

**SUDAN
WATER RESOURCES MANAGEMENT PROJECT
SD/90/001**

FINAL MISSION REPORT

**TRAINING IN MODFLOW GROUNDWATER MODELLING
AND THE
DEVELOPMENT OF GROUNDWATER MODELS
FOR THE GASH BASIN (KASSALA) AND WADI NYALA (NYALA)**

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- Development of groundwater models for the Gash basin and Wadi Nyala
- Prepared for : Ministry of Energy and Mining,
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Khartoum, Sudan
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- Directorate General of
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Ministry of Foreign Affairs,
The Hague, The Netherlands
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Abbreviations

IC	=	Information Centre
GWRD	=	Groundwater Resources Department
NRWC	=	National Rural Water Corporation
PC	=	Project Coordinator
PM	=	Project Manager
TC	=	Technical Committee
WRM	=	Water Resources Management Project
PM	=	Processing MODFLOW; pre- and post-processor for the MODFLOW programmes; by W. Kinzelbach and W.H. Chiang, Germany.
MODFLOW	=	MODular three-dimensional finite-difference groundwater FLOW model; by M.G. McDonald and A.W. Harbaugh, U.S.G.S., U.S.A.

1 Introduction

This is the last and final report summarizing the results of a number of training missions, given by the TNO Institute of Applied Geoscience (TNO-IGG), to the Technical Committees (TC) in Nyala and Kassala. The general aim was to train both Technical Committees in the development of groundwater models for economically important alluvial aquifers near both towns. The activities have been carried out in the final stages of the Water Resources Management Project (WRM) funded by the National Rural Water Corporation, Khartoum and the Directorate General of International Cooperation, Ministry of Foreign Affairs, The Hague, The Netherlands

A first mission to both TC's was organized in november 1992 during which an on-the-job training was given to build a numerical groundwater model of the alluvial aquifers built up by the ephemeral rivers the Gash and Wadi Nyala. In this mission much attention was paid to the training aspects of constructing a model with the MODFLOW code (U.S. Geological Survey), operated from a users-friendly pre- and post-processing shell developed by Kinzelbach and Chiang. The whole sequence of steps starting with initial hydrogeological reconnaissance fieldwork, modelboundary and -parameter selection, model data input etc. was carried out at length to demonstrate all possible pitfalls and details of a modelling exercise. This approach with a strong emphasis on the component of training, instead of only building a full-fledged groundwater model, was strongly advocated from the beginning by the National Rural Water Corporation in Khartoum.

At the end of the first mission assignments were specified for both TC's to collect additional data on both alluvial aquifers. In the second mission, in May 1993, further improvement of the models, initially built, was achieved by entering newly collected data sets, mainly concerned with the geometry of the aquifers and groundwater abstraction rates. During this mission the understanding of the dynamics and general hydrological behaviour by sensitivity analyses can be mentioned as the main objectives.

In the final mission, held in October 1993 and reported in the following pages, the use of the developed models as tools in water management were highlighted. A major step in the

improvement of the models was achieved by a better estimation of the actual evapotranspiration from landuse and data on predominant crops, which was given as one of the assignments at the end of the mission 1 and 2. A reliable estimate of total groundwater abstraction is crucial in answering questions of whether overdraught occurs in both groundwater basins. These questions have been answered during this reported mission 3 and a number of scenarios have been formulated to meet with present and future water demands. An important element of the third mission was the preparation of a presentation, to be given by the TC managers in front of an audience consisting of members of the Water Board and other officials involved in water management, in which the results and present status of hydrogeological knowledge and modelling activities so far were reviewed and discussed.

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2 Mission to Nyala

2.1 Summary of the mission activities

Mr. M.E. Ibrahim (Project Manager, PM) and Dr. Izzeldin (Project Coordinator, PC) accompanied the TNO experts during the mission in Nyala. After arrival by airplane in Nyala, the program for the coming days was presented and as usual the results of the assignments given at the end of the second mission in May '93 were evaluated.

Additional data concerning the thickness of the Wadi aquifer in the downstream areas had unfortunately not yet been collected. The same went for the inventory of wells and abstraction rates, preferably at a monthly or seasonal basis. The TC proved to be more successful in the assessment of actual evapotranspiration values for both the town and downstream areas, taking into account the areas with horticulture, natural and man-made forests. As was already suggested at the end of the previous TNO mission, the calendar year should be divided into the following three model stress periods:

Table 2.1 Defined stress periods for the NYALA03 model.

Stress period	Season	Calendar months
I	Winter	10, 11, 12, 1 & 2
II	Summer	3, 4, 5 & 6
III	Wet	7, 8 & 9

For each season actual evapotranspiration values were derived based on monthly values for open pan evaporations corrected for crops and actual rates. The TNO mission was surprised to note that the evapotranspiration calculations had not been carried out on a computer but still by hand.

Another assignment was to define a new model NYALA03 based on NYALA02 incorporating this new division into three stress periods. Although a serious attempt was made the TC did not completely succeed in defining a new model. Due to a lack of sufficient knowledge of file handling within the DOS shell the old model NYALA02 was uninten-

tionally ~~overwritten~~ on the new 386 computer. After this unexpected event the TC decided to work only with the available NYALA models on the older 286 computer and entered the new evapotranspiration data in the most recent model.

At the end of the second mission it was stressed that the availability of reliable well hydrographs showing the rise of the groundwater table at the end of the summer period when the first floods arrive, would be of a great help to understand the mechanism of expected rapid recharge by the Wadi Nyala. The TC was able to record the rise of the water table near the Wadi Nyala after a number of floods. The hydrograph chart showed an amazingly rapid rise of about 3 m in less than a day after the first flood. After a second and almost certainly after a third flood the Wadi aquifer appeared to have been fully replenished. Infiltration tests in the Wadi bed had not yet been performed which now seem to be somewhat redundant after visual inspection of the well hydrograph showing rapid infiltration in the coarse Wadi bed sediments.

Apart from the failure to develop a new model NYALA03, most of the assignments had been carried out reasonably well and the overall impression was positive. Although it remained doubtful whether the model experts of the TC had been practising seriously after the second mission. It was reported that too much fieldwork prevented them from practising with the modelling software. None of the additional programs (to convert PM output to SURFER) specially made during the second mission had been used.

After checking and recalculating the actual evapotranspiration values for the town and downstream areas a new model NYALA03 was defined with the three stress periods as defined above. The evapotranspiration values were entered in the model, as a stress per cell in the well package. The TC model experts were given the task of entering and checking the abstraction rates of the town supply wells, which subsequently should be added to the previously entered abstraction data for evapotranspiration. The TNO mission was astonished by the fact that all the abstraction data had been filed on pieces of paper only. Deleted, overwritten and almost unreadable figures appeared on a number of paper sheets which were found in a number of drawers or file cabinets. It took considerable time before the abstraction data, including the correct values for the town wells, could be

entered into the model. The poorly developed basic computer skills and the lacking attitude of filing data on a computer is still a major obstruction in the development of the TC. From the first mission it was stressed that simple column-wise data such as water levels, abstraction rates etc. should always be entered in a database on a computer to facilitate error checking and further processing. Data filing, one of the major tasks of the TC, seems still chaotic and old-fashionably written down on a large variety of forms and sheets of paper.

After the evaluation of assignments from the previous mission, the model NYALA03 was defined incorporating three stress periods together with the new screened abstraction data. In order to refresh existing knowledge, training was given in basic computer skills and the handling of the new PM software package. A number of runs were made with the final model NYALA03 to calculate the total cumulative model water balance.

The total volume of the Wadi Nyala aquifer (model area) was estimated with the Surfer package using altitude data of the top of the surface and top of the basement. The results are listed in table 2.2.

Table 2.2 Total volumes of aquifer sediments in the modelled area and maximum amounts of storage for groundwater.

Area	Total volume of sediments (in mln m ³)	Estimated maximum storage for groundwater (in mln m ³)
Model area	107	20
Town area	39	7
Downstream area	68	13

Some problems were encountered with the model concerning the rewetting of dry cells under the river during the wet period. On Monday 11 October the initial heads were changed and the number of time steps in each stress period were raised from 3 to 9 to improve the rewetting of dry cells. Finally, it was decided to adjust the MODFLOW code forcing a wetting of dry cells at the beginning of each time step loop. These adjustments finally resulted in an improved numerical rewetting procedure.

Once the problem of rewetting had been solved, much attention was paid to the calculation of the cumulative water balances for the entire model area. Given the fact that during the wet period, as judged from the rapid rise of the groundwater levels, abstracted groundwater is almost instantly and fully replenished during next floods, the model was run only with abstractions during the summer and winter period. As a result of the rapid replenishment practically no water is withdrawn from storage, implying that at the end of the wet period the aquifer is fully recharged almost irrespective of the pumped amounts of groundwater and withdrawals for evapotranspiration. For such a situation typical cumulative water balance figures are shown in table 2.3.

Table 2.3 Typical values for the cumulative water balance for the entire model at the end of a one-year model run (end of wet period).

Waterbalance item	Well packages attached in the stress periods I & II only		Well packages attached in all three stress periods	
	Incoming cumulative volumes in mln m ³	Outgoing cumulative volumes in mln m ³	Incoming cumulative volume in mln m ³	Outgoing cumulative volume in mln m ³
Recharge by Wadi Nyala	7.3		8.7	
Groundwater runoff by Wadi Nyala		0.5		0.3
Evapotranspiration + city supply wells		6.5		8.6
Change in groundwater storage		0.3	0.2	
Total cumulative water balance	7.3	7.3	8.9	8.9

The table shows that during the dry period (stress periods I & II) a total amount of 6.5 mln m³ of groundwater is withdrawn by the existing wells and vegetation in the entire model area. Referring to the total amount of groundwater storage of about 20 mln m³ it can be deduced that at present the Wadi Nyala aquifer as a whole is not yet overexploited. Local overdrafts may occur resulting in dry wells at the end of a dry period, but this can be attributed to improper site selection for wells (clustering of wells and/or insufficient aquifer thickness) for instance in the town area.

At the end of the mission in Nyala much time was spent on the problems of water management given the results of the model calculations as shown in the previous tables. A number of scenarios were formulated concerning groundwater use in the future. At the very end of the mission a presentation was prepared by the TNO experts and the TC staff to announce the results of the modelling activities to local government officials involved in problems of water management. It was decided that the presentation should be given by the TC manager Mr. Hamdan using a number of specially prepared flip-over sheets and illustrations. The flip-over sheets were designed to contain condensed readable information and essential data important to planners and managers. The following items were dealt with during the presentation:

- 1) *Objectives of the presentation;*
- 2) *General characteristics of the Wadi Nyala aquifer;*
 - *hydrogeology, size, storage, modelled area, etc.*
 - *recharge characteristics by Wadi Nyala, groundwater level recoveries, flow data etc.*
- 3) *Present water demands from the Wadi Nyala aquifer;*
 - *domestic water supply (town and water vendors)*
 - *irrigation of horticultural areas*
 - *evapotranspiration by man-made and natural forests*
- 4) *Expected future water demands (time horizon 2003)*
 - *population growth and expected domestic water demands*
 - *irrigation*
 - *industrial demands*
- 5) *Management of groundwater resources and problems of safeguarding water supply the year around;*
 - *presently no severe problems of water supply*
 - *strongly increasing demands in the coming decade.*
 - *water supply options and scenarios*
 - *modelling results*
- 6) *Preliminary conclusions.*

On Wednesday morning 13 October a well-prepared and well-illustrated presentation was given by the TC manager in front of an audience consisting of the Deputy Commissioner, the Minister of Social Welfare and Housing, members of the Nyala Water Board and staff of the Urban Water Supply. At the end of the presentation a vivid discussion followed in which a number of interesting questions were raised and important items were discussed. Through this presentation Mr. Hamdan as the TC manager obviously strengthened his position and that of the TC, which from now on hopefully is being recognized as the institute which possesses all the relevant data on groundwater and the hydrogeology in the area. Together with the newly developed groundwater model and the existing modelling skills among the staff, the TC should be able now to conduct all kinds of scenario evaluations concerning groundwater use from the Wadi Nyala aquifer.

Some major problems remain concerning the progress in modelling skills of the TC staff. These problems were discussed in a final evaluation meeting with the PC, PM, TC staff and TNO experts. Serious concern was expressed about the poor progress in basic computer and modelling skills. Further improvement of these skills are definitely needed to make model building abilities sustainable. All were convinced that Mr. Hamdan plays a crucial role in this process and that he should draft a working plan for the TC model experts and urge them to practice with spreadsheets, databases (entering existing routine data) and PM/MODFLOW. It was strongly advised to make a working plan for the entry of the routinely collected data at the TC, which contains all elements for practice and computerised data processing. This working plan should also contain a number of check points to evaluate progress.

The NRWC, in Khartoum, should put more emphasis on monitoring the model activities and computer skills development in Nyala. This may be achieved by visiting Nyala regularly and inviting staff members to come to Khartoum for further training.

2.2 Results of the model calculations regarding present and future water demands

Due to intense migration patterns the town of Nyala has experienced a very rapid growth in the last decade up to a present population of about 0.5 mln people (from about 15,000 in the year 1955). In the coming years it is predicted, also a result of the town extensions in the east, that the rapid growth will continue. The present-day abstractions for the piped water supply system amounts to 2.5 mln m³/year, equalling about 2.0 mln m³/year effectively in the dry period.

The model calculations indicate that presently no serious problems are encountered with the supply of water for irrigation, evapotranspiration and domestic supply. The total amount withdrawn in the dry period from the entire model area amounts to 6.5 mln m³, whereas the total storage of the Wadi Nyala aquifer amounts roughly to 20 mln m³. The problem of city supply wells running dry in the course of a dry period is a matter of poor design and improper well locations. According to the model, the total amount of water withdrawn from the Town area by city supply wells and evapotranspiration totals 2.5 mln m³ during the dry season. The total storage in the Town area has been calculated at about 7 mln m³, rendering enough storage even for severe and long dry seasons. The problem of inadequate city supply at the end of the dry season is a technical problem of proper well design and optimization of well locations (too much wells are concentrated in the upstream part of the model area with a relatively shallow basement).

A number of scenarios have been evaluated which are thought to present viable solutions to the increasing water demand. The goal was to arrive at a sustainable total water supply of 5.0 mln m³ annually, equalling 4.0 mln m³ withdrawn from storage in the dry season, for a projected population in the year 2003. The following scenarios were evaluated:

- 1) Doubling the amount of water pumped from the existing city supply wells;
- 2) Increasing the yield from 2.0 to 3.0 mln m³ in the dry season from the presently available city supply wells by optimization techniques. The additional 1.0 mln during the dry season to be abstracted by means of a new well field to be located in the area east of the Town area up to the area of the Kundua Forest.

The model calculations demonstrated that doubling the capacity of the present-day well field for the city supply will result in a number of dry wells during the dry season, leading to strongly declining total capacities. The second option appears to be a feasible solution including an optimization of withdrawals from the present wells. According to the model an additional 1.0 mln m³ during the dry season can be safely abstracted in the area up to the Kundua Forest.

Even higher future demands of groundwater are most likely to be satisfied by well field extensions farther to the east, towards the natural forest. Although the hydraulic conductivity decreases in eastern directions, as a result of the increasing clay contents in the aquifer materials, groundwater can be abstracted by means of wells or when necessary even by collector wells and drains. Due to the deep root systems of both the natural and man-made forests it is not expected that higher seasonal variations of the groundwater table, due to groundwater pumping, will adversely affect the forest ecosystems.

2.3 Conclusions and recommendations with respect to groundwater use in the Wadi Nyala

- 1) Presently, there are no serious problems with the availability of groundwater to meet present water demands for domestic supply and evapotranspiration;
- 2) The poor service of the piped water supply system is mainly caused by technical problems in the supply network and above all by the improperly designed and outdated well field;
- 3) It is recommended to carry out a detailed study with the presently available model NYALA03 to optimize the present well field and when necessary to select new additional well sites;
- 4) With respect to hazards of groundwater pollution of the phreatic alluvial aquifer from human activities (especially the market place in the Wadi bed), it is recommended to shift most of the abstractions to the downstream part of the Town area. With the available groundwater model optimum abstractions should be determined given these constraints;

- 5) Given present high rates (average 9.6%) of population growth of Nyala, future water demands for domestic supply will certainly increase. Even to supply an amount of at least 30 litres per capita per day, total annual demands will swell to about 5 mln m³;
- 6) Model calculations indicate that an additional 1.0 mln m³ during the dry season can be abstracted from the wells in the Town area by a proper optimization of well abstractions. The remaining 1.0 mln m³ can be safely withdrawn from the area stretching from the Town area up to the Kundua Forest.
- 7) In view of the expected extensions of well fields in the near future, present hydrogeological investigations of the Wadi Nyala Aquifer by the TC should be focused on the area stretching from the Town area up to the Kundua Forest;
- 8) Even higher demands in the future are likely to be satisfied from the almost untapped groundwater resources in the eastern part of the Wadi Nyala Aquifer (downstream area) bordering the natural and man-made forest.
- 9) In the coming decade the water demands of Nyala can be met by the available groundwater resources in the Wadi Nyala Aquifer. There is no convincing need in the coming decade to transport water from remote areas to Nyala;
- 10) The total volume of groundwater stored in the Town area is calculated at about 7 mln m³. The total amount of storage in the whole model domain is estimated at about 20 mln m³;
- 11) Replenishment of the Wadi Nyala Aquifer by floods in the wet season is almost complete. Floods cause a rapid rise of the water table and after a few floods the aquifer appears to be almost completely recharged;
- 12) Additional investigations should be carried out in the downstream area to collect much more data about aquifer thicknesses and hydraulic conductivities;
- 13) The importance of systematic monitoring of groundwater levels cannot be overemphasized in such typical hydrogeological settings with unexpectedly rapid recharge mechanisms.

2.4 Conclusions and recommendations with respect to the MODFLOW training at the TC in Nyala

Concerning the modelling progress and development of basic computer skills the following conclusions and recommendations can be put forward at the end of the third and final TNO mission:

- the majority of assignments given at the end of the second mission had been carried out reasonably well;
- although some progress in PM/MODFLOW and basic computer skills is evident, as compared with previous missions, the present level is still considered to be insufficient to carry out groundwater modelling successfully and sustainably;
- practising with PM/MODFLOW and the supporting software packages was insufficient in the period between the second and third mission;
- the habit of entering any routinely collected data in a computer is still lacking, while this type of data collection is considered one of the major tasks of the TC as is apparent from the recently issued "Wadi Nyala Basin Water Development & Utilization Order";
- data filing and model archiving is still chaotic in Nyala. Sheets of paper with important model data are kept in a number of file cabinets without any labelling of versions etc., which increases the risk of losing important data;
- it is recommended that the TC manager drafts a working plan to start entering most of the routinely collected data in the computers. This constitutes a suitable exercise for the Nyala model experts to become fully acquainted with computers and software;
- the TC manager has given a clear and comprehensive presentation for members of the Waterboard, the Minister and representatives of the Urban Water Supply Company about the state of affairs of the hydrogeological investigations and the recently developed modelling activities;
- the TC of Nyala is now recognised as the institute which possesses all the relevant data on groundwater and the hydrogeology in the area. Hopefully, those parties

involved in water management will urge the TC-of Nyala to continue and further develop scenario evaluations for groundwater management;

- the position of the TC of Nyala has obviously been strengthened;
- it is strongly recommended that the NRWC in Khartoum monitors the development of modelling and computer skills at the TC of Nyala.

3 Mission to Kassala

3.1 Summary of the mission activities

Mr. M.E. Ibrahim (Project Manager, PM) and Dr. Izzeldin (Project Coordinator, PC) accompanied the TNO experts also during the mission in Kassala. Thursday 14 October was spent with travelling from Nyala, via Khartoum to Kassala. On the next day the program for the coming days was presented and as usual the results of the assignments given at the end of the second mission in May '93 were evaluated.

All the assignments, except for the infiltration tests of the Gash river bed, had been carried out satisfactorily. The results were well-reported, documented and a maximum use has been made of computer software. More data had been collected about the thickness of the separating layer from borehole descriptions and vertical electrical depth soundings (VES measurements). A thickness map had been prepared with the Surfer software. As was suggested at the end of the second mission, a number new boreholes were drilled along a row perpendicular to the Gash channel to monitor the rise of the water table during the wet period. Some level data had already been collected and was shown by the TC staff. All the level data from the groundwater monitoring network, as requested in a previous mission, had been entered into the computer, screened and checked. The database with the information about wells used for irrigation had been screened and further updated, to be compared with the values derived for evapotranspiration by using Penman.

The existing model GASH03 was updated and renamed as GASH04 incorporating the newly derived thickness data for the separating layer. New files for the altitude data of the bottom of the upper aquifer and the top of the lower aquifer were generated. The primary files with the Penman calculations for the evapotranspiration were checked to arrive at a total amount withdrawn for evapotranspiration. Table 3.1 shows the results of the Penman evapotranspiration calculations and the abstractions as gathered from the irrigation well inventory. Applying an irrigation efficiency factor of 40% results in a similar total loss of water from the aquifers within the model boundaries as derived from total evapotranspiration.

Table 3.1 Summary of abstractions (in mln m³/year) by two different approaches i.e. by well inventory and estimation of evapotranspiration by Penman.

Inventory of irrigation wells		Estimation of evapotranspiration by Penman and landuse	
Effective abstraction by irrigation wells, taking into account an irrigation efficiency of 40%	68	Actual evapotranspiration from irrigated horticulture areas	66
Evapotranspiration from forests	90	Evapotranspiration from forests	90
Total actual evapotranspiration	158		156

The order of stress periods in GASH04 was rearranged to start the simulation at the end of the wet period. The model GASH04 and higher version incorporate 12 stress periods (see table 3.2).

Table 3.2 Defined stress periods in the models GASH04 to GASH09.

Stress period	Calendar Months
1 - 8	October - May
9 - 12	June - September

Saturday and Sunday (16 and 17 October) were spent on checking the evapotranspiration files, generating a new bottom of the upper aquifer and top of the lower aquifer. The rearranging of stress periods together with the TC staff took considerable time, but was considered a good exercise. The TC staff checked the water level data from the monitoring network in a computer database. After running the newly defined models, problems were still encountered with the process of rewetting cells. On Monday a new model GASH05 was defined in which the vertical leakance of the separating layer was given a value in each cell inversely proportional to its thickness, which considered to be more realistic than the earlier assumed division in the downstream area with 2500 days and the remaining area 5 days. Quite a number of runs were made with different vertical leakances for the separating layer to determine the effect on the rewetting of cells.

Based on new altitude data of the top and bottom of the lower aquifer, a similar exercise was carried as in Nyala to estimate the total amount of groundwater storage in the Gash basin. For the whole model area a total amount of ca. 1230 mln m³ was calculated in the lower aquifer, taking into account a specific yield of 20%.

Tuesday and Wednesday 19 and 20 October were spent on the analysis of the water level data from the monitoring network. A fairly complete data set is available from 1980 to 1992. A number of observation wells was selected with at least eleven years of observations. This resulted in a number of 37 observation wells. For each data set from these wells, the weighted average water level was calculated and from these average yearly levels a linear trend was determined to reveal long-term declines in levels. The derived trends were classified and ordered in frequency diagrams to reveal the predominant trends. Additionally, the derived long-term trends were plotted on a map to show the spatial variations.

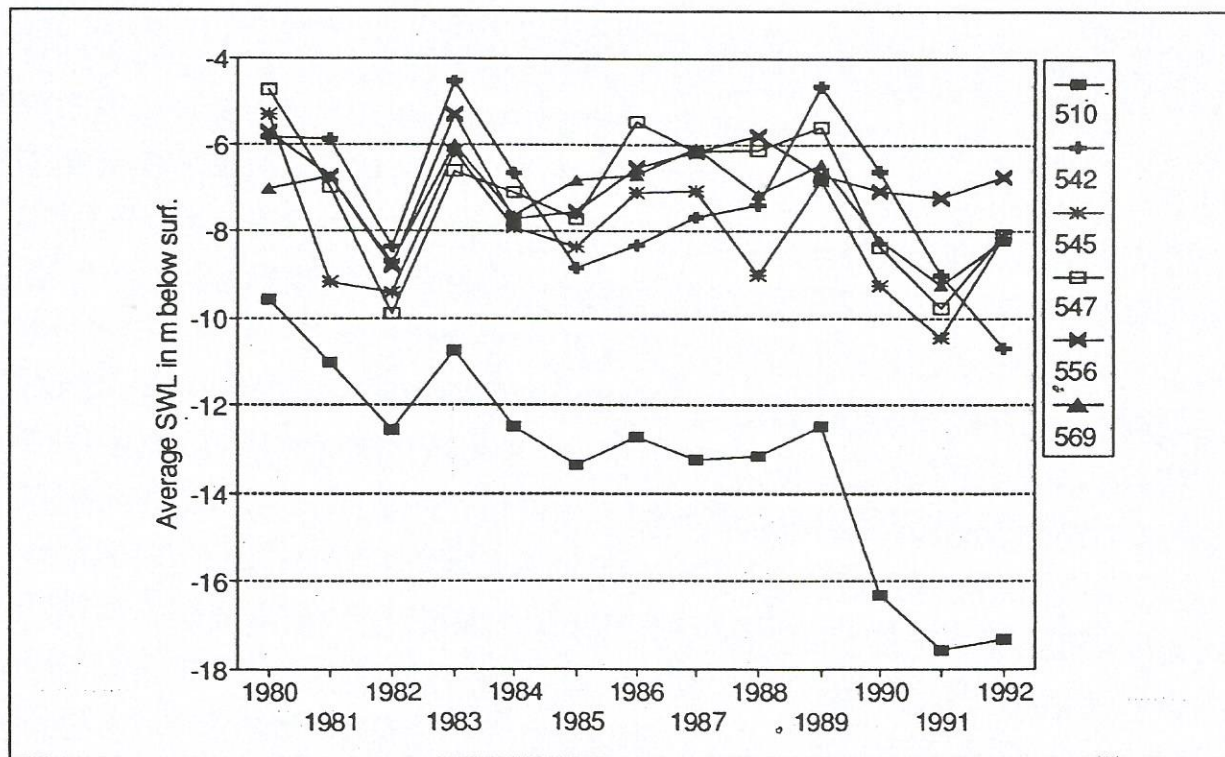


Fig. 3.1 Some characteristic monitoring well hydrographs in the Gash basin.

In figure 3.1 and 3.2 some characteristic well hydrographs are shown for the period 1980 to 1992. Most of the observation wells show more or less constant or slightly declining

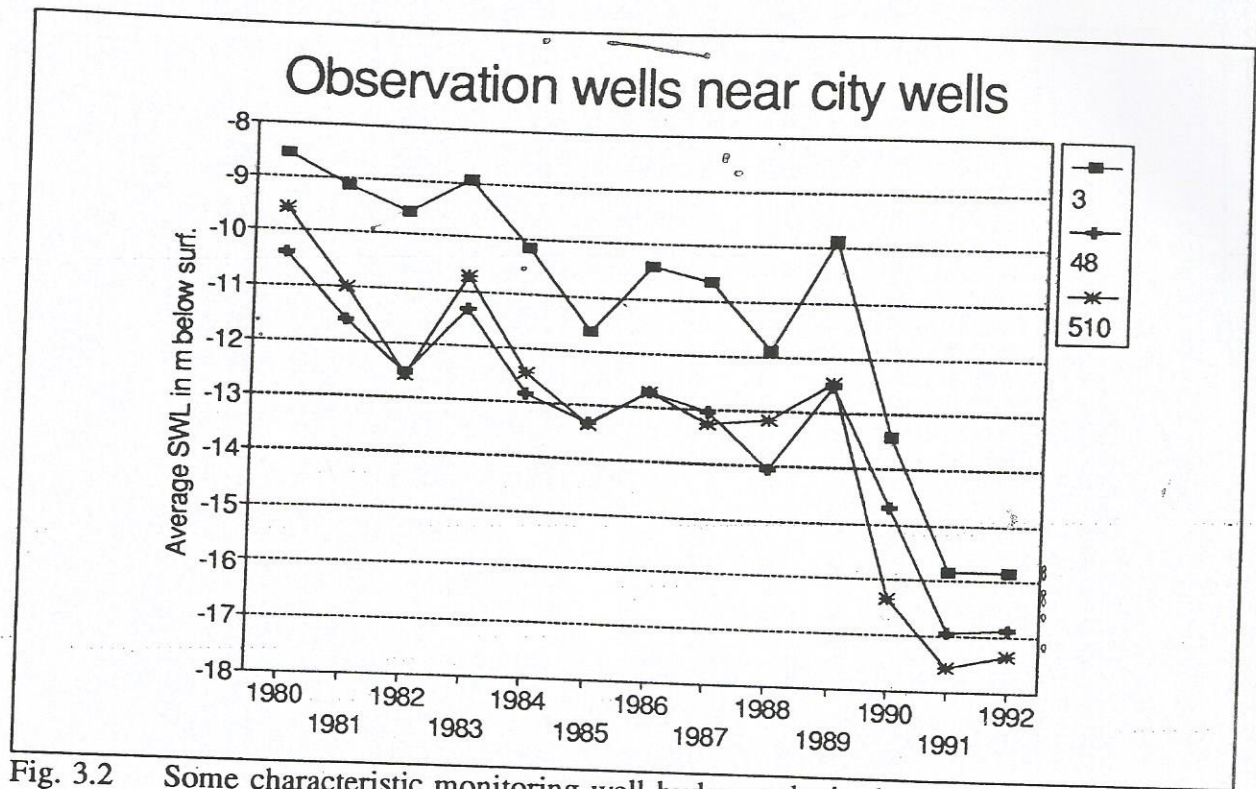


Fig. 3.2 Some characteristic monitoring well hydrographs in the Gash basin.

heads during the last decade, whilst wells like number 48 and 510 show significantly declining heads in the 1980s with a rapid, almost alarming, drop starting in 1989. Figure 3.2 displays hydrographs of observation wells in the vicinity of the city supply wells near the town of Kassala. As this city supply has undergone a major extension of the total capacity in 1989 it is conceivable that pronounced structural declines in heads are directly related to this extension. Before this year a long-term structural decline is already noticeable. However, these severe structural declines are apparently local phenomena. In figure 3.3 a frequency histogram is shown of the long-term trends derived for the 37 observation wells with record of 11 years or more. This remarkably symmetrical diagram, resembling a Gauss distribution, clearly shows that the maximum frequency of trends is found to be in the class from 0.0 to -0.1 m/year. Even upward trends are found in some areas of the Gash groundwater basin. A cumulative frequency diagram is shown in figure 3.4 indicating that the median value is found in the class from 0.0 to -0.1 m/year. A plot of these trends on a map clearly shows that the high structural declines in head are found only in the direct vicinity of the city supply wells. Apparently, the withdrawals of groundwater for irrigation do not seem to cause serious overdrafts and even if declines occur they are strictly local with a limited sphere of influence.

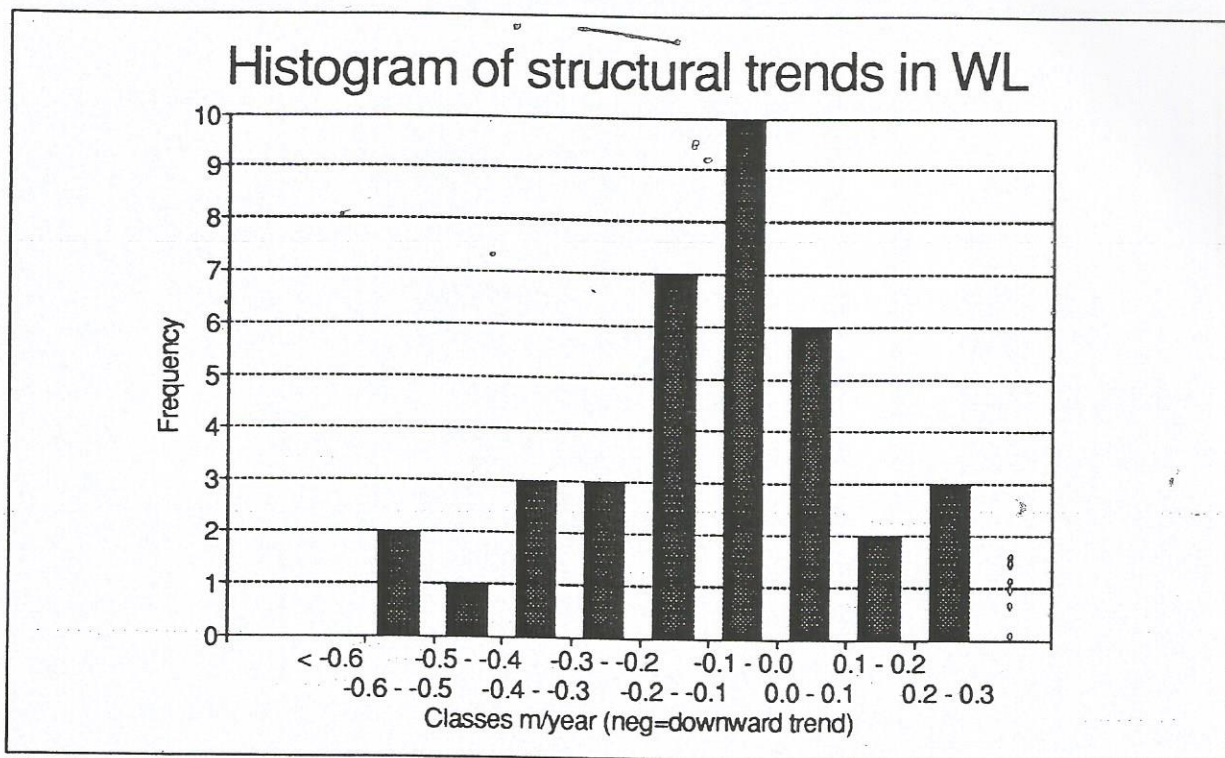


Fig. 3.3 Frequency histogram of the long-term structural trends in groundwater heads in the Gash basin.

The analysis of recorded water levels from the monitoring network reveals a number important and interesting details on the dynamics of the Gash groundwater basin. The following conclusions can be drawn:

- 1) The present total rate of abstraction from the Gash groundwater basin equals or slightly exceeds the maximum capacity;
- 2) The majority of the observation wells show small long-term declining trends. The median value amounts to ca. 10 cm/year;
- 3) Areas with high structural declining heads (maximum about 7 m decline) are very local;
- 4) The 37 analyzed observation wells do not show a basin-wide structural decline of groundwater heads at an alarming rate. Only in some areas structural declines are evident;
- 5) There appears to be no relation between the magnitude of trend and location distance from the Gash river;
- 6) Maximum long-term trends amount to 0.5 - 0.6 m/year;

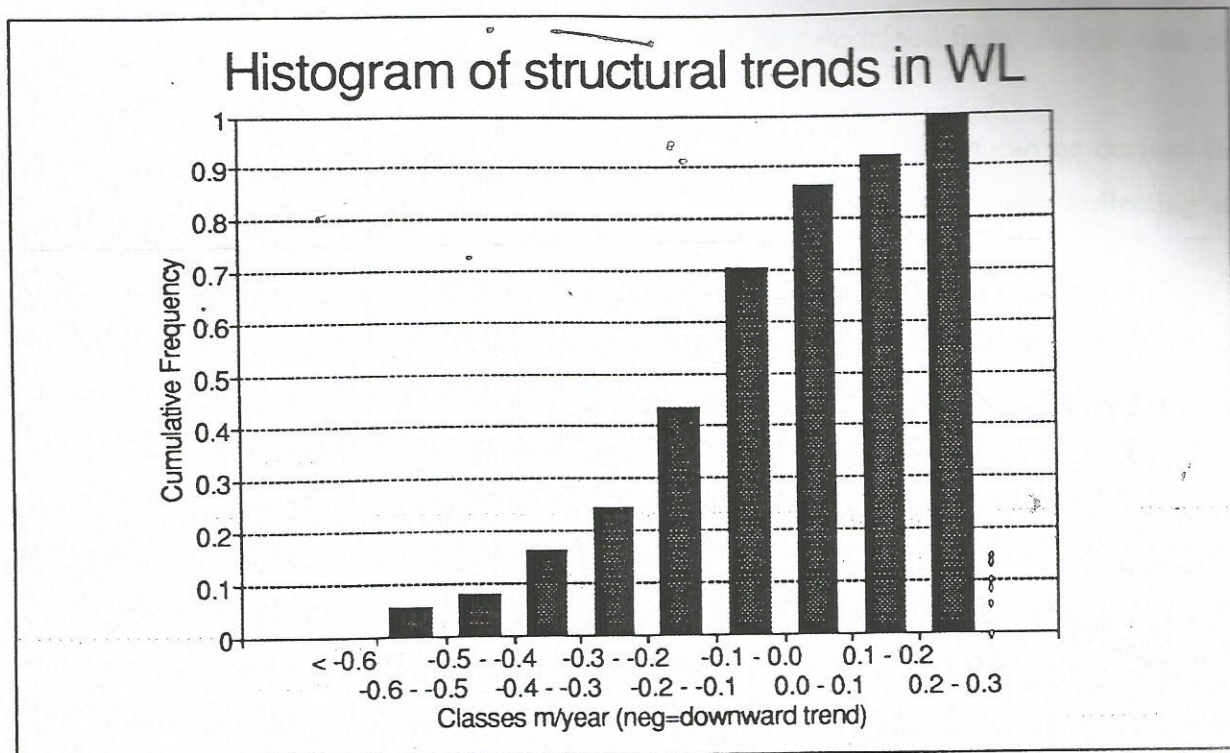


Fig. 3.4 Cumulative frequency of long-term structural trends in groundwater heads in the Gash basin.

- 7) Observation wells with trends of 1 to 2 m/year from 1989 onwards are found only in the garden areas west of Kassala and are clearly related to the effects of improperly designed well fields for the city water supply;
- 8) The reaction times of the groundwater heads upon recharge from the Gash are in the order of years and increase with distances from the Gash up to about 10 years near the aquifer fringes;
- 9) Due to the long reaction times it makes no sense to compare the levels or average levels from two consecutive years, because the effect of erratic annual recharge by the Gash propagates through the aquifer with a certain lag time;
- 10) Declining heads during a number of years may also be attributed to a number of consecutive years with less recharge from the Gash, due to climatic cycles, fluctuations etc.;
- 11) Present deep depressions in groundwater heads are exclusively caused by local overdrafts which result in abstracting groundwater largely from storage. These depressions will recover when abstractions are reduced. The time of recovery increases with distance from the Gash;

- 12) Long-term structural declining heads can only be determined from records with more than ten years of level data;
- 13) Much insight into the behaviour of the Gash groundwater basin can be derived from analysis of groundwater level data. It demonstrates that systematic collecting data from a groundwater monitoring network is of paramount importance.

After this comprehensive analysis of groundwater level data, Thursday 21 October was spent discussing remedial options and methods to calibrate the groundwater model with this new information on long-term trends. The following remedial options were mentioned:

- 1) Reduce abstractions for irrigation in the garden area west of Kassala with 50% and re-allocate garden areas to the upstream part of the model area;
- 2) Reduce the high abstractions of the city water supply, being concentrated too much in three areas only, by designing an additional row of wells on one or both sides of the Gash;
- 3) Reduce all abstraction for irrigation in areas with structural declines exceeding 4 m;
- 4) Induce extra recharge by the Gash to the lower aquifer by mechanical perforation of the separating layer for instance with large-diameter sand or gravel pipes drilled from the river bed down to the lower aquifer;
- 5) Induce extra recharge by the Gash to the upper aquifer by constructing drain pipes perpendicular to the channel. Buried perforated pipes in an excavated trench filled with sands/gravels starting from the river bed up to distances of several hundreds of metres from the river. Hydraulic contact with the Gash will then take place only through the existing river bed thereby avoiding problems of silt deposition.

On Friday and Saturday, 22 and 23 October, many calibration runs were performed with the model to simulate the long-term average head decline of 10 to 15 cm/year. It was found that the initial heads chosen so far (bottom of upper aquifer for layer 1 and top of lower aquifer minus 1 m for layer 2) were incorrect due to very long reaction times (many years) of the Gash basin. The horizontal hydraulic conductivity of layer 2 was raised by a factor of 1.5 (model GASH07, see also Appendix for more technical details). New analysis

of the horizontal conductivity data as collected in the first mission indicated that the median value is a better regional estimate than averages when dealing with skewed distributions.

The model was also run for 10 consecutive years, up to 1989, using the calculated heads as initial heads for the following simulated year. These newly generated initial heads gave much more realistic results and an acceptable approximation of the long-term structural declines up to the year 1989 in which the city supply capacity was drastically expanded. The rest of Saturday was used to draft a set up for the presentation. The structure and items were adopted from the presentation in Nyala with the exception that more attention was paid to the modelling results. The following is a general outline of the items discussed during the presentation:

- 1) *Objectives of the presentation;*
- 2) *General characteristics of the Gash groundwater basin;*
 - *hydrogeology, size, storage, modelled area, etc.*
 - *recharge characteristics by the Gash, flow data etc.*
- 3) *Present and future water demands from the Gash aquifers;*
 - *evapotranspiration from horticulture areas and natural forests*
 - *city water supply*
- 4) *Results of the analysis of groundwater level data from the monitoring network 1980-1992;*
 - *long-term trends and patterns*
 - *causal relations*
- 5) *Management of groundwater resources and problems of safeguarding water supply the year around;*
 - *statement of present problems*
 - *dynamic characteristics of the Gash groundwater basin*
 - *options for remediation*
 - *feasible medium-term scenarios for the coming decade*
- 6) *Results of the model calculations*
 - *scenarios*

6) *Preliminary conclusions and recommendations.*

On Monday morning 25 October a summary of the prepared presentation was given by the TC manager to the Minister of Housing of the Eastern State. Later the TC manager delivered his full presentation to the Commissioner, representatives of the Waterboard, farmers, irrigation department and Kassala city supply company. Also this presentation in Kassala was considered to be very successful, reinforcing the position and status of the TC as the centre for hydrogeological investigations, data collection and groundwater modelling. At the end of the presentation many interesting questions were posed by the audience, the more so as the results of the modelling indicated that in the upstream area a limited extension of the horticulture seems possible.

3.2 Results of the model calculations regarding present and future water demands

In a previous section it was shown that according to the trend analysis of groundwater level data, the city supply abstraction are the major cause of structural declining heads at an alarming rate from 1989 onwards. The following most important scenarios were evaluated in which more emphasis is given to the city water supply:

- 1) Abstracting 9.0 mln m³/year for the city water supply from three cells in the model (8220 m³/day) simulating the present designed situation;
- 2) Abstracting a total of 9.0 mln m³/year from two existing wells and a new row of wells along the western bank of the Gash. From each cell an amount of 3082 m³/day has to be abstracted;
- 3) Cultivating an area in the upstream parts of 1275 ha (3035 feddan) with an evapotranspiration of 5 mm/day;
- 4) Cultivating the same area but with an evapotranspiration of 2.5 mm/day.

With the model GASH07 it was impossible to abstract the designed amount of 8220 m³/day from the three well location (three cells) the year around. In the course of the dry

season one or two cells fell dry thereby strongly reducing the total amount of pumped water. Even the model GASH08 (see also Appendix), similar to GASH07 except for higher horizontal hydraulic conductivities in both layers, showed the same results of cells falling dry. According to the TC, this apparently happens during the dry season when the pumped capacity is reduced by switching off wells to prevent air suction.

The second scenario of pumping the designed amount of groundwater but by means of an extended well field proved to be a much better alternative. A row of wells was designed along the westbank of the Gash with a length of about 9 km. Abstracting 3082 m³/day from a total of 8 cells, 2 existing and 6 new ones, thus much lower rates spread over a much larger area exhibited a stabilization after about two years. This scenario shows that the designed amount can be abstracted but it is just a matter of proper well field design, preferably along the Gash, to allow the pumped amount to be replenished by the Gash instead of depleting groundwater from storage. According to the nearby observation wells this depletion of storage is occurring at an alarming rate of about 1 to 2 m/year in the vicinity of the present production wells of the city water supply.

In the third scenario an area of 3035 feddan was chosen by the TC in the upstream part of the model area, adjacent to the Gash channel, with an abstraction of 5 mm/day at each cell (17 cells totally). Model calculations indicated that this rate of 5 mm/day evapotranspiration appeared too high and the calculated heads persisted to decline even after a number of years. Calculations with a rate of 2.5 mm/day from the same area showed that the levels stabilized after a period of 2 years with model GASH08 and 4 years with GASH07, indicating that abstracted amount of water becomes replenished by the Gash.

Typical values for the cumulative water balance were calculated with the model GASH07 for the present situation (scenario 1) and one in which an additional area of 3035 feddan is cultivated in the upstream parts (scenario 4). Table 3.3 summarizes the most important items of the water balance. Due to cells falling dry the amount of water pumped for the city water supply is strongly diminished according to the model calculations. The amount

withdrawn for evapotranspiration is practically matched by the replenishment from the Gash.

Table 3.3 Typical values for the cumulative water balance for the entire model at the end of the wet period.

Present-day situation evaluated with model GASH07; abstracted volume by city supply wells through existing well field decreased down to 2.5 mln m ³ /year			Situation after 4 years of cultivating 3035 feddan in upstream part, abstracted volume by city supply wells through existing well field decreased down to 0.6 mln m ³ /year	
Water balance item	Incoming cumulative volumes in mln m ³	Outgoing cumulative volumes in mln m ³	Incoming cumulative volume in mln m ³	Outgoing cumulative volume in mln m ³
Recharge by Gash river	123.5		127.9	
City supply wells		2.5		0.6
Evapotranspiration		122.0		129.2
Change in groundwater storage	1.0		1.9	
Total cumulative water balance	124.5	124.5	129.8	129.8

3.3 Conclusions and recommendations with respect to groundwater use in the Gash basin

The following conclusions and recommendations can be listed concerning the present and future situations of groundwater withdrawals from the Gash basin:

- 1) The Gash groundwater basin is exploited practically up to its maximum sustainable yield;
- 2) Further extension of groundwater abstractions in the existing horticultural area near Kassala in the near future should be prevented. On the long-term the total amount should be decreased;
- 3) It is strongly advised to raise the present relatively low irrigation efficiency by a factor of two. New irrigation techniques should be introduced to the farmers to make more efficient use of the available groundwater resources;

4 Summary of day-to-day activities

DATE	ACTIVITIES
October 6	Departure to Khartoum by KLM.
7	Meeting with Dr. Izzeldin and Mr. Nauta at NL embassy. Meeting at NRWC headquarters at kilo ten with Mr. M.E. Ibrahim and Mr. A.M. Kheir, discussing the mission program and general matters.
8	Departure to Nyala by Sudan Airways; meeting at TC Nyala in the afternoon discussing the program and the results of additional data collection as mentioned in the report of mission II; installation of new PM/MODFLOW (version 3.0) software on new 386 computer.
9	Defining a new model NYALA03 with the new abstraction data and three stress periods. Refreshing knowledge of TC staff in basic computer skills and PM. Calculation of total model water balances.
10	Attempting to identify and solve some problems of poor model rewetting of cells under the river reach during the wet period. Best settings, WETTINGFCT = 40, WETTING INTERVAL = 8, THRESHOLD = 0.25 and using equation 3B. Detailed water balance calculations. Determination with Surfer of the total volume of the Wadi Nyala aquifer.
11	Still problems encountered with rewetting option. Finally, MODFLOW code adjusted to force dry cells to become wet at the very beginning of a time step loop. Initial heads changed to 0.5 m below the surface. Time steps in each stress period raised from 3 to 9. Calculation of water balances. Problems of water management discussed, in the sense of scenarios, based on the NYALA03 model results.
12	Set-up prepared of the presentation to be given by Mr. Hamdan, the TC manager. Preparation of draft flip-over sheets, illustrations etc. Preparation of the final version of the presentation. Discussing all details about the modelling results etc. with Mr. Hamdan. Final checking of the model NYALA03 by Mr. Minnema.
13	Presentation given by Mr. Hamdan for members of the Waterboard, the Deputy Commissioner, the Minister of Housing of the Darfur State and representatives of the Urban and Rural Water Supply Departments. Evaluation of the mission. Backing-up model files. Visit to the man-made Kundua Forest in the afternoon.
14	Travel by El Dinder Air from Nyala to Khartoum in the morning and to Kassala in the afternoon.
15	First meeting at TC Kassala discussing the program and the results of additional data collection as mentioned in the report of mission II; installation of new PM/MODFLOW (version 3.0) software on new 386 computer. Sightseeing in the afternoon, accompanied by a security officer.
16	Checking model GASH03. Generating new bottom of upper aquifer (BG1) and new top of lower aquifer (TG2) using newly collected data on the thickness of the separating layer. Defining new model GASH04. Checking spreadsheets with Penman calculations for evapotranspiration estimates. Rearranging sequence of stress periods.