processing of the February 1973 scene was made using an IDP 3000 system at the Space Department of the Royal Aircraft Establishment Farnborough. To provide a single image of the study area computer tapes from Landsat path 175 rows 58 and 59 were combined. Various enhancement techniques were employed to produce false colour composites and enlarged sub-images for detailed study as colour and black and white photographic prints. These are reported in Chapter 10.

A false colour composite (MSS bands 4, 5 and 7) is shown in Plate 1. Here colour contrasts are developed to show maximum detail of the Shebeelle valley and the areas of irrigation surrounding the main river channel (deep red). The principal features of the physiography are given on the overlay to show the regional setting.

Four geomorphological zones occur aligned parallel to the coast:

A. Beach sands and unstabilised dune sands

This narrow strip bordering the sea widens noticeably to the north-east of Muqdisho. Evidence is presented in Chapter 4 to suggest this may represent a recently emerged coastal area.

B. Stabilised Dune Sands

These occupy the tract of land between the beach sands and the alluvium of the Shebeelle flood plain. The major aquifer of the area underlies this zone which again widens to the north east from about 10 km to over 80 km with elevations ranging between + 30 m and + 200 m above sea level. The Landsat imagery shows much of this zone to be virtually devoid of any drainage features within the regional study area. However, to the northeast, between the Shebeelle upstream of Mahadday Weyne and the coast, the stabilised dune sand belt extends sharply inland. Here there is evidence of surface water and it appears that the Shebeelle in the recent past has encroached into the dune belt zone.

Within the dune belt the imagery clearly shows the effect of fuel wood de-forestation in the Muqidsho, Afgooye and Balcad area. On the image overlay we have shown the main area affected in 1973. Removal of the vegetation enhances the surface reflectance and increases soil albedo. Whilst not central to this water resources study recognition of such de-forestation is important since in this setting it could lead to the break-up of the stabilised dune sands. Small scattered patches occur elsewhere

IMAGE MADE BY SPACE DEPT. RAE FARNBOROUGH 18 NOV 82 00002

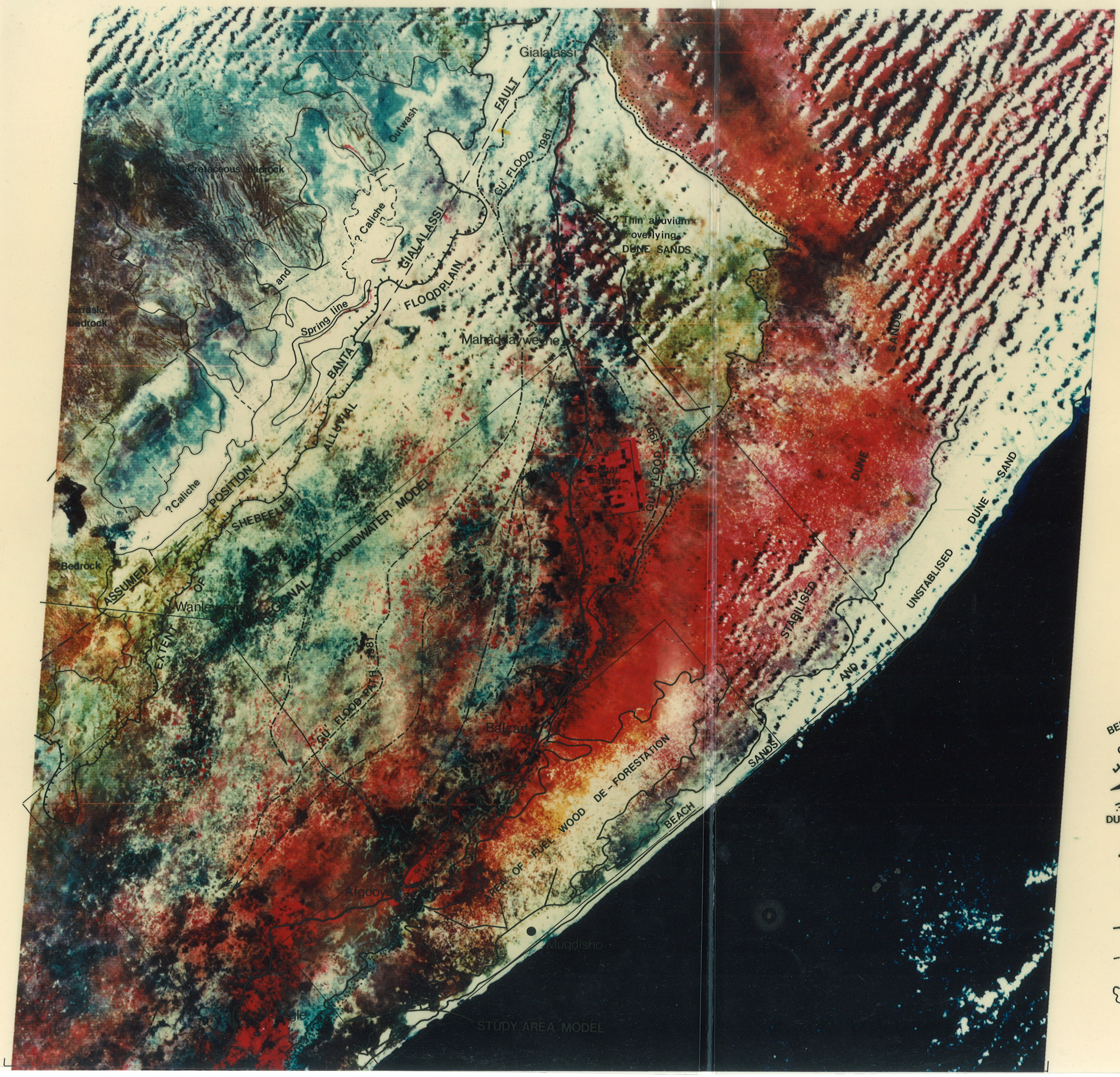


IMAGE OVERLAY

NASA LANDSAT-1 12 FEB 1973

COMBINED IMAGE FALSE COLOUR

PATH 175 ROWS 58/59 BANDS 4, 5, 7

KEY

BEDROCK & OUTWASH	Western extent	Alluvial floodplain
	Principal old river channels	
DUNE SANDS	Eastern extent	
	Main channel present day	

PHOTOGEOLOGICAL FEATURES

- Fault
- Minor lineation
- Principal geological boundary

in the dune belt zone. Casual inspection of more recent imagery does not suggest a serious deterioration of this 1973 situation but in view of dust storms in the Muqdisho area more detailed study could be warranted.

C. Shebeelle Alluvial Floodplain

The area of the satellite image presented in Plate 1 has been chosen to show the floodplain beyond this report's study area. The setting is important in order to appreciate the role of the Shebeelle as the source of water to the Muqdisho area.

The river enters the image at Gialalassi in the north within a narrow floodplain contained between the extended dune sand area to the east and the hard rocks of the interior. Downstream of Gialalassi the floodplain expands rapidly to over 50 km width apparently at the expense of dune sands and we must assume that the river whilst running about parallel to the coast is in fact moving seawards slowly eroding the dune sand area and depositing clays and silts.

Currently the main channel of the River Shebeelle transgresses the floodplain from Gialalassi to some distance downstream of Jawhar. Here contained within the main area of alluvium the river is isolated from the dune sand aquifer. For a distance of 10 km upstream and downstream of Balcad the river is in close proximity to the dune sand area, almost in direct contact with the permeable sand aquifer. In places the river is contained in an alluvial lined channel within a disected dune belt. Our hydrogeological studies indicate this to be the main area of groundwater recharge to the coastal aquifer.

Within the image the course of the present day river is picked up mainly through the vegetation - both natural and irrigated along the banks. Old channels of the river show up clearly in places on the image. Several general channel alignments are shown on the image overlay marking the general trend of water courses which are in detail characterised by extensive meander belts. It is noticeable that the present-day channel does not meander to the same extent and also in places there are quite clearly large and small scale meandering river courses.

These are also picked up by vegetation growing in or immediately around the channels. Some of these old channels appear still to carry flood waters from the Shebeelle following breaching of bunds. Two channels active in 1981 following intentional breaching of the flood bunds prior to the arrival of the 'Gu' floods in May are shown on the overlay. These have been reconstructed from information provided by Gemmel (FAO Report TCP/SOM/8906 and 0104, May 1982) and by inspection of enlarged images. The main flood diversion flowed for over 120 km through old channels along the middle of the floodplain. A second flow bypassed Mahadday Weyne to flow towards low depressions near the sand dunes in the vicinity of the Jawhar Offstream Reservoir.

These serve to illustrate the dynamic nature of the floodplain and the difficulty of interpreting surface water information. Clearly one flood path removed water from the main channel and from the system which might benefit Muqdisho either directly as surface water or indirectly by recharge. The smaller flood path whilst depleting the main river channel may well have served to provide an unexpected recharge to the dune sands.

D. Hard rocks of the interior

The northwestern area of the image shows the hard rocks of the interior and patterns of peripheral drainage into the floodplain. Here the image shows a zone between the floodplain and the main hardrock area of outwash deposits, probably an extensive springline and associated surface carbonate deposits. The image fails to provide any direct evidence for the major geological structure of the area, the Banta-Gialalassi fault. This structure down throwing some 4 km on the seaward side is believed to control the northwestern boundary of the floodplain. Its approximate position has been marked on the overlay beneath the outwash and caliche area. Sub-parallel lineations, almost certainly faults, are visible in the hard-rock area but no direct evidence for the main fault location is visible in the imagery.

1.5 STUDY BOUNDARIES

This report is concerned with the hydrogeology of 10,400 km^2 extending 130 km along the coast, centred approximately on Muqdisho, and inland for 80 km. This corresponds to the regional groundwater model of our 1980 study. However, instead of having to rely on published information we have now been able to collect new data by visiting existing boreholes and drilling at important points. We have again assessed the groundwater situation in this area through a REGIONAL GROUNDWATER MODEL. Area boundaries are shown on the Landsat image overlay (Plate 1) to show the setting relative to the physiography.

The important area where the River Shebeelle is in close proximity to the dune sand area at Balcad is located centrally within the model area. The coastline forms a natural southeastern limit and we have established the northeastern and southwestern extent sufficiently far upstream and downstream of Balcad to minimise model boundary problems. Inland a relatively arbitrary boundary has been taken between Wanleweyne and Mahadday Weyne to include a significant part of the alluvial plain. We have deliberately not extended the study to the inland edge of the floodplain since the existing data sources were inadequate to cope with apparently complicated geological, surface water and groundwater conditions in the vicinity of the presumed Banta-Gialalassi fault. Instead our limited drilling exploration has been contained in the area of greatest concern nearer the Shebeelle.

Again this report follows the procedure established in 1980 by considering in greater detail the groundwater resources and their management in the immediate vicinity of Muqdisho. This is also shown in Plate 1 as the STUDY AREA MODEL, covering 2,550 km^2, reaching 85 km along the coast and inland for 30 km. This model extends from the sea to the river to include the main aquifer and its principal source of recharge. By comparison with 1980 we have extended the model area to the northeast to allow new aquifer abstraction to be simulated between Muqdisho and Jawhar.

Surface water studies are also contained primarily within the reach of the Shebeelle shown on Plate 1. Hydrological data exist at the principal towns given and are discussed.

1.6 SUMMARY OF FINDINGS

The results of the groundwater modelling suggest that aquifer recharge from the river is in the order of 70 M m^3/year. Independent estimates made from our surface water studies suggest recharge is between limits of 42 to 160 M m^3/year with a best estimate of 82 M m^3/year for the same area (20 km upstream of Jawhar to 35 km downstream of Afgooye).

The surface water estimate takes account of recharge from a large number of irrigation schemes recently developed along the river. We believe much of this water is held in perched aquifers and has not yet influenced the main water table. The configuration of this main water table used in our modelling is influenced by long term river bed infiltration, historic overbank flooding and perhaps the long established irrigation schemes. This we believe explains the small differences between the two quite independent recharge estimates.

During the investigation we have considered the question of detailed study of the perched water table condition which our exploratory drilling so clearly demonstrated at Jawhar. The sparse data concept of the exploration phase of this study precluded any more detailed investigation of this component of the groundwater system. There is clearly insufficient existing information to model this phase either separately or in conjunction with the main groundwater model since we have little information concerning the dimensions of the perched water bodies or in fact whether or not they will eventually recharge the main groundwater body. However we are satisfied that our approach to the resources represents a realistic but conservative attitude with regard to groundwater.

Water demands at source in Muqdisho have been estimated to grow as follows:

Year	Annual Demand at Source (million m^3/year)
1980	7.5
1985	17.7
1989	24.5
1995	39.6
2000	57.4

Clearly by the year 1995 the water demands begin to approach the lower limits of our estimated recharge from the River Shebeelle.

Our findings suggest that groundwater alone might meet the water demands of Muqdisho to the year 2000. However, our modelling studies which have examined the consequences of such large abstractions beyond this date to the year 2020 suggest that this may not be appropriate. Control of the saline interface between the sea and the wellfields and also the presence of poor quality water in the alluvium aquifer is central to the long-term groundwater potential. We believe there may well be difficulties in this respect after the turn of the century if groundwater alone is developed.

Overall the position is surprisingly complicated and no clear cut decision on groundwater appears since there are factors other than water resources which seem to have a direct bearing upon the long-term aquifer performance. For example currently there is very limited sewage and waste water removal in Muqdisho. This will produce significant artificial recharge of untreated water between the sea and the wellfields which if allowed to continue provides an unexpected advantage producing control of the saline interface and thus allowing larger and more prolonged inland abstractions than were originally envisaged. Furthermore there are water quality considerations inland which need also to be examined with and without waste water recharge at Muqdisho. This we refer to as a northern boundary constraint.

We have found it useful to present the various options for groundwater in the form of decision matrices. These allow the consequences of pumping from the aquifer at the annual requirements for each year from 1989 to 2000 to be considered through to the years

2010 and 2020. The consequences of pumping with and without recharge at Muqdisho on both the coastal saline intrusion and the northern boundary constraints are considered.

With regard to the coastal saline interface we conclude that Muqdisho water requirements up to the year 2000 could be met from groundwater providing artificial recharge of imported water continued at the capital. With waste water removal and hence no artificial recharge rapid inland movement of the saline interface requires abstraction to be limited to the 1992 demand level of 31 M m^3/year in order to preserve the aquifer to the year 2020.

The effect of the northern boundary water quality constraints appear more severe. Groundwater alone cannot meet demands above 46 M m^3/year (the 1997 demand) without serious consequences by the year 2020. Indeed we find that by 2010 abstraction at the 1997 level of demand would be only provisionally acceptable.

Surface water availability for Muqdisho is controlled by seasonality of flow in the Shebeelle. The shortfall between the existing 25 M m^3/year from groundwater and the year 2000 demand is 32 M m^3 or approximately 1 m^3/sec. Our analysis suggests that historically the river would not have been able to supply such a demand throughout the whole year. However it could have met the requirement for 95% of the time during the months of April to May and July to November.

To assess future surface water availability a simple model was used to predict the consequences of the operation of the Jawhar Offstream Storage Reservoir and the increasing irrigation demands. The most important result is that the availability of a surface flow capable of sustaining a 1 m^3/sec offtake is very much reduced. At Afgooye and Balcad there are respectively approximately a 40 per cent and 25 per cent reduction in the historic flow duration.

The surface water studies conclude therefore that although there are considerable seasonal resources available at both Balcad and Afgooye these could only be useful as part of a conjunctive use scheme with additional groundwater.

2. RECONNAISSANCE STUDIES

2.1 INTRODUCTION

In our previous study reported in March 1980 we demonstrated that recharge of groundwater in the vicinity of Muqdisho derived mainly from the River Shebeelle. However we could not directly measure the total quantity of recharge or its distribution along the river. Instead we made use of groundwater modelling techniques to infer the quantity of recharge from aquifer property and water table information. The work comprised two separate models. The main modelling was of the Muqdisho-Afgooye-Balcad study area using information from the recent drilling and test pumping exploration. To establish important boundary conditions for this we first produced a simple regional model of a much larger area using earlier information from a 1969 study (Project for Water Control and Management of the Shebeelle, Hunting Technical Services and Sir M. MacDonald and Partners).

Our present investigation began with a re-survey of that regional study area. Sources of information were researched in Muqdisho and all wells and boreholes which could be located were visited to collect up to date information on water levels and water quality. This reconnaissance data was used to extend and modify the original regional groundwater model. Our strategy intended to complete the regional modelling before new exploration began in order to focus drilling and test pumping in the main areas of possible additional groundwater resources. However in the event we were unable to produce a satisfactory model of the regional area. During a series of 14 model formulations it was found impossible to reproduce accurately the apparent groundwater configuration or to identify with certainty the precise data problem. Consequently our drilling and test pumping strategy was adjusted and two boreholes were required to resolve the problem and allow re-interpretation of the data for subsequent modelling. This second and major phase of modelling followed after completion of the full drilling and test pumping programme. The information collected is presented in the various appendices and forms part of the main hydrogeological interpretation. Similarly the mathematical basis for the modelling and the detail of the calibrated regional model are contained within chapter 6. Here we wish to record in broad outline this phase of the work and indicate the significant contribution of the early modelling phase to the later field studies.

2.2 FIELD RECONNAISSANCE

During September and October 1982 an extensive search for borehole information was made. Records of over 100 wells and boreholes were obtained for the regional study area. The following sources were visited:

Muqdisho Water Agency
Water Development Agency
Libraries of United Nations Development Programme
Ministry of Planning
Ministry of Mineral Resources and Water Affairs.

Few new records were obtained for the dune sand area between the Shebeelle and the coast and in particular it was evident that very little drilling had occurred between Balcad-Jawhar and the sea. Existing records suggested a fairly uniform geological and hydrogeological condition with the sands gradually being replaced by limestones at the coast. Groundwater seemed to be present at depth everywhere along the coastal province but water quality appeared to deteriorate outside the Muqdisho-Afgooye-Balcad area. Drilling between Balcad-Jawhar and the coast was clearly an exploration priority.

Many of the borehole records related to sites in the alluvial plain of the River Shebeelle. Documentation was not good. In particular site information was poor, many useful geological records could not be located, whilst several borehole sites visited could not be correlated with existing records. Broadly the geological data indicated thick clay sequences alternating with thinner layers of water bearing gravels, sandy gravels and clayey gravels. Inland, toward the hardrock areas to the west, gravels and coarse sands from local erosion and outwash increased in importance. Little if any evidence was available regarding the nature of the boundary between the alluvial plain and the coastal sand dunes. No evidence was found to suggest that the Shebeelle had flowed directly to the sea. Instead the river appeared to be eroding along the edge of the dune sands when the river meandered toward the southeast margin of the floodplain.

Perhaps the most significant aspect of the alluvial plain reconnaissance related to the regular reporting of gravels in borehole records. Although relatively thin by comparison with the sands of the coast, a higher permeability and hence an important hydrogeological significance was implied. However the occurrence of intercollated gravels and clay outside the obvious zone of hardrock erosion was difficult to explain. An examination of old drill sites failed to indicate any true gravel pebbles in spoil heaps and a closer examination of drilling records suggested that loosely cemented sands rather than true gravels could equally well occur at depth. This provided a second exploration target, to check on the lithology and establish the aquifer properties of these deposits through pumping tests.

2.3 REGIONAL GROUNDWATER LEVELS

The reconnaissance survey broadly confirmed the regional piezometry used in our earlier modelling studies. Groundwater elevations were highest beneath the river reaching a maximum elevation of + 95 m upstream of Jawhar. Downstream the groundwater elevation declined beneath the river to about + 30 m at Afgooye, but formed a second mound at about + 50 m between Afgooye and Aw Dheegle.

Away from the river groundwater levels fell indicating flow not only toward the sea but also inland into the alluvial plain. Beneath the alluvial plain a groundwater basin was confirmed. The reconnaissance provided only minor modifications to the 1969 regional picture with no evidence of any recharge source to the groundwater system other than the river.

2.4 PRELIMINARY MODEL FRAMEWORK

The basis for the computer model was a 13 x 8 (10 km) grid aligned parallel to the coast and centred on Muqdisho. Thus 104 grid points represent a modelled area of 10,400 km^2. A steady state unconfined situation was simulated using an inferred recharge method developed by the Institute for sparse data arid zone groundwater problems. The technique depends upon allowing recharge only in certain known areas. By allocating water level elevation and aquifer transmissivity throughout the grid the model then computes the recharges which best match these water level and transmissivity data. Fuller details are given in Chapter 6.

For the preliminary modelling water levels were obtained by superimposing the model grid upon a water table map and determining a representative level at 104 points by inspection. Saturated thickness and aquifer permeabilities were similarly derived from geological information to give transmissivity throughout the grid. Thirteen grid squares across the model simulated the Shebeelle as inferred recharge nodes. Output from the model comprised a prediction for each of these river nodes as an average annual recharge. Additionally a model water level was computed for each grid node and given as a water level elevation. This allowed the model water table configuration to be compared with that from the field observation. An additional calibration check was obtained using a quantitative measure of the quality of fit across the model between the observed water levels and those predicted. This was expressed as a root mean square error.

Model studies were originally planned to examine two facets of the river recharge regime. Firstly the reconnaissance had shown a very broad groundwater mound at Jawhar which suggested a possible component of offstream recharge beneath the main sugar cane irrigation area. This was to be tested through the addition of an extra inferred recharge node. Also there was evidence to suggest that between Aw Deegle and Afgooye a perched water table existed with the regional groundwater elevation at only + 20 m rather than + 50 m. It was anticipated that the initial transmissivity estimates derived from the geological data would need to be adjusted to reproduce the best water table configuration whilst the alternative recharge options would be assessed through the best root mean square error.

2.5 MODEL RESULTS

Four early model runs produced fairly high but not unacceptable root mean square errors. The best fit was obtained assuming a perched water at Aw Dheegle and offstream recharge at Jawhar. However the model failed to represent the main feature of the water table configuration, the recharge mound beneath the river or any of the 4 recharge options. Water levels were depressed at river nodes and a groundwater mound was produced within the area representing the river floodplain. This was clearly unacceptable.

Through a series of 10 more model runs adjustments were made to the transmissivity values. These were based upon reassessment of whole or selected parts of the grid through adjustments to boundary conditions, and reassessment of the geological basis for the allocation of permeability or saturated thickness of the aquifer. At no stage were we able to reproduce a groundwater mound beneath the entire length of the river. Also it became evident that no systematic improvement in the position of the modelled groundwater mound could be achieved concurrently with an improvement in the root mean square error. The model was evidently relatively insensitive to transmissivity but very dependent upon either the allocation of inferred recharge nodes or to head distribution. Table 2.1 summarises the main features of the various model runs.

Sensitivity to the inferred recharge node distribution was examined by allowing all model nodes to behave as recharge sources. A very close match of water table configuration with virtually no prediction error was inevitable in this case. However the magnitude and distribution of the inferred recharges predicted around Jawhar were unacceptably large suggesting either that here the water table elevation was too high, or that the hydraulic gradients were too steep. This raised the possibility of a perched water table in the Jawhar area of a similar nature to that suspected between Aw Dheegle

TABLE 2.1 PRELIMINARY MODELLING - SUMMARY

RUN No.	TRANSMISSIVITY ARRAY	AW DHEEGLE-AFGOOYE WATERTABLE (m.a.s.l.)	JAWHAR OFFSTREAM RECHARGE	ROOT MEAN SQUARE ERROR	NUMBER OF RIVER NODES FORMING RECHARGE MOUND
1	Best Hydrogeological	20-23	No	7.23	6
2	" "	40-55	No	8.57	7
3	" "	20-23	Yes	7.10	6
8	" "	40-55	Yes	8.42	7
4	Uniform T = 1000 m^2/d	20-23	Yes	6.53	4
5	)Best Hydrogeological)but lower T at Jawhar	40-55	No	9.12	7
6	)and Aw Dheegle	40-55	Yes	8.41	5
7	Coastal T = 1500 m^2/d Alluvium T = 300 m^2/d	40-55	Yes	7.47	8
9	As 7, T = 10 m^2/d Aw Deegle	40-55	Yes	6.91	8
10	Alluvial T = 500 m^2/d	40-55	Yes	7.42	7
12	Alluvial T = 1000 m^2/d	40-55	Yes	7.01	7
13	Alluvial T = 1500 m^2/d	40-55	Yes	6.56	7
14	Alluvial T $\geqslant$ 1500 m^2/d	40-55	Yes	6.94	7
11*	As low 7	40-55	Yes	0.12	13

*RUN 11 - All nodes behave as recharge nodes. River recharge mound fully simulated.

and Afgooye. Alternatively there was a possibility that a model error existed due to the very steep hydraulic gradient across a few model nodes between Jawhar and the sea.

At this stage exploration drilling was about to begin. The first drill site was moved therefore to the centre of the recharge mound at Jawhar and the work designed specifically to test for perched aquifer conditions. A second drill site was allocated to explore the true nature of the gravels or cemented sands within the alluvial area. This comprised a further check on overall regional model concepts.

Whilst drilling was underway the form of the inferred recharge model was adjusted to take account of the actual water level data points (the observation boreholes), rather than just interpolated grid values. This was seen as a safeguard for later modelling if the exploration drilling failed to disclose a large interpretative error.

In the event the first exploration borehole clearly demonstrated a significant perched water table at Jawhar. A recharge mound was shown to exist beneath the river in a deep regional groundwater system but separate from shallow irrigation recharged groundwater. The difficulties of the preliminary model had arisen from over-estimating the height of the groundwater levels in this area. It resulted in hydraulic gradients which were too steep to allow the regional groundwater configuration to develop within the range of possible transmissivities.

SECTION 2

EXPLORATION PROGRAMME AND HYDROGEOLOGY

3. THE EXPLORATION PROGRAMME

The results of our reconnaissance and preliminary modelling work highlighted several key aspects of the hydrogeology that demanded specific investigation. These included:

(a) the nature of the contact between the sand and alluvium formations

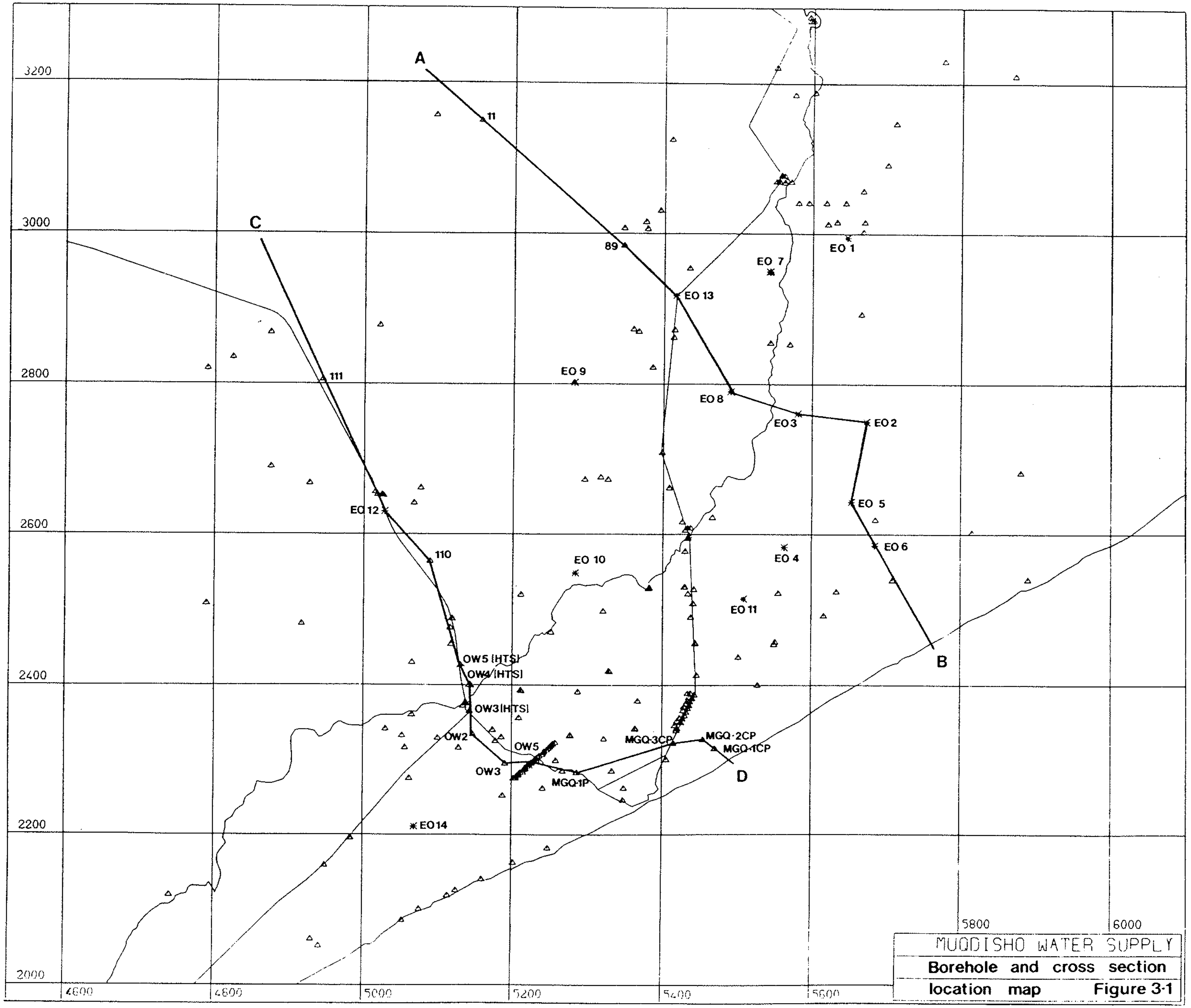
(b) the hydrogeological relationship between the perched aquifers and the regional water table

(c) the depth to the base of the main aquifer within the expanded area of study.

In order to realise these objectives exploratory boreholes were drilled at the fourteen sites labelled E0 on figure 3.1. Depths ranged from 150 to 285 metres with the exception of E07A which was drilled to 29 m. The lines of section A-B and C-D are discussed in Chapter 4 and the triangles indicate the positions of all the boreholes which are included in our data base.

Although difficult to recognise from the drilling return samples an attempt was made to terminate the boreholes in a plastic red-green clay. Because of the techniques being employed clay samples during drilling were difficult to recover. However a sharp decrease in the rate of penetration was taken to be indicative of the formation especially as the clay could be recovered from the drill bit. In addition to measuring the rate of penetration during drilling, disturbed formation samples were collected every metre and on completion of the drilling electric (single point resistivity and self potential) and gamma logs were run in the fluid filled hole. Details of the borehole construction and these logs are presented in Appendix A.

All the exploration boreholes were completed to ground level using 102 mm UPVC casing and 0.4 mm slotted screen with a sediment trap. The screen was normally a single 12 m length and surrounded



MUQDISHO WATER SUPPLY

Borehole and cross section location map **Figure 3·1**

with a filter pack of crushed Bur Acaba gravel. The top 6 m were sealed with a cement grout between the PVC casing and a 250 mm steel conductor casing installed at the start of drilling.

The boreholes E07 and E01 were constructed in a different way in order to examine the regional piezometric surface in areas of suspected perched conditions. In these boreholes a bentonite seal was placed above the filter pack and then the boreholes were backfilled with cement grout to the surface. There are several shallow wells in the Jawhar sugar estate where E01 was located so that the shallow and deep water levels could be determined. At E07 there was no convenient shallow well so borehole E07A, was drilled to a depth of 29.6 m.

As part of the exploration programme two aquifer tests were performed at sites E07 and E09 on the alluvium and one test on the sand in the Afgooye Road Wellfield at PW21. Each test well was constructed about 30 m from the observation borehole with the 12 metre length of 0.4 mm slot wire-wound screen positioned at the same depth as the observation borehole screen. The test data from the three sites are given in Appendix B and the results discussed in Chapters 5 and 6.

The locations of the exploratory boreholes were selected to investigate specific problems. In addition to the two sites examining the perched aquifers four more sites investigated the alluvial sequence. Two sites, E03 and E010, were drilled to examine the contact between the sand and alluvium and the remaining sites were all on the sand examining areas of potential abstraction.

To supplement the chemistry and stable isotope sampling programme carried out as part of the reconnaissance survey a further 20 chemistry samples and 14 stable isotope samples were taken from the exploratory boreholes and the river at Balcad and Afgooye. The results of the analysis are given in Appendix C and discussed in Chapter 5.

4. REGIONAL GEOLOGY

4.1 INTRODUCTION

The study area lies coastward of the Banta-Gialalassi fault within part of the coastal geological province of S.W. Somalia. Extending sub-parallel to the coastline the fault is situated between 90 km and 110 km inland. To the northwest of the fault uplifted folded and eroded Jurassic, Cretaceous and Tertiary limestones, marls and sandstones crop out and almost encircle a pre-Cambrian basement ridge of granites and gneisses (Figure 4.1). In contrast, on the downthrown southeastern side, continued subsidence has allowed the accumulation of a massive thickness of sediment ranging from Jurassic to Recent in age. Because of continued subsidence the older strata are hidden from view so that only Quaternary and Recent sediments crop out.

Our investigation has been restricted to the top 300 m of this sedimentary sequence and consequently we are likely to be dealing with strata no older than Pliocene. Within the study area are sediments of aeolian, fluvial and marine origin. The essential features of the succession are shown in Figure 4.3.

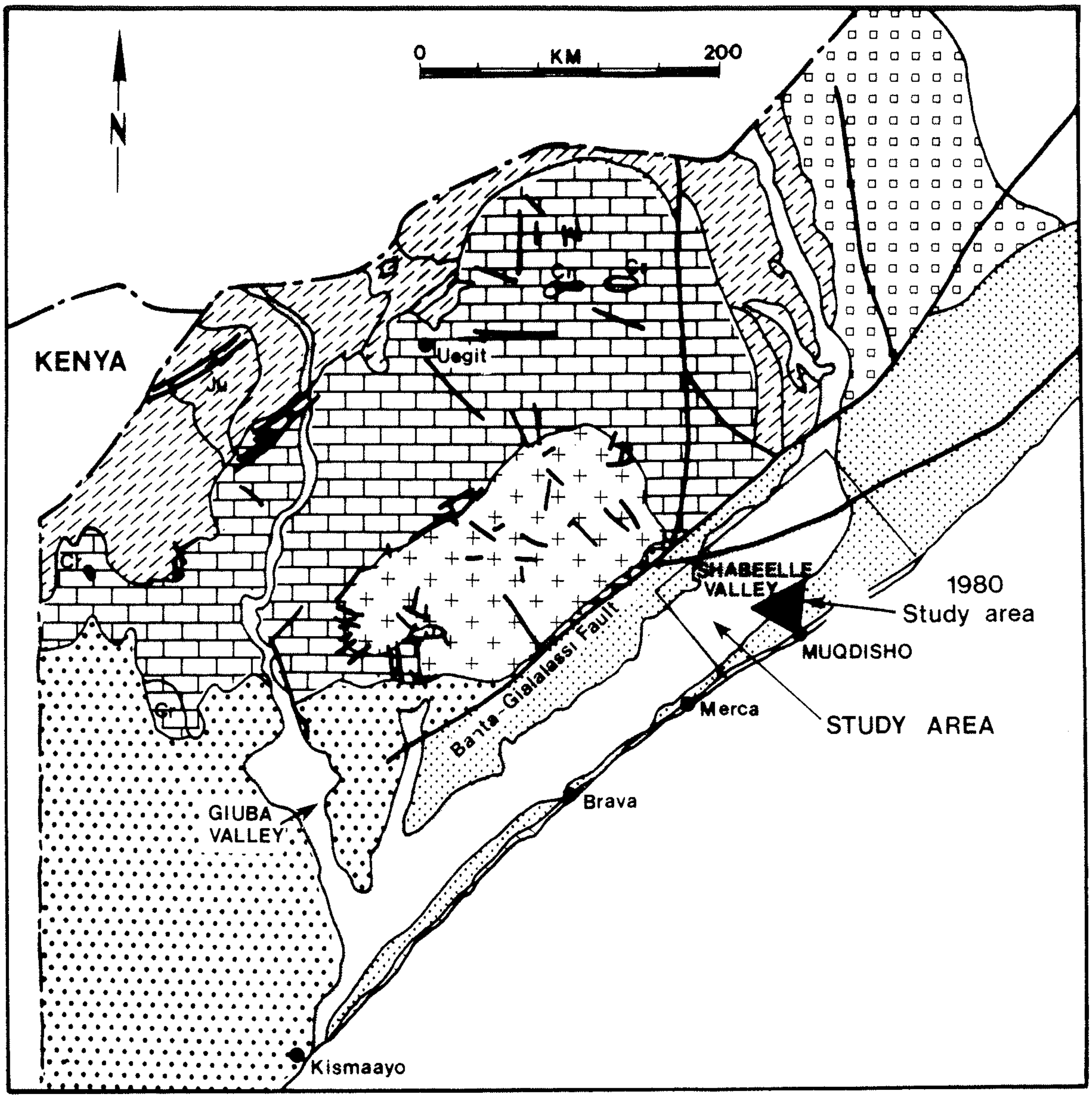
A series of limestones, sands and sandstone of both marine and aeolian origin underlies the coastal zone for distances between 20 and 55 km from the coast. Further inland the succession gives way both vertically and laterally to the thick alluvial sequence of the Shebeelle flood plain. At its widest the plain stretches for 75 km to its north western boundary the Banta-Gialalassi fault.

In the following sections we describe the lithology and distribution of the major formations and put forward a generalised geological history.

4.2 RED-GREEN BASAL CLAY

A relatively thin but persistent red-green clay appears to

GEOLOGICAL PROVINCES



LEGEND

Giuba and Shabeelle Valleys	Quaternary		Coastal Province
Benadir Coastal Plain	Tertiary – Quaternary		
Lower Giuba Plain	Tertiary – Quaternary		
Coastal Belt	Tertiary – Quaternary		
Oddur Border Plateau	L.Cretaceous – U.Jurassic		Inland Province
Cretaceous Border Region	U.Jurassic – Cretaceous – L.Tertiary		
Mudugh Plateau	L.Tertiary		
Bur Region	Pre-Cambrian		

ADAPTED FROM "INTER RIVERINE AGRICULTURAL STUDY"
FINAL REPORT: HUNTING TECHNICAL SERVICES, NOV 1977

Figure 4·1

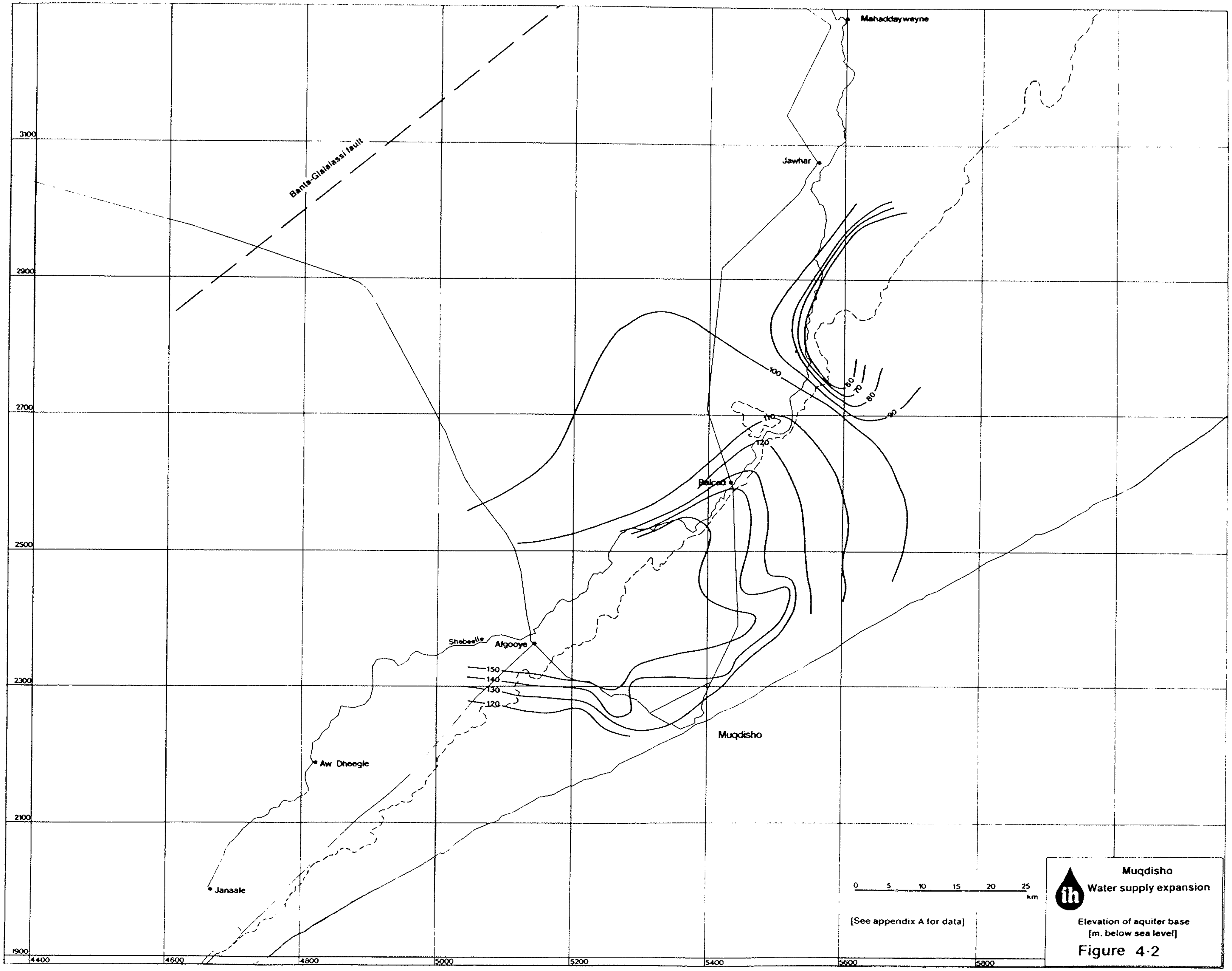
underlie the regional study area and acts as a lower aquiclude to overlying aquifers. It is most easily recognised beneath coastal marine/aeolian sands where it presents a clearly-defined contrast with overlying sediments, but beneath the alluvial plain within a dominantly clay succession it is more difficult to identify. In this region we have had to rely to some extent upon rate of penetration logs as a guide to its position since, when encountered, the clay invariably slows down the drilling rate significantly.

At most sites, because of the difficulty of drilling, the clay has only been partially penetrated. Where it has been fully penetrated, as at E012, MGQ 9P and 5.5TW (Parsons Corporation borehole), the thickness ranges from 6 to 15 m. Borehole MGQ 9P penetrated the clay to prove 50 m of fine-grained light-brown sand below, whereas at E012 a 90 m thickness of chocolate-brown mudstone with occasional sand horizons was encountered. Elsewhere the geology below the aquiclude is not known.

Although there is no palaeontological evidence to confirm this a shallow marine or lagoonal origin seems likely. Figure 4.2 shows the elevation of the top surface of the clay to be variable. Whether this variation reflects ancient sea-bed topography or has resulted from post depositional earth movements is uncertain; however, it has led to the development of several distinct topographic features. These are important, and have a bearing upon the transmissivity distribution used in our model studies. The main features comprise:

1. Within the Balcad, Afgooye, Muqdisho triangle a distinct "trough" is present where elevations fall to below -150 m. It is this feature that partly accounts for the high transmissivities in this region. Toward the coast the elevation gently rises to above -120 m, as it also does to the northeast and southwest. Inland, however, there is a rapid rise in elevation to -110 m approximately along the present line of the Shebeelle.

2. To the east of the river between Balcad and Jawhar is a poorly-defined region with elevations higher than -150 m, where subsidence has apparently been less intense than elsewhere.



Muqdisho
Water supply expansion

Elevation of aquifer base
[m. below sea level]

Figure 4·2

3. Over the alluvial floodplain the small amount of data available points to a uniform elevation of approximately -100 m.

4.3 THE LIMESTONES

From the coast, where they attain a thickness of over 120 m, a series of arenaceous and bioclastic limestones wedge inland for a distance of up to 14 km. They form a variable sequence of hard to soft, white and buff arenaceous and bioclastic limestones, which pass down into grey hard bioclastic limestones becoming marly at the base. Bioclasts are commonly bivalve and coral fragments, though in the grey limestones sharks teeth, vertebrae and formanifera are also present.

Where the limestone sequence is fully penetrated (eg. MGQ-9P, 1P, 2CP and 8P) it usually passes abruptly into a monotonous series of medium and fine-grained light-brown or occasionally pale-green sands. In turn, these pass into the lower aquiclude. Laterally and upwards there is a gradation into buff variably-cemented calcareous non-fossiliferous sands and sandstones.

There is little doubt that the limestones are marine and mark the southeastward migration of the present coral reef in response to a continued marine regression. In general the poorly-fissured nature of the formation together with the lack of intergranular permeability make this an aquifer of only moderate potential and less productive than the enveloping sands and sandstones.

4.4 THE BUFF SANDS - THE MAJOR AQUIFER

Inland, the limestones grade laterally and vertically into a thick (up to 160 m) series of buff-coloured sandstones which constitute the major aquifer within the study area (Figure 4.3). Typically the sandstones are fine (0.1 mm - 0.25 mm) to medium grained (0.25 - 0.5 mm) with the quartz content varying between 70-90 per cent. Grains are rounded to subangular and set in a carbonate matrix. Although the degree of cementation is on the whole poor and samples generally friable, well-cemented horizons of indeterminate

Lines of geological section

[See Figure 3.1 for locations]

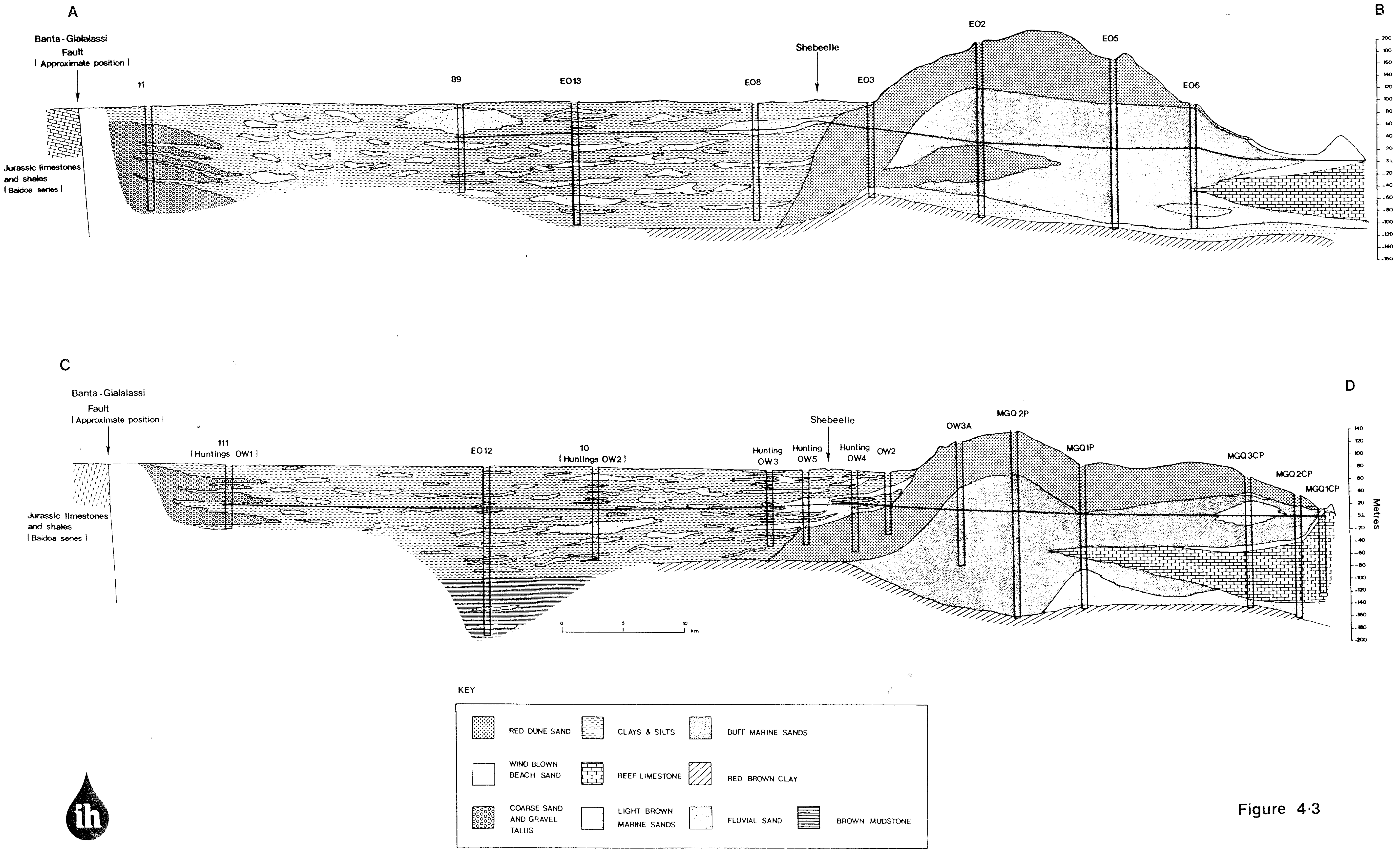


Figure 4·3

the recently emerged land has been progressively blanketed by the wind blown and re-worked beach sands while inland the red dunes represent a much older formation.

These older red sands sweep inland for distances of 25 to 50 km before plunging beneath alluvial deposits of the Shebeelle flood plain to wedge out rapidly within a distance of 10 km (Figure 4.3). In this way they separate the buff sandstone/limestone sequence from the alluvium.

The sands which are predominantly quartz, are wind-blown, red, fine to medium grained, well sorted and have a poor iron oxide cement. Occasionally the red colour becomes red-brown or even brown such as at E02 and E03, but this is atypical of the sequence. Thicknesses range from a few metres near the coast to a maximum of over 80 m in the central part of the area (MGQ-1P).

Generally the sands lie above the water table and are consequently of limited hydrogeological importance, but in places (MGQ 11P, 13P, 5P and E02) bands of red sand are interbedded with the buff sandstones below the water table. At these points, because of poor cementation, the sands form good aquifers.

From the evidence of sections it appears the formation has been deposited as a belt of wind-blown dune sands built up between the Shebeelle and the coast and has always provided a barrier preventing the river from discharging at the coast in the vicinity of Muqdisho. Continued marine regression has caused the eastward migration of the dune belt and the expansion to its present size.

4.6 THE ALLUVIAL SEQUENCE

The alluvial plain of the Shebeelle is confined between the northeast southwest trending Banta-Gialalassi fault and the inland margin of the red aeolian dune sands that sweep in from the coast. Broad and featureless the plain fans out downstream from Mahadday Weyne, sloping gently to the southwest, to reach a maximum width of 75 km.

thickness are commonly present. Despite being friable the sandstones are sufficiently consolidated to form aggregates and make grain size analysis of limited value.

There is little variation in lithology except near the base where light-brown fine to medium grained poorly-cemented sandstones are developed especially beneath the coastal limestones (Figure 4.3). In other areas (eg. MGQ-1P) the lower 50 m takes on a pale green colour.

Fossil remains are extremely rare throughout but where present comprise small broken fragments of coral and bivalve though recognition is not always possible.

From the relationship with the limestones together with limited fossil evidence a barrier sand origin is inferred with the sands having been deposited coastward of the coral reef and seaward of a line of aeolian dune sands built up along the coast.

4.5 THE AEOLIAN DUNE SANDS

These sands crop out over the entire coastal area extending inland for a maximum distance of 50 km. Two distinct types of sand deposit are present. Fringing the coastline are a series of white active dune sands which push inland up to 2 km along the coastline to the southwest of Muqdisho but progressively increase in width to over 10 km along the coastline to the northeast (Plate 1). Inland these give way to red semi-stabilised dune sands which cover most of the coastal region.

The white sands are wind transported beach deposits piled into a series of unstabilised dunes, up to 50 m in elevation and elongated parallel to the coast. Typically the sand is fine to coarse grained, poorly sorted and uncemented with most grains comprising angular to rounded shell and coral fragments. Quartz is present but generally accounts for less than 10 per cent of the sample. Where they give way inland to red semi-stabilised dunes the contact is relatively sharp and shows particularly well on Landsat photographs. We suggest that this contact marks the position of a former shoreline. Coastward

Building up the plain is a 200 m thick complex succession of alternating clays, silts and sands. These have been deposited within a subsiding basin by the Shebeelle river, which over geological time, has migrated back and forth across the region. The present course of the river is confined to the south eastern side of the plain. From Afgooye to a point 25 km upstream of Balcad it hugs the southeastern margin so closely that in places such as Balcad it almost migrates onto the sand dune area.

Lithologically the alluvium is a complex alternation of brown silts and clays with subordinate sands and fine gravels. In general clays and silts dominate and account for 50-80 per cent of the sequence. These include the products of low energy regions of the environment and comprise levée, channel fill, flood plain and flood basin deposits, which because of their fine-grained nature have low permeability and behave as aquicludes.

Poorly sorted brown to light brown quartz sands and fine gravels account for the remaining 20-50 per cent of the succession. Angular to rounded quartz grains dominate but limestone grains and pebble are also common. Apart from the occasional pebble, grain sizes are generally less than 2mm with a median size of between 0.2 to 0.4 mm. Cementation is poor and on the whole samples are friable though some cohesion is provided by a thin iron oxide coating around most grains.

Sand layers occur at random throughout the sequence and vary in thickness from less than 1 to over 35 m but appear to be of limited lateral extent. Because of their coarse and poorly sorted nature these sand bodies are likely to have been deposited in the main river channel, the highest energy region of the environment. Here sand is built up as point bars on the inside of meander loops or as lag deposits on the river bed. In both cases the sand tends to accumulate as elongated lenses parallel to the river channel. Continued traversing of the Shebeelle back and forth across its subsiding flood plain accounts for the widespread and haphazard occurrence of these sands throughout the sequence.

Under such cirumstances it is difficult to assess the extent of hydraulic connection between sand bodies. It is probable that while some are isolated by clay and silt, others are not and may to some degree be linked.

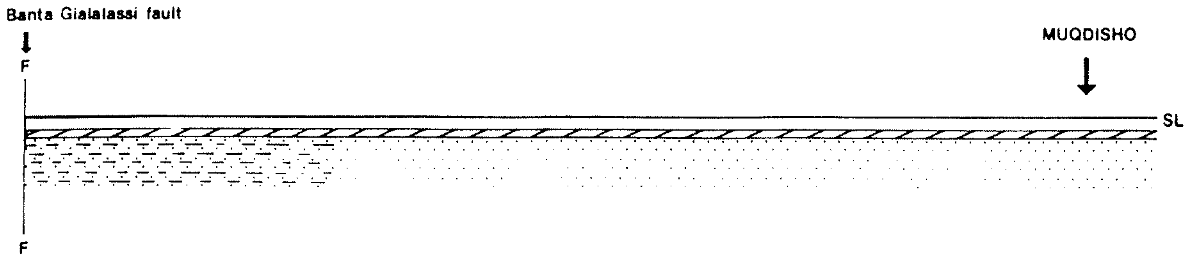
Along the northwest margin of the basin, in the belt of land adjacent to and extending 10 km from the Banta-Gialalassi fault, there is evidence that the percentage of clay and silt decreases, to be replaced by thick accumulations of coarser gravel and sand material. This conclusion is based on the geological records of two boreholes, 11 and 111. In borehole 11 the clay percentage is reduced to 15 per cent while in 111 it remains at approximately 50 per cent, but with the interbedded sands and gravels being significantly coarser than those in more central parts of the basin. This suggests that here in the marginal area of the alluvial plain, coarse materials have periodically been washed down from the region to the northwest of the fault during periods of heavy flooding. Landsat photographs show the existence of a multitude of channels extending across the fault discharging onto the alluvial plain indicating that this process is still at work.

4.7 GEOLOGICAL HISTORY

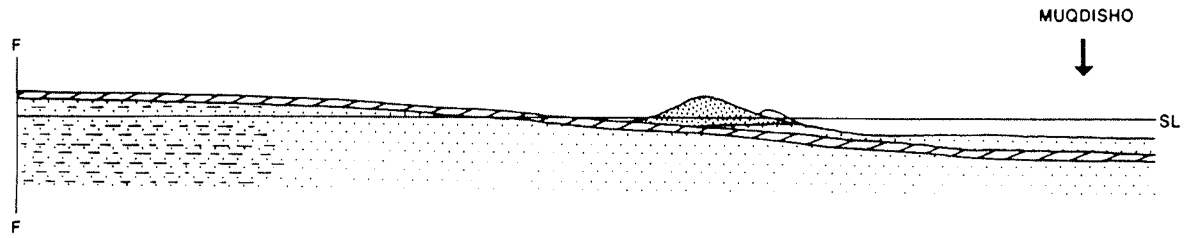
There are clearly large differences in the nature of the material deposited across the study area and in the aquifer potential of the two main rock types; the coastal sands and the inland alluvium. As we shall show, the position of the river Shebeelle relative to the sand/alluvium boundary controls recharge to the sands and hence the groundwater resource of Muqdisho. We found it useful to develop a conceptual model of the geological history to understand the sand/alluvium contact boundary and construct geological cross-sections from the scattered drilling records.

A major sedimentological study would have been required to describe the contact in detail; this was clearly outside our terms of reference. Through a simplified geological history of the region, shown diagrammatically in Figure 4.4, the major processes and the distribution of the main unconsolidated rock types are described.

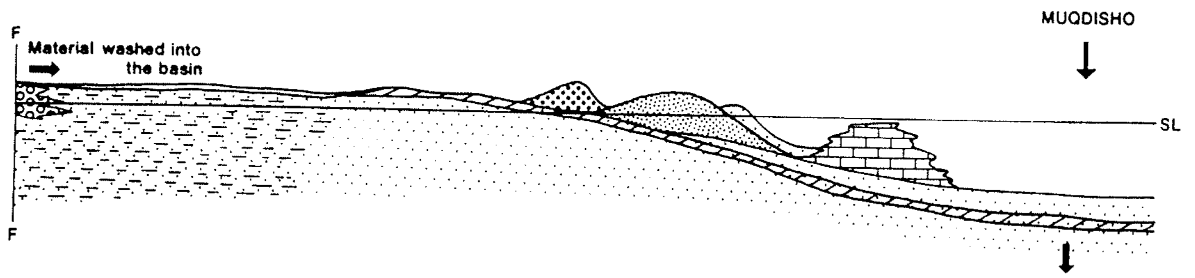
GENERALISED POST-PLIOCENE GEOLOGICAL HISTORY



(1) SHALLOW MARINE or LAGOONAL conditions exist as far inland as the Banta-Gialalassi fault, with deposition of RED-GREEN CLAY underlain by LIGHT BROWN SAND becoming more silty and clayey toward the fault.

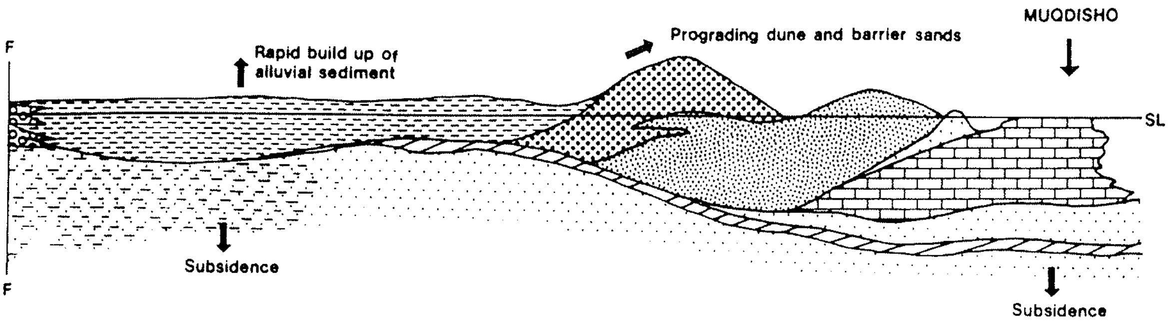


(2) REGRESSION of sea either due to falling sea level or rising landmass. Development of off shore barrier sands (BUFF SANDS) parallel to coast. Deposition of LIGHT BROWN SANDS beyond the barrier islands with beginning of REEF development.

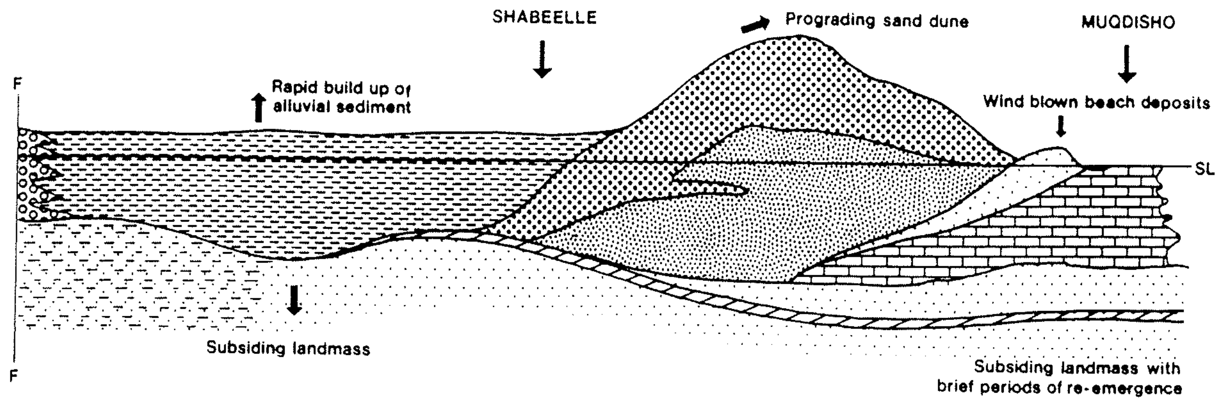


(3) GENERAL SUBSIDENCE of whole landmass seaward of the Banta-Gialalassi fault. Subsidence not continuous but probably interrupted by short periods of emergence. SHEBEELLE begins to flow and to build up its alluvial sequence. Barrier sand deposition continues with RED DUNE SAND build up along the coast on the mainland possibly with material derived from the alluvial plain. Coastward of the barrier sands reef development continues, with wind blown CALCAREOUS BEACH SANDS built up on the coastward side of the reef.

Figure 4.4



(4) CONTINUED GENERAL SUBSIDENCE. Shebeelle plain continues to subside but rapid build up of alluvial sediment proceeds at an even faster rate. Along coast subsidence also continues, but dune and barrier sands rapidly build up and prograde eastward. This results in increasing build up of sand. Subsiding land mass causes reef to migrate eastward. Subsidence not continuous but probably intermittent with brief periods of emergence.



(5) UP TO PRESENT DAY subsidence of Shebeelle alluvial plain with concurrent rapid build up of alluvium is continuing. Material is still being periodically washed from the N.W. side of the fault into the margin of the basin. Coastward the RED DUNE sands have prograded over the barrier sands which appear to have by now been completely blanketed and no longer exist. At the coast WHITE CALCAREOUS BEACH SANDS are being deposited representing material washed off the REEF. Presently there seems to be a brief period of re-emergence taking place along the stretch of coast to the N.E. of Mugdisho.

Figure 4·4 cont

5. REGIONAL HYDROGEOLOGY

5.1 INTRODUCTION

In this section we examine all major aspects of the study area hydrogeology. We begin with the configuration of the water table before moving on to discuss aquifer properties and finally the sources and distribution of recharge.

5.2 THE WATER TABLE AND GROUNDWATER OCCURRENCE

For the purposes of our study the regional water table is assumed to be a single surface and continuous between the alluvial and sand formations. Throughout the study area this assumption is valid since a continuous water table can be recognized everywhere. However, during the current study we have established that in the vicinity of the Shebeelle there are perched water tables held in sand horizons at elevations significantly above the regional water level. These are particularly well recorded in the Afgooye and Jawhar regions.

At Jawhar irrigation at the Sugar Estate has built up groundwater levels in perched aquifers to within a metre of ground level. Perched water table elevations in this vicinity, shown in Figure 5.1, range from 80 to 100 m above sea level. These compare with the 1982/83 regional water table levels of between 60 and 75 m above sea level for the same area (Figure 5.3).

Work done by G.K.Z. in April 1976 in and around Afgooye incorporated data from 30 shallow wells to show the existence of a perched water table at a depth of less than 10 m. Elevations ranged from 70 to 75 m above sea level in comparison to regional levels of between 25 to 28 m above sea level. The situation for April 1976 is presented in Figure 5.2, where the contours clearly indicate significant recharge to the perched aquifer along the course of the Shebeelle along the reach to the south west of Afgooye bridge.

During the current study boreholes have been specifically drilled to demonstrate the existence of perched levels. At site E07, one

Perched water table elevations (metres above sea level) : Jawhar, 1982

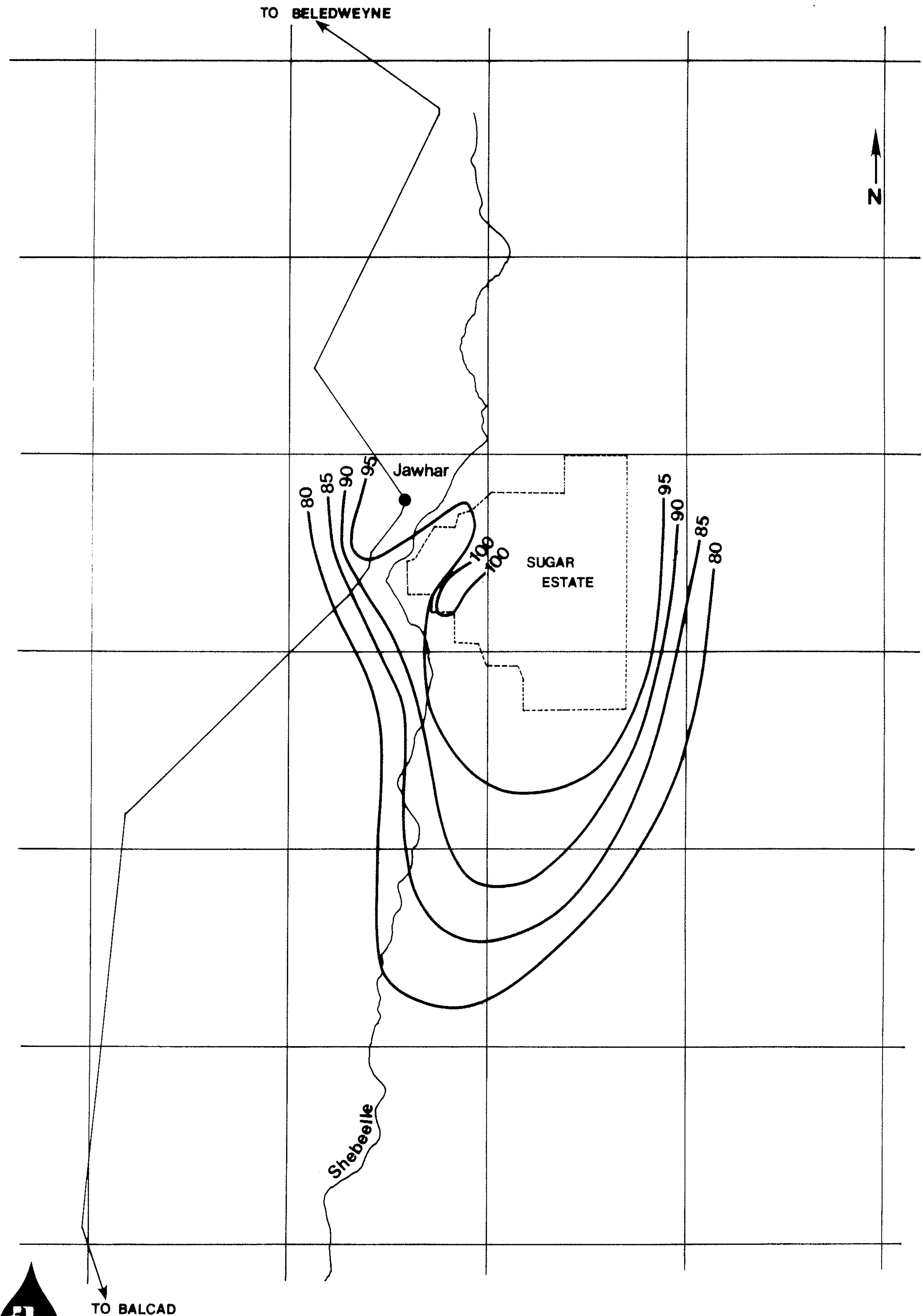


Figure 5·1

Perched water table elevations (metres above sea level) : **Afgooye, April 1976**

[Taken from G.K.Z. report to W.D.A.]

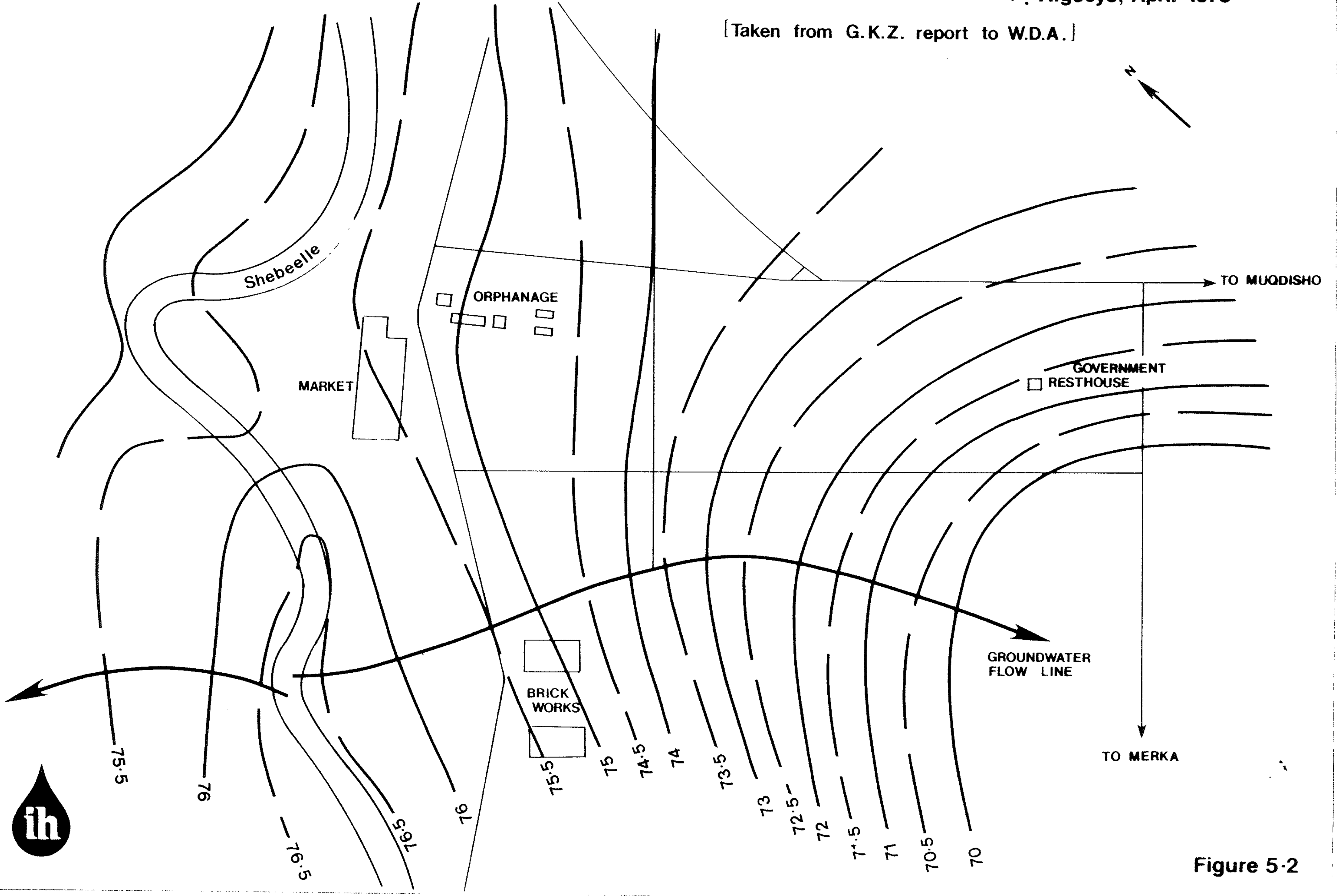
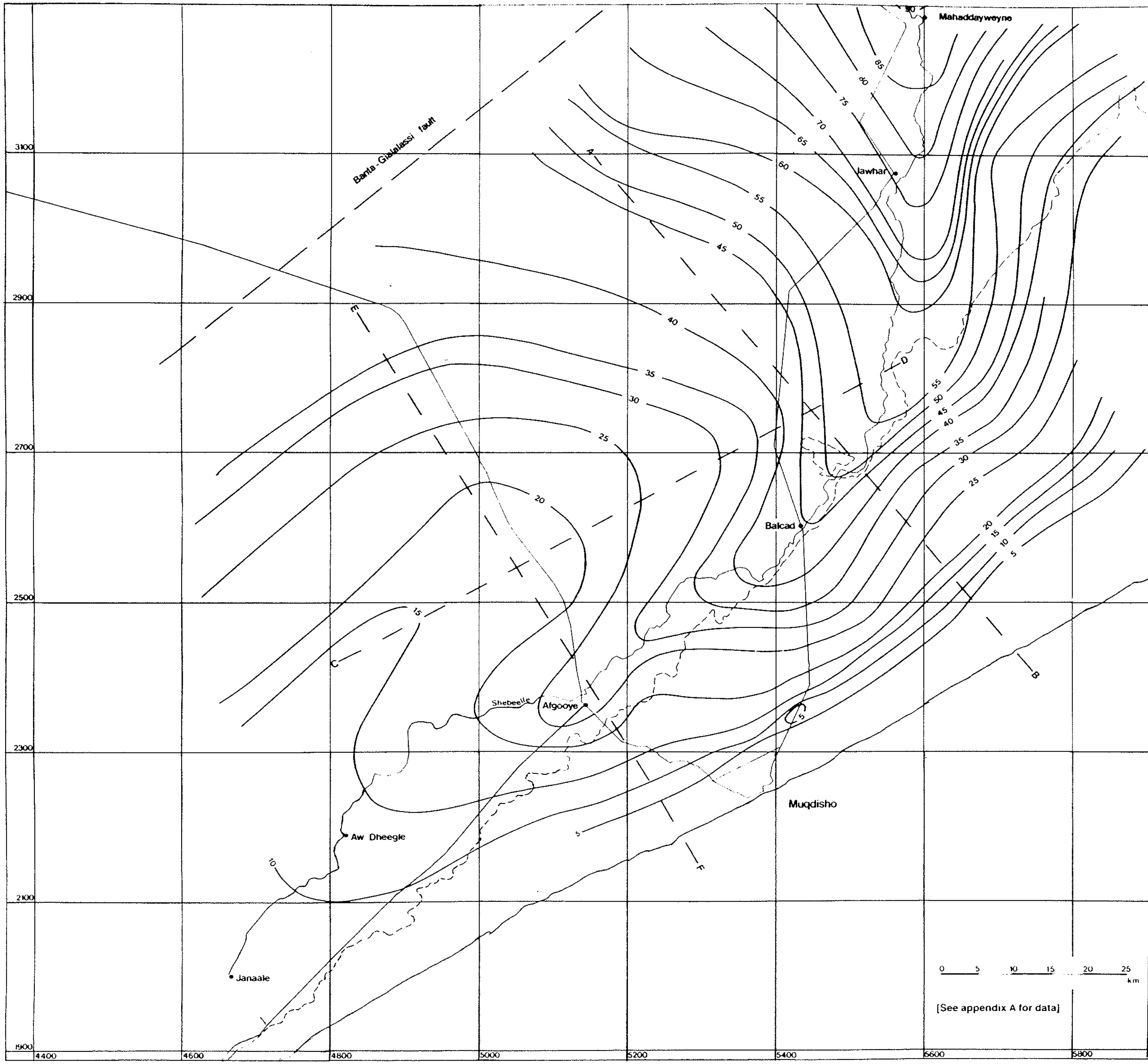


Figure 5·2



Muqdisho

Water supply expansion

Groundwater elevation [m.a.s.l.]

Figure 5·3

kilometre to the west of the river, two boreholes were drilled, one shallow and one deep, to show the presence of a perched water table some 20 m above regional levels. A 24 hour pumping test demonstrated a lack of local connection between the deep and shallow aquifers, although on a more regional scale and over longer time periods some movement of water inevitably takes place.

It is important to remember that although transfer of water from upper to lower aquifers takes place in the long term, water infiltrating from irrigation schemes and the river bed is initially held up to form perched water tables. In this way infiltration from many of the newer irrigation and offstream storage schemes has not yet influenced the regional water table; so far it has only built up storage within higher aquifers. Only where schemes have been established for long periods, such as the Jawhar Sugar Estate, where irrigation has been continuous since 1920, have regional levels been affected.

Moving now to the main water table, the configuration of this surface is essentially very simple. Elevations are highest along the length of the river, beneath which a mound is developed, implying that recharge is taking place by seepage. Groundwater flows from the mound either coastward, toward the south east or inland toward a shallow NE-SW oriented groundwater 'trough', which carries water away to the south west. Beneath the river elevations along the crest of the mound range from + 90 m at Mahaddayweyne to + 10 m between Aw Dheegle and Janaale. Between these points the profile of the water table along the river length is not a uniform gradient but is stepped, as shown in Fig. 5.4.

Gradients range from 1 in 750 between Afgooye and the coast to 1 in 500 coastward of points upstream from Balcad. Flow inland toward the 'trough' tends to be along shallower gradients of 1 in 1250.

However, on both sides of the river the slope of the water table along any one flow line is not uniform but possesses a single step-like break in the profile, giving rise to sections such as those shown in Figure 5.5. On the inland flanks of the river this notch or

Profile of water table beneath river

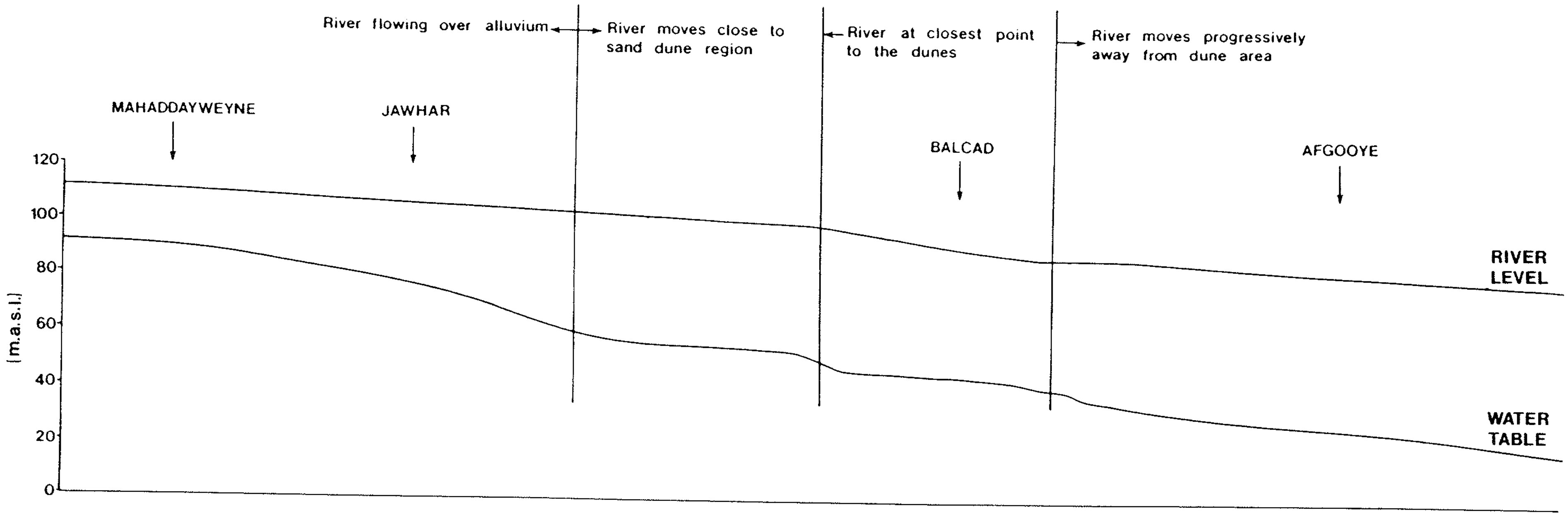


Figure 5·4

Water table cross-sections

[For lines of section see figure 5·3]

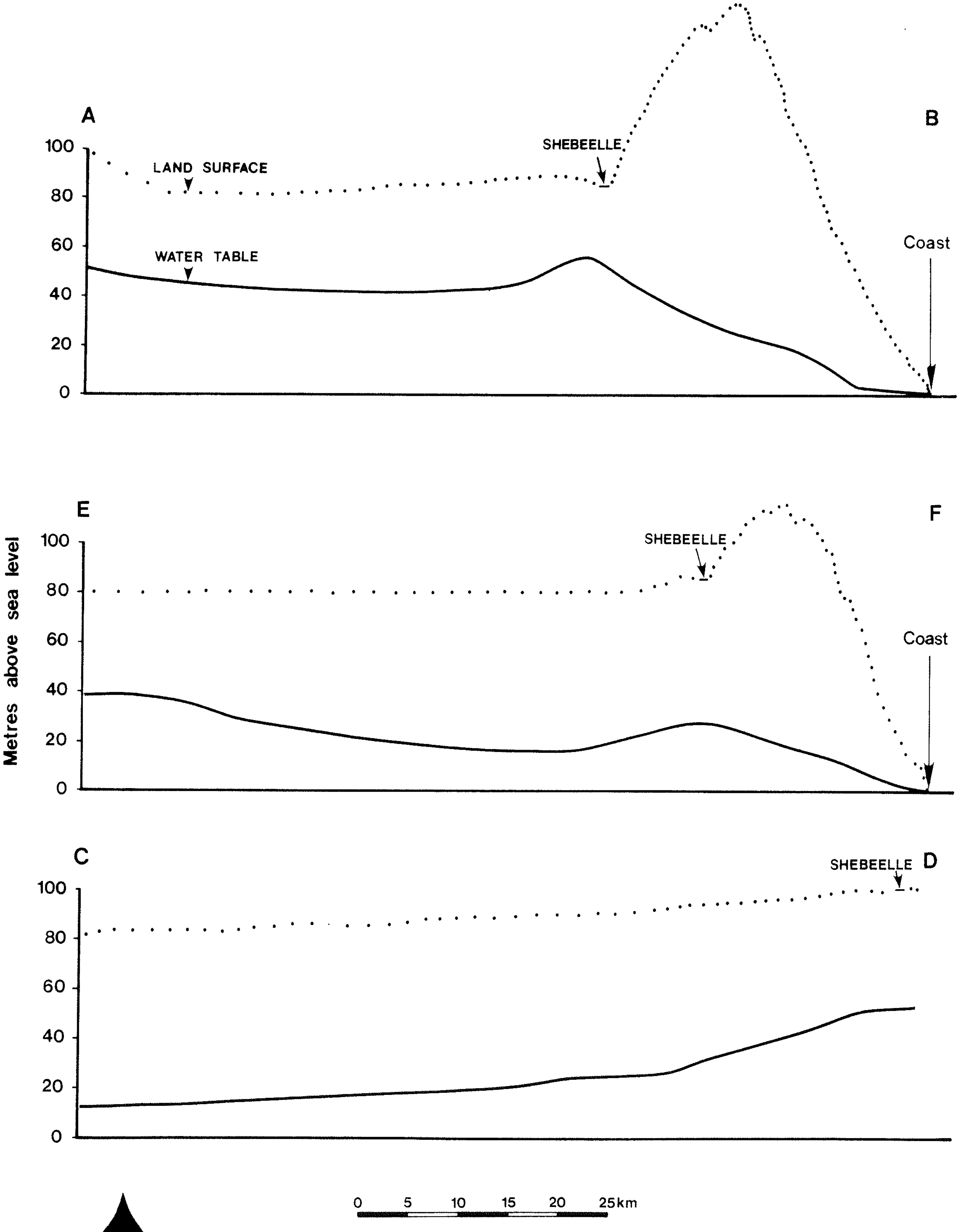


Figure 5·5

step is developed approximately 15 km from the river, measured along flow lines, and is most prominent in northern and central regions. Toward the coast a similar but more pronounced step exists in the water table to the north east of Muqdisho. Here the feature is developed between 3 and 11 km inland and 25 km from the river. To the south west of the city it ceases to become a recognizable feature.

If the water table is assumed to represent a condition of steady state flow then the stepped profiles can only be explained in terms of sudden and large scale variations in transmissivity. There is, however, no geological evidence to indicate that such variations exist and therefore, we need to look beyond the assumption that the water table represents a steady state condition to the possibility that at least part of it is still in the process of adjusting to newly-established conditions. Bearing this in mind there are two ways in which the form of the water table could be explained.

(1) Firstly, the break of slope might represent the front of a recharge pulse advancing slowly away from the river on both sides and generated at a time in the past when recharge from the Shebeelle suddenly increased. Such an increase could have been associated with the migration of the river toward and onto the sand dune area. The closer proximity of the front to the river on its inland flank would be consistent with a slower rate of advance through the alluvium than through higher permeability sands coastward. Our computer model studies have shown the rate of groundwater movement to be of the order of 1.5 m per year in the alluvium to 10 m per year through the sand aquifer. Although these are crude estimates they serve to give a general indication of rate of groundwater movement. For example, groundwater moving through alluvium from the river to the water table trough in the south west, requires a journey time of approximately 40,000 years. In contrast flow from the river to the coast through the sand aquifer requires less than 5000 years. The implication is that the recharge pulse we see today was probably generated in the relatively recent geological past.

(2) It is also possible to interpret the origin of the existing water table configuration in a slightly different way. There is, for example, strong evidence to indicate that the break of slope along the coast to the north east of Muqdisho is caused, not by the advancing front of a recharge pulse, but by the recent emergence of this stretch of coastline. In this case the recharge pulse generated in the manner described earlier has, on the coastward flank of the river, already reached the present shoreline and is no longer recognizable, while the slower moving inland front is still preserved. Thus the break of slope in the water table to the north east of the capital may not represent a recharge pulse front but rather the abandoned line of a former shoreline, which has subsequently moved seaward in response to recent emergence of the coastal region. Re-establishment of equilibrium with the newly-imposed discharge line along the present coastline has not yet taken place due to relatively slow rates of groundwater movement. Support is provided by the fact that the region of low-lying water table coastward of the break of slope coincides precisely with the area of recent coastal emergence, identified by its blanket of unstabilised wind-blown beach sand deposits (Plate 1). Further support is given by the saline nature of the groundwater throughout the recently emerged area, this representing seawater not yet flushed out by freshwater flow from inland.

On the whole the balance of evidence favours the second interpretation. However, of most importance is that both argue against the water table being everywhere in a steady state condition. We are dealing instead with a composite surface having different origins. Under these circumstances we might expect to find problems when simulating such a water table in a steady state computer model, of the type used in part of our resource evaluation. Problems were indeed encountered and are discussed in Chapter 6.

5.3 WATER TABLE FLUCTUATIONS

The regional water table responds to seasonal variations of infiltration rate from its major recharge source, the Shebeelle river. Such response, however, is restricted to a narrow zone a few kilometres wide on either side of the river; beyond this the water table shows no seasonal variation but maintains a remarkably consistent level throughout the year. Details of the relationship between groundwater levels and river stage are discussed in our next section dealing with recharge.

Superimposed upon these large scale water level changes are small scale daily fluctuations that develop in response to barometric pressure. These are particularly marked within the sand aquifer, where daily fluctuations can exceed 6 cm. Such a response is generally taken to indicate confined conditions. Clearly, however, within the sand aquifer the water table is not confined. In this instance the barometric response results from the effect of the thick cover of unsaturated fine-grained sand. This completely absorbs atmospheric pressure changes at the surface and prevents its transmission to the water table. The result is that the water surface in the borehole is allowed to act as a barometer with water levels falling in response to increased pressure and vice versa. As the thickness of sand decreases coastward so the barometric effect becomes progressively reduced.

Similar daily fluctuations have also been recorded at boreholes E09 and E07 within the alluvium. However, here it is likely that confined conditions prevail locally and the response can be attributed to the effects of overlying clay aquicludes.

5.4 AQUIFER PROPERTIES

5.4.1 Introduction

Our 1980 study was directed specifically toward establishing the transmissivity and storage of the sand and limestone aquifers coastward of the Shebeelle. To achieve this, 6 pumping tests, each of

10 days duration, were carried out; five in the sand aquifer and one in the coastal limestone. All tests were confined to the Muqdisho-Afgooye-Balcad area. At this stage there was no attempt to determine aquifer properties within the alluvial sequence, since in the context of the 1980 study, the formation was of marginal importance.

In terms of the present study on the other hand it has taken on an increased significance. With our present expanded study area, the role played by the alluvium needs to be more fully understood. As a result two pumping tests were carried out to determine its characteristics, one at E07 and a second at E09. Expansion of the study area has also taken in an increased area of sand aquifer. However further testing here has been restricted to production boreholes within the Stage IIA wellfield, to take advantage of drilling and testing already being undertaken at this site. Test sites in areas of newly-encompassed sand aquifer have not been considered necessary because of its uniform and predictable nature. In these regions aquifer properties have been extrapolated from the 1980 study area.

5.4.2 The sand aquifer

The results of tests on boreholes within the stage IIA wellfield generally confirm the results corrected for partial penetration obtained during our earlier study as shown in Table 5.1. At the two sites tested, PW21 and PW17, transmissivities proved to be 2020 and 2550 m^2/day respectively. No partial penetration correction has been carried out because observation wells are at a sufficient distance for the effect of this to be insignificant.

In addition to purpose-built test sites, further transmissivity data have been obtained by taking advantage of water levels monitored within the Stage I wellfield over the first 400-500 days of production. Pumping from this 8-borehole wellfield began in May 1982 at a total rate of 11,520 m^3/day. By the middle of 1983 production had been continuous for over 400 days. At this time the drawdowns in two observation wells, MGQ 2P and OW1 were 1.21 m and 1.58 m

TABLE 5.1

AQUIFER PROPERTIES

WELL NUMBER	TRANSMISSIVITY Jacob m^2/d	TRANSMISSIVITY Boulton m^2/d	TRANSMISSIVITY Partial Penetration	PERMEABILITY m/d	STORAGE COEFFICIENT Jacob (per cent)	STORAGE COEFFICIENT Boulton Early (per cent)	STORAGE COEFFICIENT Boulton Late (per cent)	SPECIFIC CAPACITY $m^3/d/m$	AQUIFER
MGQ-IT (Test Well)								155	Buff Sand
MGQ-3P (Obs. Well)	972	982	2136	15.2	.02	.03	1.1		
MGQ-2T(A) (Test Well)								187	Red Sand
MGQ-6P(A) (Obs. Well)	743	124	2286	16.3	.07	.07	2.3		
MGQ-3T (Test Well)								188	Buff Sand
MGQ-7P (Obs. Well)	1350	840	-	-	.02	.04	4.6		
MGQ-5T (Test Well)								101	Buff Sand
MGQ-10P(A) (Obs. Well)	493	703	4570	36.6	.09	.05	5.7		
MGQ-6T (Test Well)								116	Buff + Red Sand
MGQ-12P (Obs. Well)	317	646	1400	10.1	.07	.07	5.5		
PW21 (OW 5)	1300	2022	-	12.9	-		6.1	154	Buff Sand
PW 17A (OW=PW17)	2990	2548	-	16.3	-	-	-	-	Buff Sand
MGQ-2P (Stage 1)	3250		-	20.8	-	-	-	-	Buff Sand
OW1 (Stage 1)	3000		-	19.2	-	-	-	-	
MGQ-4T (Test Well)								49	Limestone
MGQ-9P (Obs. Well)	245	234			.03	.03	-		
E07TW	125	-	-	15.6				147	Alluvium
E07 (Obs. Well)	120	-	-	17.3	.04				
E09TW	274	-	-	22.8		-	-	92	Alluvium
E09 (Obs. Well)	274	-	-	22.8	.002	-	-	-	

respectively. With these data it has been possible, by using a small groundwater interference model, to calculate regional transmissivity. For MGQ 2P this is 3250 m^2/day and for OW1 3000 m^2/day. Again no correction for partial penetration is required.

Table 5.1 lists all transmissivities calculated during both the 1980 and present studies. This shows a range from 1400 to 4570 m^2/day with corresponding permeabilities (unit transmissivity) varying between 10.1 and 36.6 m/d. We have selected a figure of 15 m/d to be a representative, but conservative, estimate of regional permeability and one which is entirely compatible with the nature of the aquifer material. This value is 20 per cent lower than the average shown in Table 5.1. It is the product of this figure and the total saturated thickness, obtained with the aid of Figures 4.2 and 5.1, that provides the eventual transmissivity distribution for the computer model. Where red sands are encountered within the saturated part of the sequence as at EO3, MPGQ 11P a slightly higher permeability of 17 m/d has been assigned, to reflect the less cemented nature of the material.

Permeabilities of 15 m/d and 17 m/d for the buff and red sands respectively contrast with those of 12 m/d and 14 m/d quoted in our 1980 report. This increase is accounted for by the slightly higher values of transmissivity derived from our latest phase of test pumping.

Results from these same tests also led to an increase of the original storage coefficient assigned to the sand aquifer. Previously a value of 2 per cent was adopted as a conservative estimate based on the results of 5 tests giving a range from 1.1 to 5.7 per cent and an average of 3.8 per cent. Now, however, with the inclusion of PW21 with a storage of 6.1 per cent the average is raised to 4.2 per cent with 4 of the 6 values available being over 4 per cent. At the same time the interference model used to calculate the Stage I wellfield transmissivity demands a storage of 4 per cent to produce values that are compatible with those from pumping tests. Here a 2 per cent storage gives rise to transmissivities well in excess of 4000 m^3/day, a figure clearly at variance with all our other data. As a result for the current study we have taken 4 per cent to be a realistic sand aquifer storage.

Here storage refers to the volume of water that will drain under gravity from a unit volume of aquifer material expressed as a percentage. In Table 5.1 the early storage coefficient simply reflects the behaviour of the aquifer during the first few minutes of pumping before the effects of gravity drainage are imposed. The true storage coefficient or specific yield are calculated from data collected during the later part of the test (see Appendix B).

5.4.3 The Limestones

The emphasis of our current investigation has been directed toward the sand aquifer and the hitherto poorly-understood alluvial formation. Attention has not been focussed so intensely on the coastal limestones. Consequently no further drilling has been carried out upon them and we have relied on data collected for the 1980 report as a basis for assigning transmissivity and storage. Data available is that from a single 10-day pumping test at site MGQ-4T. Transmissivity here was 240 m^2/d with a .03% storage coefficient, reflecting a localised leaky artesian condition.

Work done at this time showed the limestone to have insignificant intergranular permeability, with groundwater flow instead being concentrated within a poorly-developed fissure network. This has created a heterogeneous aquifer in which transmissivity varies rapidly from place to place in an unpredictable manner. Such variability has made it difficult to assign transmissivity throughout the limestone region of our computer model. Eventually for the final model we adopted the strategy of assigning to each of the 'limestone nodes' a value of half that of the adjacent 'sand node' immediately inland. This is based on a comparison of the uncorrected pumping tests results for limestones and sand shown in Table 5.1. By translating this relationship to the computer model we have a strategy that, although crude, is based on fact and which also is validated by subsequent modelling work.

Storage has been equally difficult to assign. From the pumping test a value of .03 per cent, indicating leaky confined conditions, has been derived. However, such conditions only exist locally. On a regional scale there is sufficient connection between fissure systems to allow the development regionally of a true water table. Under these circumstances the regional storage is equivalent to specific yield and cannot be determined from the data available for site MGQ-4T.

In the absence of evidence to indicate true storage we have adopted the 4 per cent assigned to the sand aquifer as being a reasonable figure.

5.4.4 The Alluvium

The alluvium plays a major role in controlling the regional pattern of groundwater flow. In order to assess this role better two pumping tests were undertaken to prove aquifer characteristics and help provide a clearer understanding of groundwater occurrence in this previously poorly-understood region.

Tests were carried out at E07 and E09. At each site the objective was to establish the transmissivity of a 'typical' sand horizon. To achieve this a 12 m length of screen was positioned within the selected zone in both test and observation wells. Results of the tests are listed in Table 5.1, and the data presented in Appendix B.

Transmissivities of 120 m^2/d and 274 m^2/d were obtained for E07 and E09 respectively. With tested sand thickness of 7.5 m at E07 and 12 m at E09 these translate into permeabilities of 16 m/d and 22.8 m/d. Inevitably the transmissivities quoted refer only to the thickness of sand tested at each site. Accepting the clays and silts within the sequence to be non-productive, the formation transmissivity can be obtained by taking into account the total thickness of all saturated sand horizons. At sites E07 and E09 thicknesses of 41 m and 42 m are shown to exist by interpretation of gamma and geological logs. Taking each sand horizon to have the same permeability as that tested, formation transmissivities at the respective sites translate to 656 m^2/d and 960 m^2/d.

From this it is a reasonable assumption that alluvium transmissivity is directly related to the percentage of sand present;

the higher the sand content the higher the transmissivity. By examination of gamma and geological borehole logs throughout the alluvial plain and assigning a permeability of 16 m/d to all saturated sand horizons, we have been able to determine formation transmissivities at a further 13 sites. Together with the pumping test results these have provided the basis for the distribution of alluvial transmissivity within our computer model.

Storage coefficients derived at E07 and E09 were .04 per cent and .002 per cent respectively, pointing to the existence of confined or semi-confined conditions. Such conditions are likely to exist at most sites because everywhere clay will tend to provide local confining layers. Fortunately the problem of assigning storage within the alluvium does not arise since all regional modelling incorporating this formation is steady state.

5.5 RECHARGE

5.5.1 Introduction

In the study area the only significant source of aquifer recharge is the Shebeelle river together with attendant irrigation and offstream storage schemes. Rainfall, the only other potential source, does not materially contribute due largely to a combination of its sporadic occurrence and the effect of a thick blanket of fine-grained sand overlying the water table. This is demonstrated in our 1980 report and nothing revealed during the present study has changed our conclusions. As a result rainfall is not considered further. Attention is henceforth focussed solely upon recharge derived from the Shebeelle and associated irrigation and flood control projects.

Work for the 1980 report was concentrated along the stretch of river between Balcad and Afgooye. Evidence to link the river with aquifer recharge was presented along several lines; the existence of a water table mound beneath the river; the response of groundwater levels along the length of the mound to changes in river stage; the systematic increase of groundwater temperature at increasing distance from the river together with supporting evidence of chemistry and stable isotope data. At this stage we succeeded in showing the river to be the sole significant source of recharge. But the small size of the study area did not permit a full understanding of the regional pattern of recharge. Now, however, with a larger study area our insight into the regional picture is much more complete. Not only is it possible, with evidence currently available, to confirm the Shebeelle as the major recharge source, but also to identify regions of high and low infiltration.

We present this evidence under several headings. The first two include water level and groundwater temperature data, which are used to demonstrate the existence of the infiltration process. Successive headings incorporate conductivity, stable isotope and chemistry data, these being used particularly to differentiate between regions of high and low recharge. A final section is devoted to a separate, but parallel study, which attempts to quantify recharge through analysis of river flow, irrigation and offstream storage data. At a later stage these results are compared with those derived from computer modelling, in the light of our knowledge of the hydrogeological system.

5.5.2 Groundwater Levels

It is, perhaps, the overall configuration of the water table shown in Figure 5.3 between Mahadday Weyne and Aw Dheegle that argues most convincingly for river infiltration as the major source of aquifer recharge. Such infiltration may be direct through the bed and banks of the river, or indirectly through irrigation water abstracted from the Shebeelle. The configuration of this recharge mound at any one point is determined by a combination of the recharge rate and underlying aquifer transmissivity. In turn the recharge rate is controlled by the permeability of material blanketing and immediately underlying the river bed.

The profile of the water table shown in Figure 5.4, is stepped. These steps reflect variations in rates of recharge and underlying aquifer transmissivity. Not surprisingly areas of flattened gradient, equating with high aquifer transmissivity and recharge, generally coincide with the stretch of river centred about Balcad, where the river flows very close to the sand aquifer. At points where the river is positioned further into its alluvial plain, as for example from Mahadday Weyne to 10 km downstream of Jawhar, a combination of low underlying transmissivity and recharge has given rise to steeper gradients.

Everywhere the water table lies at a considerable depth below the bed of the river, from 20 m at Jawhar to over 60 m beyond Afgooye. This gives a clue to the mechanism governing recharge. Water infiltrating through the river bed does so at a rate determined by the permeability of river bed material and underlying alluvium. In general this rate is relatively slow. Recharge estimates derived from our computer studies show the average river bed permeability to be of the order of .04 m/d along the stretch of river from Balcad to Afgooye, though at any one point it is likely to differ significantly from the average. Continued infiltration over a long period has resulted in the almost complete saturation of the alluvial profile immediately beneath the river bed. During recharge events we suggest that infiltration rapidly brings the alluvium to saturation point, causing water to be simultaneously expelled from the base of the sequence into the underlying sand aquifer. Under these circumstances the time lag between a high river stage and response of the regional water table is determined solely by the time necessary for water to percolate from the base of the alluvium to the water table.

In our 1980 report a time lag of three weeks was reported at three sites between Afgooye and Balcad. These were boreholes at the Afgooye Mango Juice Factory, the Balcad Somaltek factory and at the site of MGQ-6T. Continued monitoring at the latter site during the present phase of investigation has confirmed our initial observations.

At each of the above sites the annual fluctuation is generally less than 0.5 m. But there is evidence that the scale of response along other parts of the river is considerably greater. For example water levels at E03, located 3 km to the east of the river and 20 km north of Balcad, show an increase of 8.6 m between June and November 1983. Here, the implication is that infiltration to the sand aquifer is of considerable volume and extremely rapid.

Borehole hydrograph

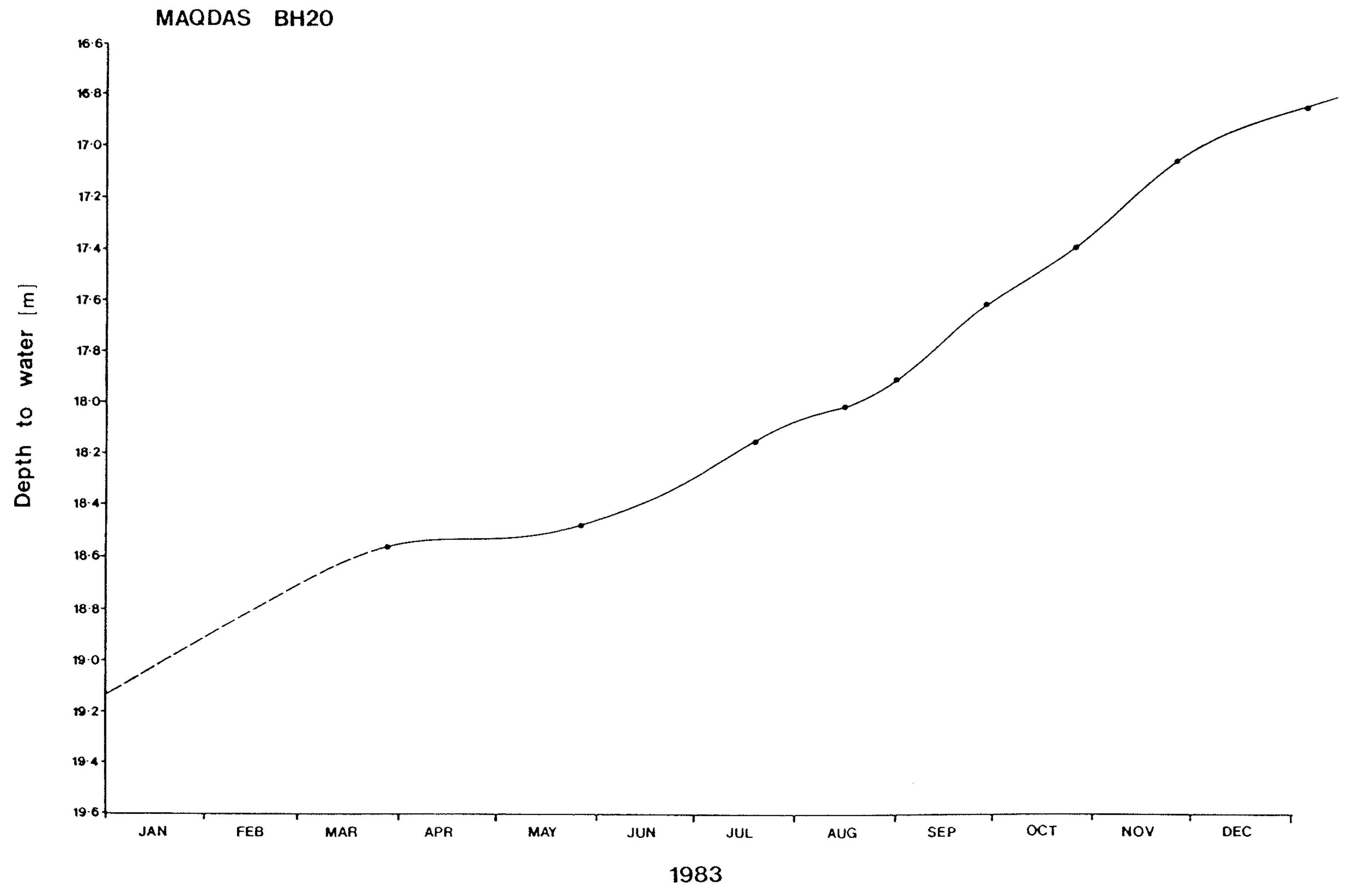


Figure 5·6

Along stretches of the river underlain entirely by alluvium, as for example in the vicinity of Jawhar, there is an increased opportunity for infiltrating water to be temporarily ponded in perched aquifers. Water stored in this way ultimately finds its way down to the regional water table at a rate and in a manner controlled by the local lithology. Generally the rate is extremely slow.

At the Jawhar Sugar Estate the continued irrigation since the 1920's has given rise to an offset of the main recharge mound from the river to beneath the estate itself (Fig. 5.3).

Similar infiltration to perched aquifers is taking place at the offstream storage reservoir between Balcad and Jawhar. The impact on local water levels, since its creation in 1980, has been substantial. Borehole 20, at Tuuluda Maqdas is situated on alluvium just south of the reservoir. When drilled in 1976 the depth to water was 25 m, this representing a perched level held approximately 20 m above the regional water table. By October 1982, in response to infiltration from the newly-constructed reservoir this had risen to 19.6 m and by January 1984 to 16.8 m (Fig. 5.6). Large scale infiltration is clearly indicated.

Finally in our 1980 report we suggested that there appeared to be a river stage threshold, below which little recharge takes place. This was the 4.5 m stage equivalent to a flow of 80 m^3/sec. Data collected during the current study has been insufficient to confirm or refute this suggestion. As a result the recharge threshold concept remains speculative.

5.5.3 Groundwater Temperature

Earlier work demonstrated the existence of a significant temperature gradient away from the river in the Afgooye-Balcad-Muqdisho region. Data collected for the current project have enabled a wider regional pattern of groundwater temperature distribution to be established. This is shown in Figure 5.7.

5.5.4 Groundwater conductivity

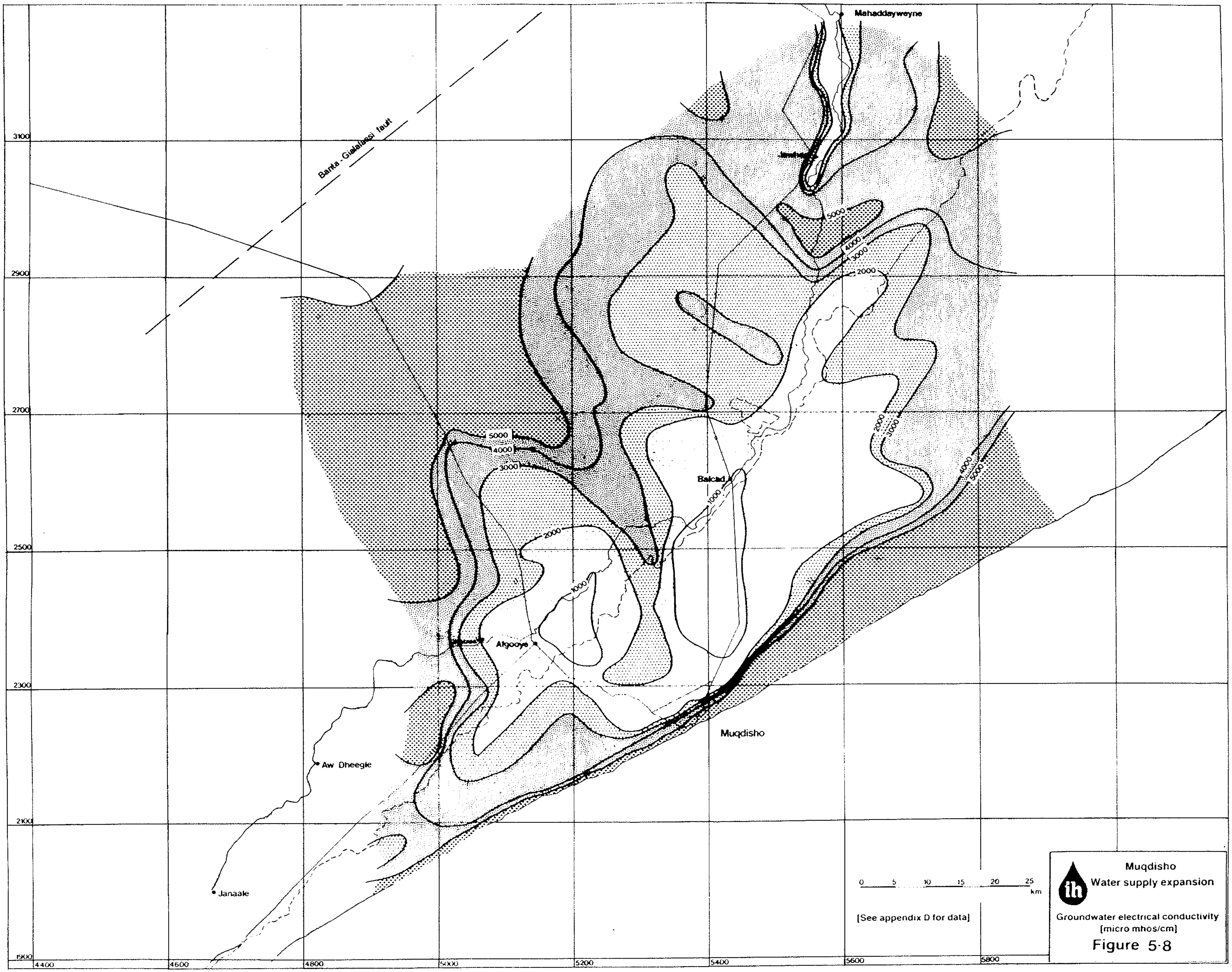
Measurement of electrical conductivity provides a rapid and reliable means of establishing overall groundwater quality. At the same time its distribution acts as a signpost to the location of recharge areas. This is particularly true for our current study area where we are dealing with a single well-defined recharge source, the Shebeelle river.

With this in mind conductivity readings were made at borehole sites throughout the study area as a priority requirement at an early stage in our investigation. Gaps in coverage were, where possible, made good by published data. The resulting conductivity distribution is shown in Figure 5.8.

Away from the coast, the pattern is dominated by the influence of river recharge. Conductivity of river water itself varies throughout the year. In 1979, for example, it ranged from 347 to 1240 micromhos/cm and averaged 690 micromhos/cm. Such values are probably typical and representative of water recharging the aquifer from year to year.

Tongues of low conductivity groundwater reaching out from the river are interpreted as zones of high recharge, where water is able to pass rapidly through river bed alluvium into the underlying sand aquifer, before flowing preferentially coastward. Figure 5.8 shows two such regions. The largest reaches out southward from the stretch of river to the south west of Balcad. It extends for 25 km from the river over a 10 km width to encompass the Balcad road wellfield. A second, but less extensive tongue, spreads southward a distance of 10 km from the 15 km stretch of river upstream from Afgooye. Both regions signal points of high recharge.

Elsewhere along the river, recharge appears to be less intense but nevertheless still substantial. In fact along most of its length, between a point 20 km south of Jawhar to 15 km south east of Afgooye, recharge rates are sufficiently high to maintain a groundwater quality of less than 2000 micromhos/cm. Water of this quality is present to within 5 to 10 km of the coast before mixing with sea water



Muqdisho
Water supply expansion
Groundwater electrical conductivity
[micro mhos/cm]
Figure 5·8

(conductivity - 40,000 micromhos/cm) raises conductivity to over 5000 micromhos/cm. Inland, toward the alluvium, low transmissivity has restricted its movement to little more than 5 km from the river. Beyond this point conductivity progressively increases to values in excess of 5000 micromhoscm in the region of the groundwater trough (eg 5350 micromhos/cm at E012). Sporadic and exceptionally high conductivities are recorded along the extreme north western margin of the alluvium (eg 49000 micromhos/cm at B.H.98 and 26000 micromhos/cm at B.H.96). We speculate that these are related to saline groundwater moving from regions beyond the Banta-Gialalassi fault.

A third, but minor region of recharge is located between Mahadday Weyne and Jawhar. Here groundwater conductivity is again generally less than 2000 micromhos/cm but because it is contained entirely within alluvium low transmissivity has restricted its occurrence to no more than a few kilometres from the river. Beyond this zone quality progressively declines.

Figure 5.8 also highlights regions of little or no recharge, characterised by high conductivity groundwater beneath and close to the river. These seem to occur at three points. The first is along a short reach 10 km to the south of Jawhar, where groundwater contained within alluvium has a conductivity locally in excess of 7000 micromhos/cm.

A second region is located midway between Balcad and Afgooye. At this point a narrow 5 km wide tongue of poor-quality water (in excess of 3000 micromhos/cm) extends across the river separating the two regions of low conductivity spreading out from Balcad and Afgooye. The zone extends southward to within 5 km of Muqdisho. We suggest that this probably represents the remnant of a groundwater body in existence prior to migration of the Shebeelle to a course adjacent to the sand aquifer. In this position the river has released plumes of fresher water from selected reaches along its length. From these sites low conductivity water has spread out to replace the existing more saline groundwater body. But in places replacement is not yet complete; the tongue of water between Balcad and Afgooye represents such a region.

A third, but less well defined area of low recharge exists 20 km downstream from Afgooye. Here data are sparse but regional conductivities coastward of the river point to limited recharge along this stretch.

Finally the distribution of conductivity along the coast provides evidence relating to the position of the saline interface. Along the coast to the south west of Muqdisho, water with a conductivity in excess of 5000 micromhos/cm extends inland no more than 1 to 2 km. But to the north east of the city this situation changes dramatically. Here saline water reaches progressively further inland toward the north east to a maximum distance of approximately 15 km. This coincides with the area of recently emerged coast discussed in Chapter 4. Water contained within this zone is saline, being trapped within the aquifer during emergence, and has not yet been flushed out.

Movement of the saline - freshwater interface is of great significance to our current study. It is movement of this feature that imposes constraints on abstraction regimes, since lowering inland water levels causes an advance of the saline front. Over-abstraction results in an uncontrolled advance and to the ultimate contamination of the aquifer.

Our earlier study monitored the position of the interface along a line of three boreholes between the Balcad road wellfield and the coast specifically installed for this purpose. The sites are MGQ-1CP, 2CP and 3CP situated 1.2, 3.5 and 5.5 km from the coast respectively. At this time the interface was identified only in MGQ-1CP, the closest of the boreholes to the coast. In MGQ-2CP and 3CP it was absent. Repeat logs undertaken in 1983 during our current study, at MGQ-2CP and 3CP, shows the situation not to have changed significantly in the interval; the interface has still not reached either site. Differences in past and present profiles shown in Figure 5.9, are related to the slow flushing out of drilling fluid, which being of considerably lower conductivity than the local groundwater has tended to improve the initial quality of borehole water. At these sites (MGQ-2CP and 3CP), the effect is particularly marked because of the significant difference between drilling fluid and groundwater quality. In regions of better quality groundwater further inland this

Coastal boreholes - Conductivity profiles

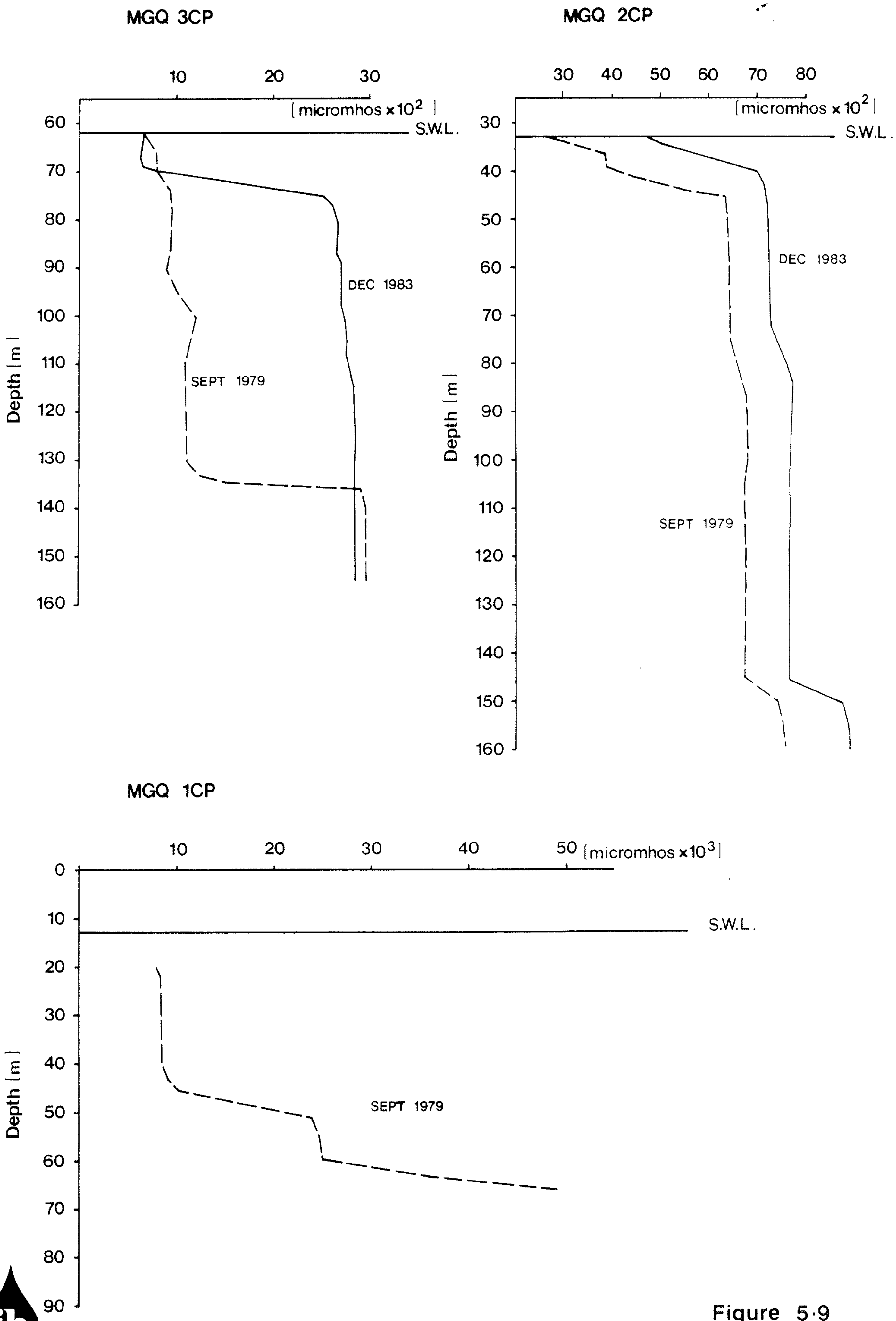


Figure 5·9

difference is much less and the problem is not so acute. A repeat log of MGQ-1CP was not possible because of access problems. Thus although we are able to show that large scale inland movement of the interface has not taken place, any local movement at the site of MGQ-1CP remains unrecorded.

5.5.5 Stable isotopes

Determination of the stable isotopes oxygen-18 (^{18}O) and deuterium (D) have been made at selected sites to provide a further and independent assessment of the source and distribution of recharge (Table 5.2). Results are presented in conventional form in terms of the per mil deviation of the isotopes from that of the International Standard Mean Ocean Water as shown in Figure 5.10.

Deuterium and oxygen-18 occur in small quantities in all natural waters as ($HD^{18}O$) and ($H2^{18}O$). Variations in their concentration depend upon the history of the water when in contact with the atmosphere. Changes in concentration take place during changes in the state of the water molecules as in evaporation or condensation. For example, evaporation tends to increase the concentration of isotopes with respect to its source.

The source in this instance is the Shebeelle river which itself is subject to changing evaporation rates throughout the year. During times of flood evaporation is low and stable isotope concentrations likewise remain generally low.

Typical concentrations are given by two samples taken during flood in 1977 (δD-29, $\delta^{18}O$-5.0) and 1983 (δD -1.2, $\delta^{18}O$+1.0). Here the range is considerable, but both are significantly lower than the istopically enriched sample collected at low flow during 1977 (δD+14, $\delta^{18}O$+26) (Fig. 5.10). These figures serve to show the link between river stage and isotopic concentration, together with the wide range likely to be encountered throughout any one year. In the absence of other data we have taken the two extreme values available to be representative of the annual range of river water isotopic composition.

TABLE 5.2

ISOTOPIC COMPOSITION
(1977 - 1979 DATA)

LOCATION		DELTA D (per Mil)	DELTA OXYGEN 18 (per Mil)
SHEBEELE (Low flow)		+ 14	+ 2.6
SHEBEELE (High flow)		- 29	- 5
MGQ	1P	+ 2.4	- 0.46
	2P	+ 4.9	- 0.07
	3P	+ 3.2	- 0.58
	4P	+ 4.3	- 0.9
	8P	+ 0.9	- 0.34
	9P	+ 1.0	- 0.72
	10P	- 2.9	- 0.22
	11P	- 0.8	- 0.17
	13P	- 3.2	- 0.40
MGQ	1CP	+ 4.8	+ 0.67
	2CP	+ 2.2	- 0.45
	3CP	- 3.6	- 0.89
MGQ	1T	- 1.9	- 1.10
	2T	- 3.3	- 0.58
	3T	+ 9.6	+ 1.17
	5T	+ 1.2	- 0.48
	6T	+ 7.4	- 0.38
AL1	AL10	+ 3	- 0.0
K23	AFGOOYE RD	+ 2	- 0.5
MILK FACTORY, MUQ		+ 1	- 0.8
K13	AFGOOYE RD.	+ 1	- 0.5
SL10T		+ 3	- 0.3
11A BALCAD RD. WELLFIELD		+ 1	- 0.7
15A BALCAD RD. WELLFIELD		+ 2	- 0.5
K5 SPAGHETTI FACTORY		- 1	- 1.2
SEA WATER		+ 7	+ 0.7

(1982 - 1983 DATA)

LOCATION	DELTA D (per Mil)	DELTA OXYGEN 18 (per Mil)
EO3	+ 2	- 0.3
EO4	- 2	- 0.6
EO5	0	- 0.2
EO6	+ 2	- 0.3
EO7	- 9	- 2.3
EO7	- 11	- 2.2
EO7A	+ 4	- 0.2
EO7A	+ 4	- 0.4
EO8	- 1	- 0.5
EO9TW	- 8	- 2.0
EO10	- 5	- 1.5
EO11	+ 3	- 0.5
EO13	- 11	- 2.6
EO14	+ 4	- 0.3
PW 11	+ 2	- 0.5
PW 14	+ 5	- 0.1
PW 15	+ 4	- 0.2
PW 16	+ 5	+ 0.1
PW 27	+ 2	- 0.3
PW 29	- 3.0	- 1.3
PW 32	0	- 0.2
OW5	+ 4	- 0.4
OW6	+ 2	- 0.7
OW4	+ 4	- 1.0
BH 5	+ 2	- 0.4
6	- 2	- 1.0
12	- 7.0	- 2.0
19	+ 4	- 0.1
34	+ 5.0	- 2.0
48	+ 5.0	+ 0.3

(1982 - 1983 DATA contd)

LOCATION	DELTA D (per Mil)	DELTA OXYGEN 18 (per Mil)
BH 55	+ 4.0	- 0.2
57	+ 5.0	- 0.7
63	+ 1.0	- 0.7
85	0	- 0.4
88	- 7.0	- 1.4
90	+ 2	- 0.6
94	0	- 0.8
98	- 9	- 2.1
RIVER (HIGH STAGE)	+ 1	- 1.2

Stable isotope distribution

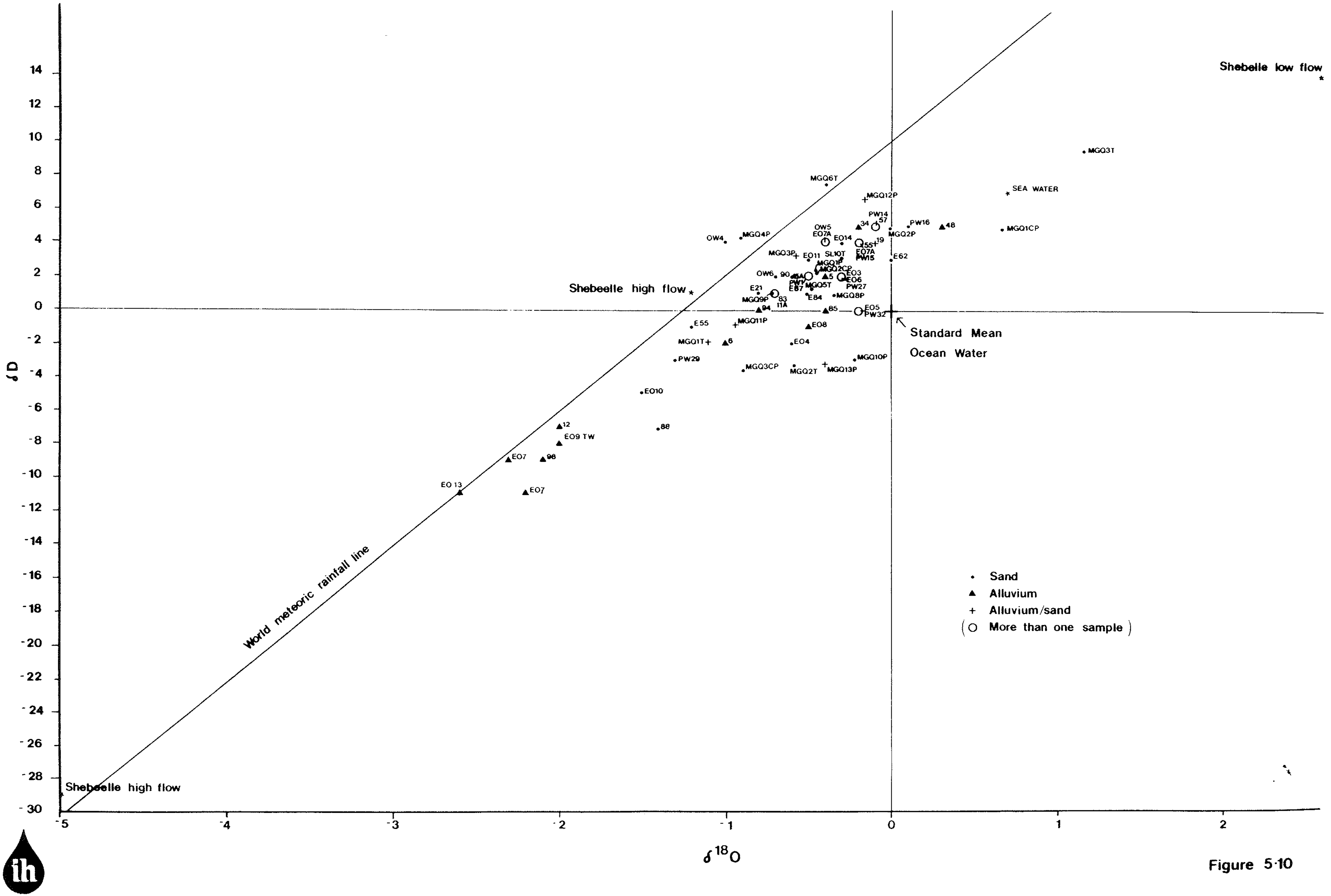


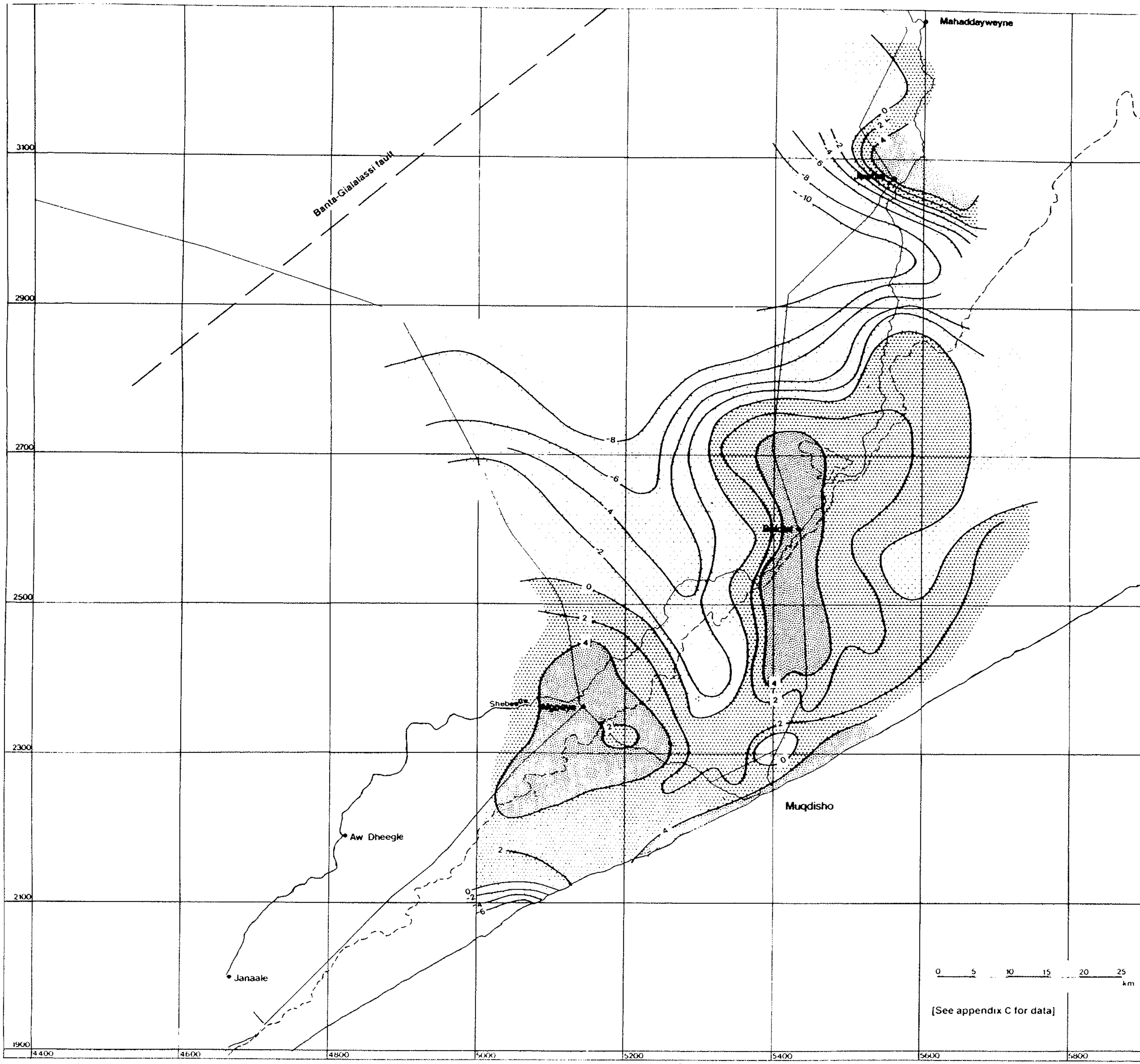
Figure 5·10

Bearing this in mind it is significant that all groundwater isotope values for our study area, numbering 65 in total, lie between these extremes, either on the World Meteoric Rainfall Line or to the side of the line which implies an evaporative oxygen-18 concentration (Fig. 5.10). A groundwater origin by recharge from the river is completely compatible with these results. Recharge over a range of flows is also implied with both high and low flow compositions being well represented. Once again the Shebeelle is confirmed as the sole significant source of recharge to the aquifer.

Stable istope concentrations observations confirm in a remarkable way the recharge pattern reflected by the distribution of conductivity. In Figure 5.11, which shows the distribution of deuterium, isotopically enriched zones in the vicinity of Balcad, Afgooye and Jawhar equate closely with those of low conductivity shown in Figure 5.8. At the same time isotopically depleted zones match with regions of high conductivity between Balcad and Afgooye and to the south of Jawhar. In effect high recharge zones are characterised by isotope enrichment while low recharge areas are isotopically depleted. The implication is that low flow infiltration is an important if not major contributor where large scale infiltration is taking place. In addition there is undoubtedly some contribution from overbank flood and irrigation water which also tends to be isotopically enriched by evaporation.

In contrast the isotopically depleted groundwater adjacent to low recharge zones might suggest that infiltration is restricted to periods of flood. But this is difficult to reconcile with its high conductivity since flood flows are usually equated with low salinity water. Instead we propose that these regions represent the remnants of an earlier groundwater body not yet replaced by the influx of more recent recharge. Replacement under these conditions are governed by rates of movement previously shown to be of the order of 10 m/year with the sand aquifer. As a result the process can be expected to take several thousand years.

Groundwater throughout much of the alluvium is also isotopically depleted. Again this tends to support our thesis that in this region groundwater is old and not directly related to the composition of present day recharge water. It is quite evidently the product of an earlier recharge regime.



Muqdisho
Water supply expansion

Deuterium concentration [δ D‰]

Figure 5·11

5.6 GROUNDWATER CHEMISTRY

5.6.1 Introduction

In this section the results of 108 chemical analyses, of which 60 were carried out during the current study, are used to achieve two objectives: firstly to establish overall groundwater quality in terms of potability, and secondly to help define groundwater origin and regions of active recharge. Full details of all analyses are presented in Appendix C.

5.6.2 Groundwater Quality

A good guide to the overall quality of water within the study area is given by the conductivity map shown in Figure 5.8. For domestic use we are, on the whole, interested only in water having a conductivity of less than 2000 micromhos/cm. This figure has been chosen on the basis of water quality criteria for drinking water standards in arid regions proposed by Schoeller and quoted by UNESCO in their guide for Ground-water studies and practice[1]. Such criteria take into account the particular problems of obtaining high quality water supplies in arid regions and as such are slightly more tolerant than WHO or EEC standards. In Table 5.3 the 2000 mg/l T.D.S. content is seen to mark the limit between 'moderate' and 'poor' drinking water. From the conductivity - TDS relationship for groundwaters in the study area established during our 1980 study this is equivalent to a conductivity of 2500 micromhos/cm. By taking 2000 micromhos/cm as the limiting acceptable quality therefore we are ensuring that all water within this contour will fall comfortably within the 'moderate' category as defined by Table 5.3.

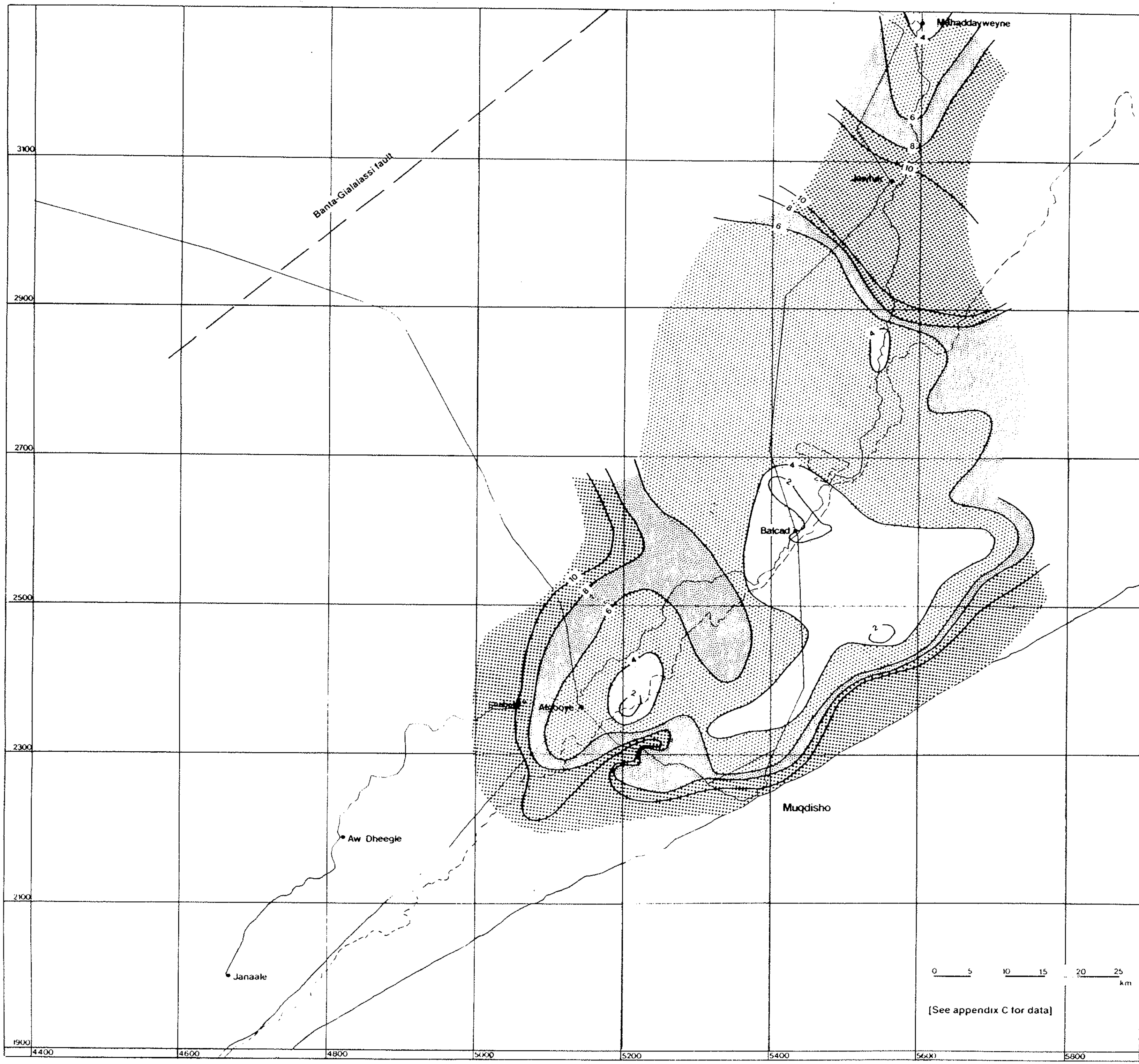
The potential for future groundwater development is restricted to

[1]Ground-water studies, an international guide for research and practice, Edited by R H Brown, A.A. Kononplyantsev, J. Inesun, V.S. Kovalevsky. UNECO.

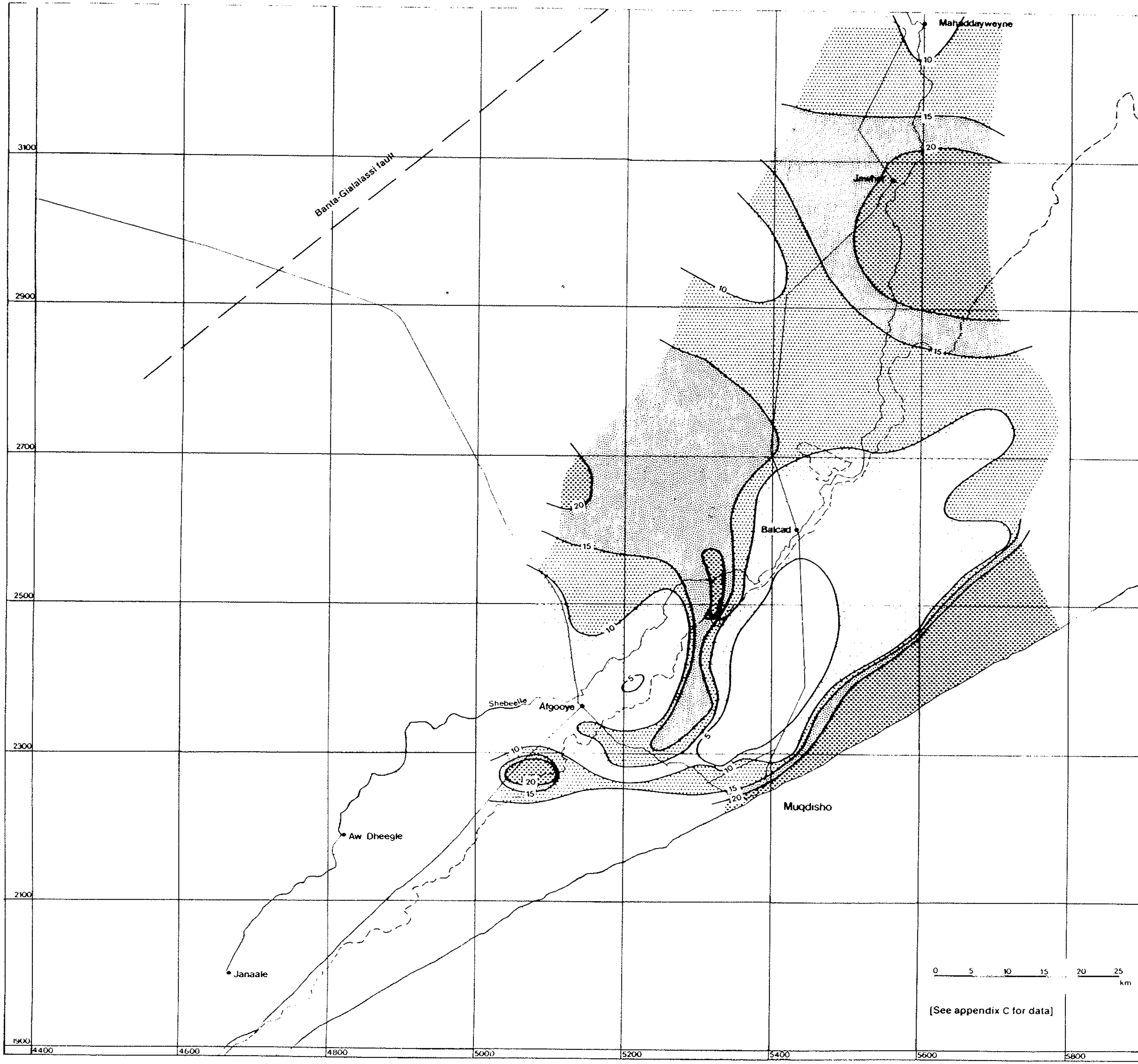
Muqdisho
Water supply expansion

Sodium concentration [m.eq/l]

Figure 5-12



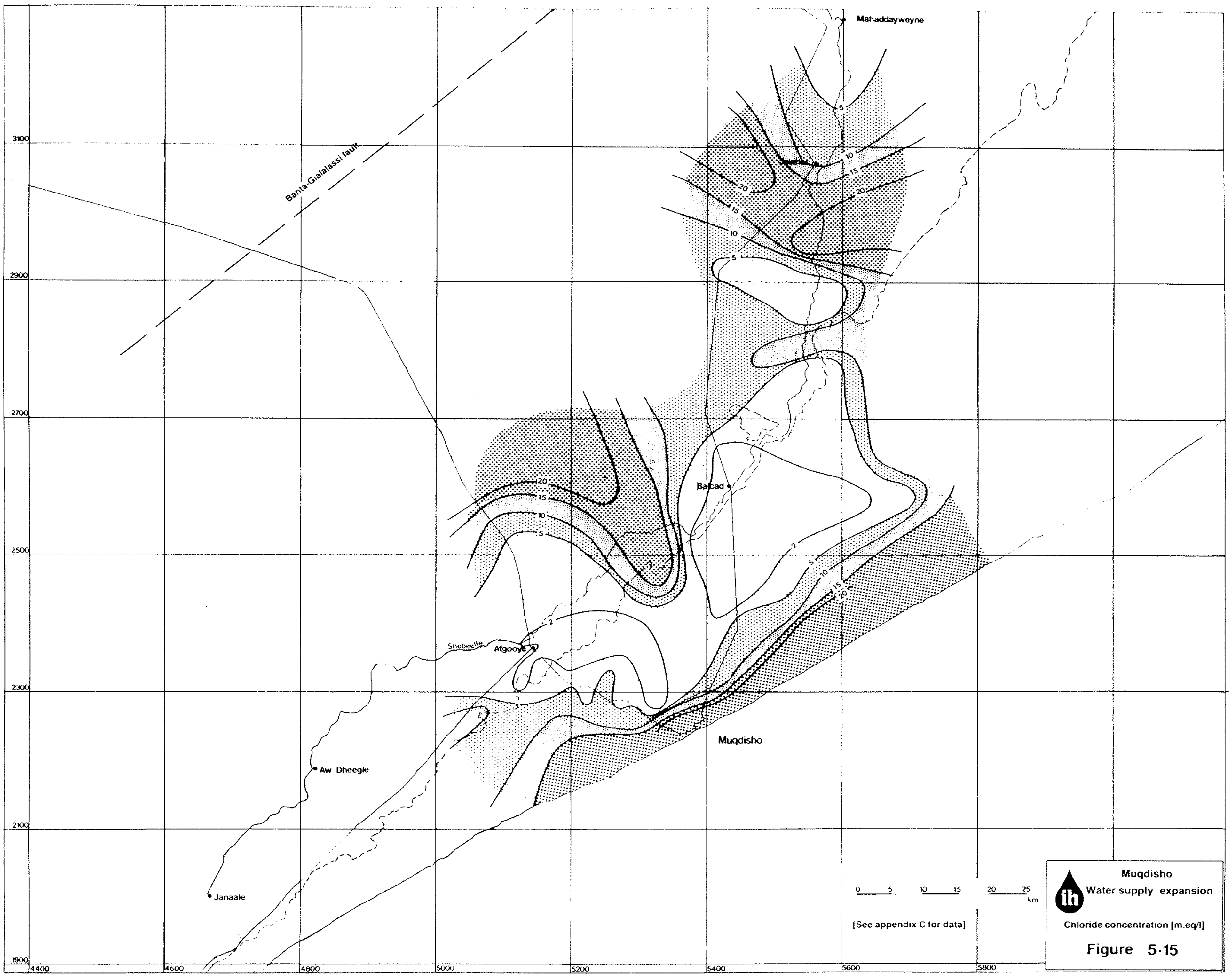
Muqdisho
Water supply expansion
Magnesium concentration [m.eq/l]
Figure 5-13



Muqdisho
Water supply expansion

Sulphate concentration [m.eq/l]

Figure 5·14



Muqdisho
Water supply expansion
Chloride concentration [m.eq/l]

Figure 5·15

the area encompassed by the 2000 micromhos/cm contour.

The largest such region lies along the length of the river between Afgooye to 20 km upstream of Balcad, extending coastward into the sand aquifer a distance of 25 km but reaching less than 5 km into the alluvial sequence inland (Figure 5.8). Within this zone resources in the Muqdisho, Balcad, Afgooye region are already utilised by existing wellfields or earmarked for future abstraction. Hence the only remaining area offering future potential is that to the northeast of the Balcad road, beyond the Stage IIB wellfield.

The overall quality of water encompased by the 2000 micromhos/cm contour is summarised in Table 5.3. This shows the concentrations of the major ions, with the exception of SO_4 to fall well below the upper limits of 'moderate' drinking water. Sulphate concentrations, however, do occasionally exceed its upper limit of 576 mg/l as for example at sites OW5 and PW2, within the Afgooye wellfield, where values of 629 mg/l and 700 mg/l respectively are recorded. However, although this slightly impairs the potability of the water it is not necessarily harmful and as such can be accepted at the concentrations encountered, particularly as it is to be mixed with better quality water from other wellfields.

TABLE 5.3 WATER QUALITY AND SUITABILITY FOR DOMESTIC USE IN ARID REGIONS

Study Area:
Range of Concentration (mg/l) — Suitability for Domestic Use

Within 2000 micromhos/cm contour	Element	Good	Fair	Moderate	Poor
-	ODOUR	Odourless	Hardly	Slight	Slight
-	TASTE	None	Perceptible	Pronounced	Unpleasant
-	TDS	0-500	500-1000	1000-2000	2000-4000
18-161	NA	0-115	115-230	230-460	460-920
12-100	MG	0-30	30-60	60-120	60-120
37-245	CL	0-177	177-355	355-710	710-1420
100-1000	SO_4	0-144	144-288	288-576	576-1152
36-180	*No^3	45	45	45	45
Less than 20					

*WHO limit

5.6.3 Groundwater chemistry; origin and evolution

Groundwater chemistries have been grouped based on whether they fall within or outside recharge zones. In this instance a 'recharge zone' is taken to be a region of groundwater having a conductivity below 2000 micromhos/cm. On this basis, three types of groundwater environment have been recognized:-

1. 'Recharge Areas', where groundwater conductivity is less than 2000 micromhos/cm.

2. 'Non-Recharge Areas' of old groundwater, situated inland and having conductivities in excess of 2000 micromhos/cm.

3. 'Coastal' groundwaters, where some mixing with sea water has taken place to give conductivities generally in excess of 2000 micromhos/cm.

The major characteristics of each group and of the source water are summarised in Figure 5.16 and Table 5.4. To begin, we investigate the chemical nature of the recharge source, the river Shebeelle.

(a) The source water

Three analyses of river water are available. These include both high and low flow discharge waters having conductivities ranging between 470-700 micromhos/cm.

By using a notation which excludes ions present in amounts less than 20% of either anion or cation totals, the water can be described as a Ca: SO_4 - HCO_3 type. The maximum recorded concentrations of dominant ions in this group are 110, 212 and 158 mg/l for calcium, sulphate and bicarbonate respectively.

Figure 5.16 presents the data in a trilinear diagram using percentage rather than absolute concentrations of ions to locate points. It provides an effective means of grouping together groundwater of similar chemical characteristics. In this case river

Conductivities (micromhos/cm)

'Recharge' area

6T	812
E04	1150
E4	730
SL10T	1000
1T	900
4P	995
83	1154
85	1833
E61	960
19	1144

'Non recharge' areas

12	5000
11P	4130
57	3720
6	6900
E010	3600
E07	7300
E01	7200
89	2040
E08	3300
E09	2900
E013	2100

'Coastal' areas

1CP	42000
2CP	2800
3CP	1300
E32	2720
88	6580
87	4570

Principal geochemical fields

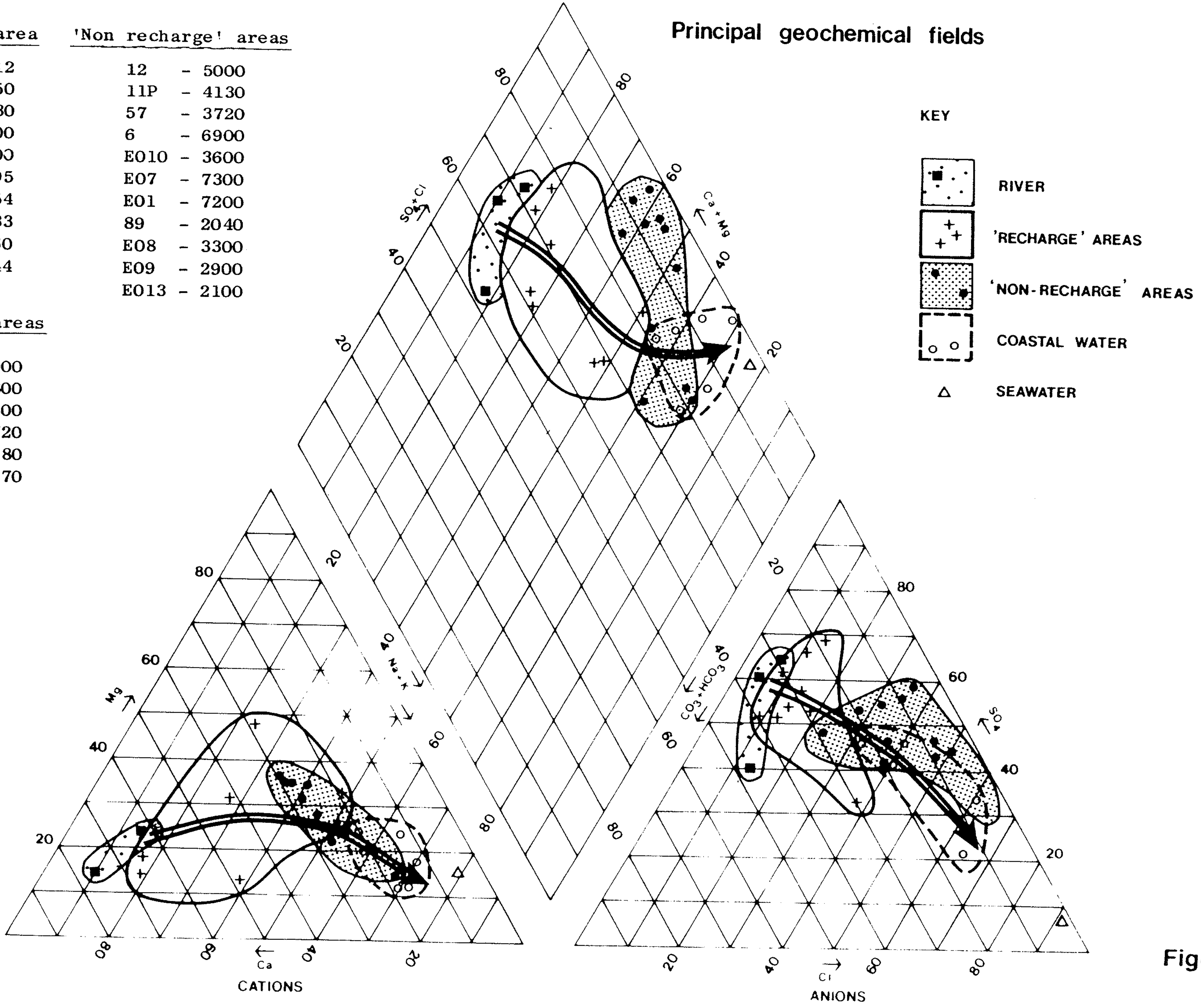


Figure 5.16

TABLE 5.4 Principal geochemical fields

	'RECHARGE' AREAS							RIVER			'NON-RECHARGE' AREAS				COASTAL AREAS			
ME/L	MGQ-1T	MGQ-4P	MGQ-6T	E4	E61	83	85	RIVER	RIVER	RIVER	57	MGQ-11P	E07	E01	MGQ-1CP	MGQ-2CP	MGQ-3CP	87
Ca	3.89	5.9	8.06	2.43	1.37	3.59	4.59	4.47	3.18	5.49	12.77	15.33	20.7	16.97	92.1	8.55	3.77	6.09
Mg	2.91	1.6	1.74	1.97	2.83	3.45	5.35	1.66	1.02	1.11	15.63	19.67	22.7	16.45	62.3	7.87	4.43	8.88
Na	2.39	4.02	2.17	1.96	3.38	4.79	10.66	0.97	0.86	0.65	16.97	17.39	35.3	36.97	343.6	23.1	9.57	34.8
K	0.15	0.18	0.21	0.11	.13	0.12	0.07	0.12	.09	0.13	0.2	0.26	0.3	0.24	6.8	0.32	0.18	0.25
HCO_3	3.20	4.4	2.80	3.2	2.5	3.49	3.64	1.97	2.40	2.60	6.10	4.4	3.87	5.41	2.8	5.2	3.2	10.6
SO_4	4.59	5.99	8.00	6.46	4.0	6.25	14.57	4.37	2.04	4.41	24.98	29.7	35.81	37.48	51.3	18.7	7.4	23.9
CL	1.21	1.18	1.38	1.74	1.13	2.26	2.82	0.45	0.62	0.33	14.66	18.4	39.48	36.1	450.7	15.8	7.3	16.2
Na:Cl	1.97	3.40	1.57	1.12	2.99	2.1	3.78	2.15	1.38	1.96	1.1	0.94	0.89	1.0	0.76	1.46	1.3	2.1
Ca:Mg	1.33	3.68	4.63	3.77	0.48	1.0	0.85	2.69	3.11	4.9	0.81	0.77	0.91	1.0	1.4	1.08	0.85	0.6
MG/L																		
Ca	77.9	118.2	161.5	148.8	27	72	92	90	63.7	110.0	256	307	415	340	1846	171	76	122
Mg	35.4	19.4	21.1	23.9	34	42	65	20	12.4	13.5	190	239	277	200	758	96	54	108
Na	54.9	92.4	49.9	45.0	78	110	245	22	19.7	14.9	390	400	812	850	7899	532	220	800
K	6.0	7.2	8.4	4.4	5	4	3	5	3.6	5.2	8.0	1.0	12	9.0	266	13	7	10
HCO_3	195.1	268.2	170.7	195.1	153	213	222	120	146.3	158.5	372	268	236	330	171	317	195	649
SO_4	220.6	287.9	384.6	310.5	192	300	700	210	98.0	212.0	1200	1426	1720	1800	2646	901	356	1150
CL	42.9	41.8	55.7	61.7	40	80	100	16	110.2	173.7	520	654	1400	1280	15982	563	260	575

water samples plot at the left hand side of each of the three fields, reflecting the dominance of calcium, sulphate and bicarbonate ions.

This type of water is consistent with the river having passed over outcrops of limestone and evaporite along its upper reaches, before entering the study area.

(b) 'Recharge Area' groundwater

Within these recharge zones groundwater conductivity is everywhere less than 2000 micromhos/cm. However, concentrations of individual ions are invariably increased with respect to river water, with the occasional exception of calcium. This increase is caused by solution of evaporite minerals during infiltration through alluvial silts and clays underlying the river. During its passage the water evolves into a Ca-Na: SO_4 - HCO_3 type.

Table 5.4 shows the concentrations of sodium, magnesium and sulphate to have been significantly increased with respect to river water. For each ion, maximum values of 245, 65 and 700 mg/l respectively, are recorded. On the other hand calcium and bicarbonate levels increase very little or in the case of calcium even decline. Such a trend is probably related to the precipitation of calcium bicarbonate cement within sand aquifers, together with cation exchange reactions of calcium for sodium on clay mineral surfaces.

When translated to a trilinear diagram (Figure 5.16) the trend of groundwater evolution becomes clearer. The percentage increase of sodium and chloride at the expense of calcium and bicarbonate has pushed this group of water more toward the right of each field in the direction of seawater composition. At the same time, however, the wide spread of points indicates considerable variation within the group, reflecting the fact that local geology plays an important role in determining the precise composition.

(c) 'Non Recharge Area' groundwater

These are regions of old groundwater that have not yet been displaced by the influx of fresh water at present being released from the Shebeelle. The water has, in places, been in residence for several thousand years and is the product of an earlier recharge regime, having, perhaps, a source water of different composition.

Conductivity is invariably in excess of 2000 micromhos and concentrations of individual ions are significantly increased in respect to both river water and 'recharge area' groundwater. At the same time it has evolved into a Na-Ca: SO_4-Cl type.

The concentration of individual ions on occasion reaches very high levels. For example, at site E01 sulphate, chloride and sodium concentrations are as high as 1800, 1280 and 850 mg/l respectively. Build up of salinity to this level is consistent with long residence times and continued solution of evaporite and associated minerals, particularly within the alluvial sequence.

On a trilinear diagram the group plots off the main trend line from river to 'recharge area' water to sea water (Figure 5.16). It is displaced by having increased percentages of magnesium and chloride at the expense of sodium and bicarbonate. This causes the sodium-chloride ratio to approach unity and suggests that long term solution of halite salts within alluvium and sand is a dominant control on the occurrence of these two ions. In the same way the build up of magnesium can probably be related to solution of magnesium-rich evaporites.

A few points, however, do plot on the river - 'recharge area' - seawater trend due to the presence of increased percentages of sodium and bicarbonate. These include samples from sites E09, E013, E08 and BH 89, all of which are within approximately 20 km of each other. They are located at the boundary of 'recharge' and 'non-recharge' areas and as such probably represent a mixture of both types of water. It is this mixing that probably accounts for their plotted position away from the main group of 'non-recharge' waters.

(d) 'Coastal' groundwater

Along the coast, for maximum distances of up to 15 km inland, intrusion of the saline interface has resulted in mixing of sea and groundwater.

Conductivity is generally above 2000 micromhos/cm but very variable depending upon the degree of mixing that has taken place. For example, within a kilometre of the coast conductivities can exceed 42000 micromhos/cm (eg MGQ-1CP) yet be as low as 1300 micromhos/cm a further 4 km inland (eg MGQ 3CP).

The zone of mixing has extended furthest inland along the coast to the north of Muqdisho. Here it reaches inland up to 15 km and is well illustrated by Figures 5.12 and 5.15 showing the distribution of Na and Cl concentrations respectively.

Overall water within this zone is of a Na: Cl-SO4 type. On a trilinear diagram the group plots between the composition of sea water and that of 'recharge area' water thus testifying to its mixed origin.

5.6.4 Summary

This work has confirmed the potability of groundwater within 'recharge zones' having a conductivity less than 2000 micromhos/cm. The pattern of individual ion distribution has at the same time confirmed the location of 'recharge zones' identified independently through stable isotope, temperature and conductivity data.

Also by plotting and grouping data into 'recharge', 'non-recharge' and 'coastal' zones, it has been possible to show that groundwaters from each of these regions have distinctly different chemical signatures.

5.7 SURFACE WATER STUDIES

5.7.1 Introduction

Up to this point we have been dealing with evidence that indirectly links river infiltration to groundwater recharge. With this evidence we have been able to establish a conclusive relationship between the two and at the same time highlight areas of maximum and minimum recharge. But no quantitative estimates have been possible, nor have we been able to separate recharge into its two main components; river bed and irrigation infiltration.

In this section, however, the results of an independent surface water study provides estimates of these two components of recharge. The work draws upon the published results of earlier studies and upon data collected during field visits made during 1982-83.

5.7.2 Recharge from the Shebeelle

As discussed earlier, all aspects of our groundwater studies conclude that the Shebeelle is the major source of recharge to the deep aquifer system. However, such recharge may occur either directly through the bed and banks of the river or indirectly from excess irrigation water abstracted from the Shebeelle; we have attempted to quantify the two recharge components separately although only the total recharge is required as a means of establishing the safe long term yield of the aquifer.

Direct estimation of recharge is not possible given the available data although a number of means of quantifying recharge in a rather crude manner may exist. Indirect evidence for the river as a source of recharge was provided by Huntings and MacDonald in 1969 in the form of an extensive regional groundwater mound beneath the Shebeelle. This was supported by flow gaugings at pairs of stations which indicated bed seepage losses which could not be accounted for solely by evaporation or irrigation abstractions. Similarly a programme of current metering was carried out in January 1979 by the Institute of Hydrology and reported on in our 1980 report. Accurate current meter measurements of dry season flows were made at Balcad and Afgooye in an attempt to measure seepage losses. However, the discharge at Balcad was about 18 m^3/sec and the apparent flow loss of 0.7 m^3/sec between Balcad and Afgooye was of the same order of magnitude as the measurement errors of the flow gaugings. Thus direct estimation of seepage losses by measurement of river flows is an imprecise method and whilst it can indicate that recharge may be taking place, it cannot accurately quantify such recharge.

In our 1980 report we further examined monthly flows at Balcad and Afgooye hoping to be able to quantify seepage losses. However, for the period of 1958 to 1968, 45 per cent of the recorded months showed flow increments along the reach rather than losses. This was considered to be unrealistic as there are no tributary inputs. In the present study, some of the flow data has been re-examined and the analysis has been repeated, not just for the reach from Balcad to Afgooye, but also for Mahadday Weyne to Balcad and Afgooye to Aw Dheegle. This revised study has similarly been very inconclusive and has not enabled seepage losses to recharge to be quantified.

A further study was undertaken using a simple water-balance accounting model of each river reach. Inflows to the reach in any month were taken as the flows at the upper gauging station. Outflows were the sum of flows at the lower gauging station of the reach plus irrigation abstractions plus evaporation losses. The difference between inflow and outflows was assumed to be an estimate of recharge as the water balance equation given below shows:-

$$\text{Recharge} = Q_{us} - Q_{ds} - RAI - EVAP$$

where

Q_{us} = Upstream station monthly inflow (all figures in million cubic metres)

Q_{ds} = Downstream station monthly outflow

RAI = River abstractions for irrigation from Tables 10.10(a), (b) or (c)

EVAP = Evaporation losses from the Shebeelle

This study proved to be almost as unreliable as those discussed above as for many months there were large negative recharges estimated, which is not possible. However, during many of the high flow months a fairly consistent pattern of recharge was suggested in most years. This was particularly true of the Der floods in October and November and was generally observed, to a lesser extent, in May and June.

The study again demonstrated that recharge from the Shebeelle occurred but was unable to quantify this in any reliable way. To an extent the observation that the water balance equation generally suggested positive recharge more often in high flow months than dry season months agrees with our comments in the 1980 report that recharge appeared to be more significant at high stages. However, because the RAI term tends to dominate the equation during dry months, there is greater scope for negative apparent recharges.

One final means of attempting to quantify direct recharge from the Shebeelle was considered. The river channel lengths were measured from the 1:100,000 scale maps for the three reaches of interest and results are shown in Table 5.5. From observations made by our staff and a number of other sources, we have taken the average river width as 40 metres at bankfull stage. The channel lengths given in Table 5.5 have been multiplied by the average width to obtain an estimate of the total horizontal bed area of the Shebeelle in each reach. These bed areas do not include an allowance for lateral seepage into the river banks which may subsequently move vertically downwards as recharge. An average bank height of 5 metres has been assumed, giving a wetted perimeter of 50 metres. This wetted perimeter has been multiplied by the river lengths of each reach to produce an estimate of the total wetted area of the river at bankfull stage. This figure is an upper limit estimate of potential recharge area; for considerable parts of the year river stages will be low and the wetted perimeter adopted will be an overestimate. However, because an attempt is being made to estimate the likely range of recharge from the Shebeelle, this overestimation is considered to be reasonable.

TABLE 5.5 River lengths and surface areas

Reach	Length (km)	Horizontal bed area (million m^2)	Total wetted perimeter area (million m^2)
Mahadday Weyne to Balcad	114	4.56	5.70
Balcad to Afgooye	66	2.64	3.30
Afgooye to Aw Dheegle	64	2.56	3.20

The material of the bed and banks of the Shebeelle is primarily silty clay. It is believed that isolated silty sand areas are not hydraulically linked to the deeper aquifer but are perched above less permeable silts and clays. Estimation of possible seepage rates through the bed and bank material is difficult. Ring infiltrometer tests would not be appropriate partly because this method generally overestimates infiltration due to edge effects and fissuring. A second problem with infiltrometers is that they operate with driving head of only a few centimetres of water while the Shebeelle stage varies from almost zero to 5 or 6 metres. A number of theoretical formulae exist for estimating surface infiltration rates such as Green-Ampt (Clapp & Hornberger, 1978) but these are also unsuitable for situations with a driving head of several metres of water. Thus because of the complex nature of the infiltration or seepage process, direct measurement or estimation of the magnitude of the seepage is not possible for the Shebeelle. The best that can be attempted is indirect estimation of the seepage rates.

For their design of the Jawhar Offstream Storage Reservoir, Sir M. MacDonald & Partners (MMP 1973) suggested an initial seepage value of 5 mm/day which might reduce over a period of years to 2 mm/day. We have studied this assumption in section

5.7.4, where an overall average seepage loss rate of 0.4 million cubic metres per day was observed. This rate occurs over a varying surface area and was for early years in the reservoir's life. The average reservoir area during the period for which seepage losses were computed has been taken as 60 km^2, giving a daily seepage rate of 6.7 mm/day. This agrees well with the 5 mm/day estimate of MacDonalds and may well be indicative of possible seepage rates in the Shebeelle. It is probable that these early seepage rates will fall off somewhat in future years as the bed of the reservoir is blanketed by fine material brought in from the Shebeelle.

It was decided that a value of 5 mm/day be adopted as a best estimate of a seepage rate for the Shebeelle but a lower estimate of 2 mm/day and an upper estimate of 10 mm/day were also considered. These three rates were applied to the area estimates of Table 5.5 and results are given in Table 5.6.

TABLE 5.6 Recharge estimates from the Shebeelle river (all figures in million cubic metres per year)

Reach	Probable lower Limit (a)	"Best Estimates" Bed Seepage Only (b)	"Best Estimates" Wetted Perimeter Seepage (c)	Probable Upper Limit (d)
Mahadday Weyne to Balcad	3.33	8.32	10.40	20.81
Balcad to Afgooye	1.93	4.82	6.02	12.04
Afgooye to Aw Dheegle	1.87	4.67	5.84	11.68

Notes (a) 2 mm/day seepage rate over bed area only
(b) 5 mm/day seepage rate over bed area only
(c) 5 mm/day seepage rate over wetted perimeter
(d) 10 mm/day seepage rate over wetted perimeter

It is apparent that the best estimates of the river seepage to recharge over the entire wetted perimeter for the Balcad to Afgooye reach are significantly lower than the 40 million m^3 estimate adopted in our 1980 report. The figure of 40 million m^3 implies a seepage rate of 41.5 mm/day or 1.7 mm/hour which is believed to be unrealistically high for the silty clay alluvial material of the Shebeelle bed and banks. In our 1980 report, however, no attempt was made to distinguish between recharge from the Shebeelle and from the adjacent irrigated areas. It was recognised that recharge could take place from both although differentiating between the two possible mechanisms was not thought to be important. This present study is considering future abstractions from the Shebeelle by other users, principally for irrigation, and so estimation of the recharge from separate sources has been necessary.

The magnitude of possible recharge inputs from the irrigated areas is discussed in the following section and this is followed by an examination of recharge from the new offstream storage reservoir at Jawhar. The total recharge estimates may then be compared with the inferred recharge from the groundwater model.

5.7.3 Recharge from irrigation

Estimates of the area presently irrigated in each river reach are given in Table 10.7 of Section 10.2.1.

Various studies have estimated the overall irrigation efficiency of the methods presently used in Somalia. We have adopted the value used by MacDonalds (MMP 1978) and Huntings (HTS 1977) of 45%. This is made up of 75 per cent distribution channel efficiency and 60 per cent field efficiency. These figures imply that 25 per cent of the water abstracted from the Shebeelle is lost as either evaporation or seepage from the distribution channels and that 40 per cent of the water applied to the field is similarly lost.

Much of the water lost from the distribution channels may be evaporated either from the channel, standing water beside the channel or from wet soil. Similarly some of the water that infiltrates into the soil may be transpired by crops or natural vegetation. However, a proportion of the seepage losses into the soil will pass, via deep percolation, to the deeper aquifer system. Similarly, although most of the water losses within the field may be lost as evaporation from the soil or standing water, a proportion is likely to percolate to groundwater.

It is not possible to estimate directly how much of the 55 per cent overall irrigation water loss goes to evaporation and how much provides recharge via percolation. In their Inter-Riverine Study, (HTS, 1977), Huntings adopted a figure of 16.7 per cent deep percolation loss, which is approximately 30 per cent of the overall 55 per cent losses go to recharge. This seems a reasonable assumption and has been adopted here. However, in view of the uncertainties associated with this estimate, a possible lower and upper limit recharge estimate of 9 and 30 per cent respectively of the total abstraction have also been quantified as well as the best estimate of 16.5 per cent.

The total river abstractions for irrigation given in Tables 10.10(a), (b) and (c) of Chapter 10 have already included an allowance for the assumed overall irrigation losses of 55 per cent. Thus the best estimate of recharge may be computed by multiplying these river abstractions by 0.3 x 0.55 = 0.165 as shown in Table 5.7 below. The likely upper and lower recharge estimates are also given in this Table.

TABLE 5.7 Recharge from Irrigated areas (Present conditions)

(all figures in million cubic metres)

Reach	Total River Abstractions for Irrigation	Best Estimate of Recharge	Lower Limit Estimate	Upper Limit Estimate
Mahadday Weyne to Balcad	213.0	35.1	19.2	63.9
Balcad to Afgooye	110.6	18.2	10.0	33.2
Afgooye to Aw Dheegle	67.1	11.1	6.0	20.1

5.7.4 Recharge from the Jawhar Offstream Reservoir

An offstream storage reservoir, of 206 million m^3 maximum storage, was brought into service in 1979 by the irrigation department in conjunction with MacDonalds. The intake canal at Sabuun is operated to direct Shebeelle flows in excess of 100 m^3/s to storage, for augmentation of dry season irrigation.

It is also intended to dispose of drainage water from the Jawhar sugar estate by pumping into the reservoir but there are no detailed plans for this development at present so this option has not been considered.

The irrigation department have kept comprehensive daily records of the upstream and downstream Shebeelle river flows, the inflows and outflow and the water level of the reservoir since 1981. A simple water balance model has been developed, using these inputs and evaporation from Afgooye, to investigate possible seepage losses from the reservoir.

The model is based on the equation

$$S(i) = Qin(i) - Qout(i) - Evap(i) - \Delta Stor(i)$$

Where S(i) = Seepage during day (i)

Qin(i) = Flow diverted to storage from Saburn during day (i).

Qout(i) = Releases from storage during day (i).

Evap(i) = net evaporation (Eo - Rainfall) calculated over the surface area during day (i).

ΔStor(i) = change in storage during day (i).

Daily seepage and the summation of daily seepage have been calculated between May 1981 and March 1982 using this model. An example of these results are shown in Table 5.8. The seepage estimates are erratic, sometimes varying from positive to negative on a daily basis. This is due to the difficulty of measuring small differences in flows and also the variation in time of daily measurements. To combat these problems the summation of daily seepage was examined but these also indicated periods of apparently unusual behaviour.

When inflows or outflows are recorded the seepage inferred by the model is negative. This indicates a shortfall in the water balance requiring additional storage input, but all the known inputs have already been included. We assume, therefore, that the inflows or outflows are not noted with sufficient accuracy to achieve sensible results from the model. Consequently we have only used periods where the reservoir has not been affected by inflows and outflows for the seepage estimation. The average seepage rate was thus calculated over the period 5th November 1981 to 21st December 1981 resulting in an observed seepage of 18.74 million cubic metres or 0.4 million cubic metres per day. The seepage rate is likely to be affected by the head of water in the reservoir and also the siltation of the bed of the reservoir. Two periods from the 1982 data were chosen and the average seepage rates calculated are shown in Table 5.9.

Table 5.8

Section of Output from JOSR Model (million m³)

DAY NUMBER	Δ STOR	INFLOW	OUTFLOW	EVAP	SEEPAGE	CUMULATIVE SEEPAGE
85	0.	0.	0.	0.1759	-0.1759	-9.757
86	-1.00	0.	0.	0.1757	0.8243	-8.933
87	0.	0.	0.	0.1755	-0.1755	-9.108
88	0.	0.	0.	0.1755	-0.1755	-9.284
89	0.	0.	0.	0.1755	-0.1755	-9.460
90	0.	0.	0.	0.1755	-0.1755	-9.635
91	-1.00	0.	0.	0.1754	0.8246	-8.810
92	0.	0.	0.	0.1752	-0.1752	-8.986
93	-1.00	0.	0.	0.1750	0.8250	-8.161
94	-1.00	0.	0.	0.1746	0.8254	-7.335
95	-1.00	0.	0.	0.1742	0.8258	-6.509
96	-1.00	0.	0.	0.1739	0.8261	-5.683
97	0.	0.	0.	0.1737	-0.1737	-5.857
98	-1.00	0.	0.	0.1735	0.8265	-5.030
99	0.	0.	0.	0.1733	-0.1733	-5.204
100	-1.00	0.	0.	0.1731	0.8269	-4.377
101	0.	0.	0.	0.1729	-0.1729	-4.550
102	0.	0.	0.	0.1729	-0.1729	-4.723
103	-1.00	0.	0.	0.1727	0.8273	-3.895
104	0.	0.	0.	0.1726	-0.1726	-4.068
105	-1.00	0.	0.	0.1723	0.8277	-3.240
106	-2.00	0.	0.	0.1719	1.8281	-1.412
107	0.	0.	0.	0.1715	-0.1715	-1.584
108	-1.00	0.	0.	0.1711	0.8289	-0.755
109	-1.00	0.	0.	0.1706	0.8294	0.075
110	0.	0.	0.	0.1704	-0.1704	-0.096
111	-1.00	0.	0.	0.2303	0.7697	0.674
112	-1.00	0.	0.	0.2297	0.7703	1.444
113	-1.00	0.	0.	0.2291	0.7709	2.215
114	-1.00	0.	0.	0.2286	0.7714	2.986
115	-1.00	0.	0.	0.2283	0.7717	3.758
116	-1.00	0.	0.	0.2276	0.7724	4.531
117	1.00	0.	0.	0.2273	-1.2273	3.303
118	0.	0.	0.	0.2277	-0.2277	3.076
119	-1.00	0.	0.	0.2273	0.7727	3.848
120	0.	0.	0.	0.2269	-0.2269	3.621
121	0.	0.	0.	0.2269	-0.2269	3.395
122	-1.00	0.	0.	0.2265	0.7735	4.168
123	-1.00	0.	0.	0.2257	0.7743	4.942
124	0.	0.	0.	0.2253	-0.2253	4.717
125	-1.00	0.	0.	0.2249	0.7751	5.492
126	0.	0.	0.	0.2245	-0.2245	5.268
127	-1.00	0.	0.	0.2241	0.7759	6.044
128	-1.00	0.	0.	0.2233	0.7767	6.820
129	-1.00	0.	0.	0.2225	0.7775	7.598
130	-1.00	0.	0.	0.2217	0.7783	8.376
131	-1.00	0.	0.	0.2209	0.7791	9.155
132	-1.00	0.	8.60	0.2201	0.0369	9.192
133	-1.00	0.	8.00	0.2192	0.0896	9.282
134	-1.00	0.	8.00	0.2184	0.0904	9.372

* 5/11/81-21/12/81 = Days numbered 85 to 131

Table 5.9 Seepage rates calculated

Period	Water Level (m)	Seepage Rate (million cubic metres/day)
Nov - Dec 1981	3.6	0.4
April 1982	1.5	0.58
June - Aug 1982	2.65	0.12

However, there is no evidence to suggest that the seepage rates are connected with the water level nor for a possible silting of the reservoir bed. There are insufficient data to draw any other conclusions than that seepage does occur and would seem to be of the order of 0.4 million cubic metres per day (or 146 million cubic metres per year). This is a substantial recharge component and could make some difference to the aquifer resource in the future. It will tend to recharge perched aquifers that have been identified in the area and any contribution to the deep sand aquifer could be much smaller than 146 million cubic metres. The recharge in the Jawhar/Mahadday Weyne reach will not be directed towards Muqdisho but should cause a recharge mound, leading to additional flow to the coast north of Muqdisho.

MacDonalds carried out seepage tests on the reservoir site before the construction of the canals. They concluded that the initial seepage rate would be between 0.75 and 0.00 mm/hr with an average of 0.21 mm/hr and they suggested a long term seepage rate of 2 mm/day. Assuming an average wetted area of 60 km^2 the initial expected seepage rate would be 0.30 million cubic metres per day.

5.7.5 Discussion

Ignoring for the moment the effects of the recently constructed offstream storage reservoir at Jawhar, the principal source of recharge at present appears to be excess irrigation water. Thus for the Balcad to Afgooye reach, our best estimate of annual recharge at present is 18.2 million cubic metres. Our best estimate of recharge from the Shebeelle for the same reach, over the entire wetted perimeter of its bed and banks, is 5.78 million cubic metres. The total estimated recharge is 24 million cubic metres.

It is suggested, however, that the present recharge estimates provide a fuller understanding of the recharge process. Hence the implications of future changes in irrigation on recharge may be considered and the effects on long term safe yield of the aquifer system examined.

The new offstream storage reservoir already appears to be providing a large recharge component to a perched aquifer system. In time this significant source of recharge may percolate down to the main source aquifer.

The best available estimates of recharge suggest that the deep aquifer system is capable of meeting a substantial part of Muqdisho's future water demands. Because of the heavy present and proposed demands on Shebeelle water for irrigation, it seems safer to rely on groundwater for the bulk of future water supplies. Our understanding of recharge mechanisms suggests that expansion of irrigation, provided traditional basin and furrow methods are used, will not have a detrimental effect on the aquifer. In fact the opposite appears to be the case; an expansion of the areas irrigated should lead to increased recharge in the long term.