Report III - 1

Water Balance Calculations with the “1995” Modflow Groundwater Model of the Sana’a Basin

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1. Introduction

In the framework of the Project Preparation Phase of the Sana'a Basin Water Management Project the World Bank has requested the Water and Environment Centre at the Sana'a University to carry out a multi-criteria analysis of sub-basins in the Sana'a Basin in order to determine the most feasible sub-basins for implementing measures aimed at optimal demand-and-supply-driven water management of the Sana'a Basin as a whole.

For this purpose the WEC has engaged an International Consultant (Mr. J.W. Foppen) from the International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE) in Delft, The Netherlands to analyse the water balance at sub-basin scale. In 1995 Mr. Foppen has made a transient groundwater model of the Sana'a Basin with MODFLOW in the framework of the "Sources for Sana'a Water Supply" (SAWAS) project, carried out jointly by the National Water and Sanitation Authority and the Netherlands Institute for Applied Geosciences of TNO in Delft, The Netherlands.

The determination of the water balance at sub-catchment scale has two objectives:

- To obtain a quantitative idea of the volumes of water that make up the water balance per sub-catchment and to determine the relative importance of the components of the water balance (recharge, abstraction, storage, etc.) per sub-catchment.
- To use the water balance per sub-catchment as one of the selection criteria in order to determine whether measures aimed at demand driven water management or measures aimed at supply driven water management would be potentially more successful.

In chapter 2 the modelling approach to the water balance calculations is discussed including a brief overview of the modelled area, important hydrogeological features and a general water balance of the main aquifer of the area, which is the Tawilah Sandstone.
In chapter 3 the water balance calculations for the year 1994 and for the year 2000 are presented and analysed. Based on the water balance calculations, it is qualitatively possible to determine the chances for success of measures aimed at demand driven water management or measures aimed at supply driven water management.
Finally, in chapter 4 recommendations for future work are given.

2. *The Modelling Approach*

2.1 General Background

In 1995 as a part of the activities of the SAWAS-project a MODFLOW groundwater model of the entire Sana'a Basin and it's environ was constructed. The specific goals of this modelling exercise were to assess the lifetime of the existing public supply wellfields and to assess the relative impacts of various groundwater management strategies on the aquifers. The groundwater modelling results were reported on in a series of six volumes (Technical Report 5, Volumes I-VI of the SAWAS Report Series: main report, data availability, calibaration and sensitivity analysis, scenario calculations and two data books).

In order to determine the water balances at sub-catchment level in the Sana'a Basin the same MODFLOW groundwater model was used with two simple modifications:

☐ The model was manually (!) upgraded from "Processing Modflow Version 3" to Processing Modflow Version 5";

☐ Since data on basin wide abstractions for the year 2000 are not available, abstractions for the year 1995 were 3.5% increased on an annual basis to arrive at realistic abstraction values for the year 2000 (see Chapter 3 for details).

As was written in chapter 1, the determination of the water balance at sub-catchment scale has two objectives:

☐ To obtain a quantitative idea of the volumes of water that make up the water balance per sub-catchment and to determine the relative importance of the components of the water balance (recharge, abstraction, storage, etc.) per sub-catchment.

☐ To use the water balance per sub-catchment as one of the selection criteria in order to determine whether measures aimed at demand driven water management or measures aimed at supply driven water management would be potentially more successful.

In this chapter first a general overview is given of the modelled area, including the geology, hydrogeology, modelled aquifer system and the general groundwater flow pattern. Then some important aspects of the groundwater model are discussed, like boundaries of the model, discretization in time, input of abstractions and recharge into the model and the way the model was calibrated.

2.2 The Modelled Area

2.2.1 Location

The Sana'a Basin is an inter-montane plain located in the central Yemen Highlands. The plain has an elevation of about 2200 m.a.s.l. but is surrounded to the west, south and east by mountains rising to about 3000 m.a.s.l. The Basin has an area of some 3200 km2 and forms the upper part of the catchment of Wadi al Kharid, a subcatchment of the Wadi al Jawf. The climate is semi-arid with an average annual rainfall of 235 mm at Sana'a. In 1995 the population of the city was estimated to be about 1,000,000.

The Sana'a Basin relies to a large extent on groundwater for both irrigation and the urban water supplies. Historically water supplies were obtained from dug wells and ghayls tapping the unconsolidated Quaternary deposits in the plain. Borehole construction and the introduction of pumps began in the 1960's and increased rapidly from the mid-1970's onwards. This enabled deeper aquifers to be exploited for irrigation and municipal supplies. The groundwater development has been largely uncontrolled.
Groundwater surveys in the 1970's identified the Tawilah Sandstone (Cretaceous) aquifer in the northern part of the Basin as a potential source of supply for the city. A wellfield (Western wellfield) was subsequently constructed in 1976 to the north-west of the city but waterlevels decline rapidly partly due to the increase in abstraction by private wells in the same area. A second well field (Eastern wellfield) was developed in 1981 to the northeast of the city and this also suffers from a decline in water levels. The wellfields now supply about 50% of the urban water demand and are supplemented by private wells.

The model area (see Fig. 2.1) covers some 6400 km^2, half of which consists of the Sana'a Basin. The city of Sana'a is located in the centre of the model area; smaller villages are Amran and Shibam in the north west part of the area and Jihanah, just outside the model area in the south east. The northern boundary of the area is in the Arhab region, some 20 km north of the Airport. The southern boundary of the area is in the Bilad ar Rus region, some 10 km north of the Yaslih pass on the road from Sana'a to Dhamar.

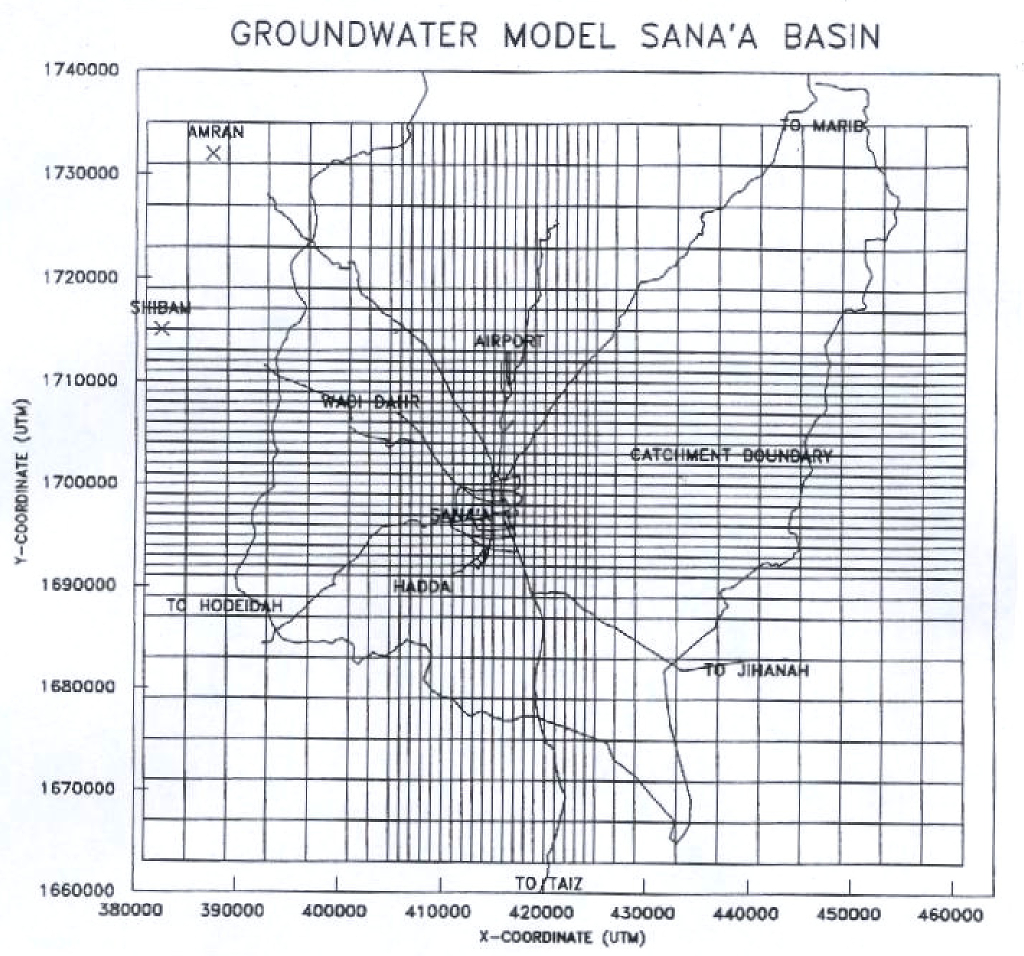


Fig. 2.1: *The Sana'a Basin (= the area within the irregular shaped line, which is the catchment boundary) and the modelled area (the grid of 37 by 37 cells)*

2.2.2 Geology, groundwater occurrence and aquifer system

Geology

The oldest sedimentary Formation in the region of Sana'a is the Amran Series (Middle to Upper Jurassic) which comprises of limestones, marls and shaly limestones some 350 to 1000 m thick. The Amran outcrops in the north of the Basin, covering about 15% of the Basin area. It occurs at depth beneath the Sana'a plain: at the airport the top of the Amran is approximately 350 m deep; at Ar Rawdah 500 m and further south near Sana'a 900 m or more. The Amran is overlain by a sequence of lagoonal shales, marls and fine grained sandstones interbedded with lignite probably of Upper Jurassic or Lower Cretaceous age (equivalent to the "Unnamed Formation" of Italconsult) which outcrop in a narrow band in the north-eastern part of the Basin.

The Tawilah Sandstone (Cretaceous to Tertiary) comprises a series of continental cross bedded sandstones generally medium to coarse grained with interbedded mudstones, siltstones and occasional silty-sandstones. The overlying Medj Zir Formation is a finer grained sandstone with a higher proportion of siltstones and clays. It also contains decomposed volcanic tuffs and "soapy clay beds" associated with the start of regional volcanic activity. It has proved difficult to distinguish the Tawilah and Medj Zir both in aerial photographs and drill cuttings. They are therefore mapped as one Formation and referred to as the Tawilah Sandstone or "Cretaceous Sandstone". The Cretaceous Sandstone outcrops over about 15% of the Basin area in the northern part of the Basin. It is thought to reach a thickness of 400 to 500 m where it has been protected from erosion by the overlying Tertiary Volcanics.

The Tertiary Volcanics (formerly called the Trap Series) outcrop over some 35% of the area of the Sana'a Basin. They form high plateaus to the south, west and east of the Sana'a plain and underlie the Quaternary deposits in the south of the Basin. The sequence is divided into two groups. The lowest group is the "Stratoid Volcanics" which include the Basal Basalt (a dense homogenous basalt flow with columnar jointing), basalts, tuffs and pyroclastics interbedded with fluvio-lacustrine deposits. The upper "Chaotic Volcanics" comprise mixed basalt flows and rhyolite lavas. The total thickness is variable, reaching an estimated maximum of 700 to 900m.

Basic intrusive rocks of Tertiary age are present throughout the area in the form of volcanic plugs, dykes and sills. The alignment of the volcanic necks is oriented NNW-SSE. Dykes are well fractured and oriented NNW-SSE and NNE-SSW.

Volcanic activity continued into the Quaternary forming a plateau of extensive basalt cones in the north west of the Basin interlayered with tuffs and alluvial sediments. The Quaternary Basalts have a total thickness of about 100 to 300 m and cover about 20% of the area of the Basin. They overlie the Amran Limestone, Cretaceous Sandstone and Tertiary Volcanics.

Unconsolidated deposits of the Quaternary cover about 15% of the Basin area. They are confined to wadi beds and low areas that form the Sana'a plain. Deposition appears to have been of fluvio-lacustrine nature which led to the accumulation of clays and silts in Basins 100 to 300 m deep. Coarse grained colluvium and alluvium occurs in the wadi beds at the foot of hills.

The sedimentary sequence is block faulted and gently folded. The regional dip is southwards under cover of the Tertiary Volcanics.

Groundwater occurrence

The Amran Limestone is generally considered to be a poor aquifer although supplies can be obtained from zones of secondary permeability. Karst features however are poorly developed.

The depth to water is over 100m in the plateau area in the northwest of the Basin. In the northeast in valleys leading to the Wadi al Kharid the depth to water is less than 35m and groundwater is abstracted mainly by means of dug wells.
The Unnamed Formation is believed to act as an aquiclude although the regional permeability may be similar to the Amran Limestone.
The Cretaceous Sandstone forms the main aquifer in the region. It has low regional permeability but locally higher permeabilities are found in weathered and fractured zones. It is heavily exploited to the northeast and northwest of Sana'a where it either outcrops or occurs beneath an unconsolidated cover of up to 50 m thickness. Depths to water in the main area of abstraction were about 30 to 40 m in the early 1970's but have declined by 2 to 4 m/yr since. In the south of the Basin the Sandstone is confined beneath several hundreds of meters of Tertiary Volcanics.
The basalt flows and stratoid sequences of the Tertiary Volcanics act as aquicludes, except where fractured or where primary permeability occurs in sediments between flows. The mixed basalt and rhyolite flows at the top of the sequence are more highly fractured and contain perched aquifers which supply dug wells and feed high level springs. The upper layers of the Volcanics are highly weathered and relatively permeable where they underlie the unconsolidated Quaternary deposits in the south of the Basin. Here they are exploited together with the unconsolidated aquifer by dug and drilled wells.
The Quaternary Basalts are highly permeable due to fracturing and to the presence of clastic deposits between flows. Where the Formation is saturated it provides an unconfined aquifer. Water levels are deep ranging from 60 to 130 m depending on the elevation. Wells are generally limited to the southern edge of the outcrop where waterlevels are less than 100 m deep. In the rest of the area surface water is stored in cisterns to provide water for domestic purposes.
The unconsolidated Quaternary deposits provide a poorly permeable aquifer which has been heavily exploited in the Sana'a Basin due to its proximity to the urban area. The aquifer is regionally unconfined but locally semi-confined. Due to the fine grained nature of the deposits in the plain recharge is expected to be mainly indirect, into coarse grained material along wadis and at the base of the hills.

Aquifer system used in the MODFLOW model

The aquifer system (Fig. 2.2a and 2.2b, resp. N-S cross section and W-E cross-section) is schematized into three separate units:

- Aquifer 1: Quaternary Alluvium
- Aquifer 2: Quaternary and Tertiary Volcanics
- Aquifer 3: Cretaceous Sandstone

The Unnamed Formation and/or the Amran Series are considered to be the impermeable lower boundary of the model.

Aquifer 1 is unconfined, only present in the centre of the model area and is modelled as an unconfined aquifer in MODFLOW.

Aquifer 2 is usually unconfined, but probably partly confined were it is overlain by saturated Quaternary Alluvium. In MODFLOW the aquifer is modelled as "confined/unconfined" (meaning that the saturated thickness of the aquifer is calculated at each iteration) and also allowing for flow under dewatered conditions. This means that if the aquifer is unconfined but overlain by saturated Quaternary Alluvium flow from the upper aquifer 1 to aquifer 2 will take place. When the groundwater head in aquifer 2 is used to calculate the amount of flow, too much water will flow into aquifer 2, so adjustments have to be made for the correct calculation.

Aquifer 3 is -as aquifer 2- partly confined (south part of the model) and partly unconfined (north of Sana'a). Also in time confined parts may become unconfined. In terms of MODFLOW the aquifer is modelled as "confined/unconfined", while at the same time also allowing for flow under dewatered conditions.

Lateral extent and estimated thickness of the each of the aquifers are presented in Volume II of Technical Report 5 of the SAWAS Technical Report Series (Foppen, 1996).

Fig. 2.2a and b: The aquifer system as defined in the groundwater model (N-S cross section and W-E cross section). The cross sections are constructed based on all available bore logs from public wells in the Sana'a Basin.

2.2.3 General groundwater flow pattern

Contour lines for the year 1972 were drawn based upon the data of Italconsult (1973; see Fig 2.3). Italconsult did not separate the data into different aquifers: all data belonged to one aquifer complex. It seems appropriate to assume that the data obtained by Italconsult regarding the central part of the Sana'a Basin belong to one aquifer and that is the Quaternary Alluvium since almost all data were collected from shallow dug wells.

From Fig. 2.3 the general trend of groundwater flow is to the north. In the mountainous areas the direction of flow is east (on the western slopes) and west (on the eastern slopes). In the Basin itself groundwater flows north and north of the Jebel as Samma groundwater level measurements lack. Part of the groundwater is discharged as surface water at the Wadi al Kharid springs. The same groundwater flow pattern can be seen on the maps of Selkhozpromexport and SAWAS-2 for the 1984 and 1990 situation, the only difference being the head decline over the years.

Figure 2.3: Groundwater Elevation (m.a.s.l.) of the aquifer complex based on 1972 (from Italconsult)

2.3 Some Important Aspects of the Groundwater Model

2.3.1 MODFLOW

The computer code used to model the groundwater flow system of the Sana'a Basin model is MODFLOW (McDonald and Harbaugh 1988). Pre- and post-processing of model runs was carried out using the pre- and post-processing software developed by Chiang and Kinzelbach (1992). Additional pre- and post-processing facilities were developed in a spreadsheet.

2.3.2 Discretization of the area

The area was discretized into 37*37 cells, the cell width ranging from 1 km in the centre of the model to 4 km near the model boundaries.
The orientation of the grid is north-south, allowing to adjust for K_{xx} to K_{yy} anisotropies due to generally north-south directed complexes of faults and fissures, as indicated by Italconsult (1973).

2.3.3 Boundaries of the model

The aquifer geometry of the Sana'a Basin is subject to speculation:

- Is there a connection of the Cretaceous Sandstone between Shibam and Sana'a on the one hand and Sana'a and Khowlan on the other hand?
- Is the Cretaceous Sandstone south of Sana'a connected with the Sandstone north of Sana'a?

To overcome these uncertainties it was decided to construct two groundwater models of the same area. The first model (A) has a maximum areal extent of
the Cretaceous Sandstone while the second model (B) has a minimum areal extent (ref. Viii-2.4).

Aquifer 1:
Only in the centre of the model area aquifer 1 is present while the northernmost cells of this aquifer are bounded by a "head dependent flow boundary" (Cauchy conditions) in order simulate some groundwater discharge into fissures and cracks of the otherwise Amran Limestone.

Aquifer 2:

Aquifer 2 is present throughout the model area and the boundaries of the model are also of the "head dependent flow"-type. Water is allowed to enter or leave the model, dependent on the difference between calculated head in the cell and the boundary head value.

Aquifer 3:

Aquifer 3 is present throughout the area except for the northern part of the model. All boundaries of aquifer 3 are also of the head dependent flow type.

2.3.4 Discretization of time

Three periods of time can be distinguished:

- To calibrate the steady state model (1972).
- To calibrate the transient model (1973-1995).
- To calibrate the year 2000.

The steady state model was calibrated for 1972, the year in which Italconsult collected the data presented in their reports. The purpose of constructing a steady state model is to calibrate time-invariable aquifer parameter values and initial head values for the transient model without having to deal with initial stability problems. Since the early seventies are considered to represent the groundwater flow system not influenced by man the initial groundwater head distribution also serves to calculate man-induced-drawdowns over the years until 1995.

The transient model is separated into 6 stress periods of five years each and each stress period is separated into timesteps. Each time step represents 365 days. Per stress period the only input change consists of new abstraction files for that particular stress period. Boundary heads, boundary conductances and recharge are kept constant.

2.3.5 Abstractions

The available information regarding the abstractions of the 4500 inventoried wells was distributed among the aquifers. Then, the abstracted volume per well per stress period was calculated and finally the total abstracted volume per model cell was determined. In stress period 5 (1991-1995) a total of 1031 model cells are used with the well package. Also a percentage of the abstracted volume was considered to be irrigation return flow. By designing a flexible structure for producing input files (spreadsheets), this percentage was calibrated with the transient model.

2.3.6 Recharge

The mechanism of recharge of the aquifers due to precipitation excess is believed to be mainly through wadi beds: during a flood, part of the surface water will infiltrate into the wadi bed.

After the flood, part of the infiltrated water will evaporate and part will serve as recharge. Given the annual precipitation distribution the amount of recharge in the western part is about three times higher than in the eastern part of the model area. The total amount of annual recharge for the whole catchment area is 20-30E6 m^3/year. In the model the exact amount varies somewhat in time since cells in the north-east part of the model area "run dry"in time thereby eliminating the recharge for that particular cell. Cells run dry due to the excessive increase in amount of abstractions, especially in the north-east part of the model. Given an average catchment precipitation of 225 to 275 mm/year the percentage of recharge from precipitation is 3 to 4%.

Another type of recharge of the aquifers is infiltration of sewage in the city of Sana'a and infiltration of sewage effluent from the sewage treatment plant. Based on figures from the 1994 census and averaged water use (l/cap/day) total sewage production for the year 1994 and 2000 was estimated to be around 20E6 to 25E6 m^3/year.

2.3.7 Calibration

The model is calibrated by means of "trial-and-error" for the period 1972-1995. Measured heads from four data sets were used:

- Italconsult (heads measured in 1972)
- Selkhozpromexport (heads measured from 1984 till 1986)
- the SAWAS project (heads measured from 1990 till 1993)
- NWSA (hydrographs of 22 observation wells)

Values of the calibrated aquifer parameters are given in Table 2.1. Some remarks:

Aquifer 1:

The whole aquifer was calibrated using only one horizontal and one vertical permeability value (resp. 0.05 and 0.005 m/d) in both models. Applying horizontal anisotropy was not necessary. It was however necessary to model the aquifer with a low vertical permeability due to the fact that measured heads in 1993 in the Cretaceous Sandstone and the Quaternary Alluvium indicated the presence of a large resistance between the two layers.

Aquifer 2:

The calibrated horizontal anisotropy value is 4, meaning that permeability values given in the Table apply to flow in East-West direction. Permeabilities are four times higher in north-south direction.

The Tertiary Volcanics were calibrated using two horizontal permeabilities: the Sana'a Basin Floor has a higher permeability (0.02 m/d) than the Tertiary Volcanics (0.002 m/d) outside the Basin Floor. Higher permeability values for the Basin Floor are mentioned in literature several times (Bloemendaal, 1991; Nash, 1991; Selkhozpromexport, 1985, Italconsult, 1973). The Quaternary Volcanics were modelled using a permeability value of 1 m/d, which indicates a relatively high permeability due to the abundant presence of fissures and cracks in this aquifer.

The vertical permeability of the aquifer was calibrated using only one (low) permeability value of 0.00006 m/d. This clearly indicates the presence of almost impermeable layers of basalts, tuffs, pyroclastics and locally fluvio-lacustrine deposits.

Aquifer 3:

There are no differences between vertical and horizontal permeability values. Horizontal permeability values were, based on the available data from pumping tests, divided into four groups: the eroded and non-eroded Sandstone and the Sandstone in fracture zone 1 and 2. Eroded and non-eroded means actually covered or not covered by Tertiary Volcanics. Except for the As Sabaeen well no pumping test data were available for the Sandstone covered by Tertiary Volcanics. However, in literature the permeability of the aquifer is associated with the presence of eroded and non-eroded Sandstone (Italconsult, 1973; Selkhozpromexport, 1985). Fracture zone 1 and 2 is indicated by the pumping test data. Some wells have very high transmissivity values of around 1000 to 2000 m^2/d and more. Given a north-south permeability of around 4 m/d and a thickness of 400 m, the transmissivity would be 1600 m^2/d, which is in the same range.

Table 2.1: Values of the calibrated aquifer parameters

RESULTS OF THE STEADY STATE MODEL	
AQUIFER 1:	
Horizontal anisotropy (-):	1
Horizontal permeability (m/d):	
Whole aquifer	0.05
Vertical permeability (m/d):	
Whole aquifer	0.0005
AQUIFER 2:	
Horizontal anisotropy (-):	4
Horizontal permeability (m/d):	
Tertiary Volcanics	0.002
Tertiary Volcanics (Basin Floor)	0.02
Quaternary Volcanics	1
Vertical permeability (m/d):	
Tertiary Volcanics	0.00006
Quaternary Volcanics	1
AQUIFER 3:	
Horizontal anisotropy (-):	4.5
Permeability (m/d):	
Eroded	0.2
Non-eroded	0.09
Fracture zone 1	0.9
Fracture zone 2	0.45
RESULTS OF THE TRANSIENT MODEL	
AQUIFER 1	
Porosity (-):	
Whole aquifer	0.02
AQUIFER 2	
Porosity (-):	
Tertiary Volcanics	0.015
Quaternary Volcanics	0.1
AQUIFER 3	
Porosity (-):	
Whole aquifer	0.08
Specific storage (m^{-1}):	
Whole aquifer	2E-7
IRRIGATION RETURN FLOW	20%

3. *Results and Discussion*

3.1 Water Balance Calculations

3.1.1 Components of the water balance

The water balance for each aquifer in each subcatchment of the Sana'a Basin is determined by using the water balance equation:

In – Out = Change in Storage

This yields per aquifer (in m^3/year; see also Fig. 3.1):

In:

R Recharge

W Irrigation Return Flow

E_h Exchange (horizontal) from one area to another (in the same aquifer)

E_u Exchange (upper) in one area from one aquifer to another overlying aquifer

E_l Exchange (lower) in one area from on aquifer to another underlying aquifer

Out:

W Abstractions

E_h Horizonal exchange from one area to another (in the same aquifer)

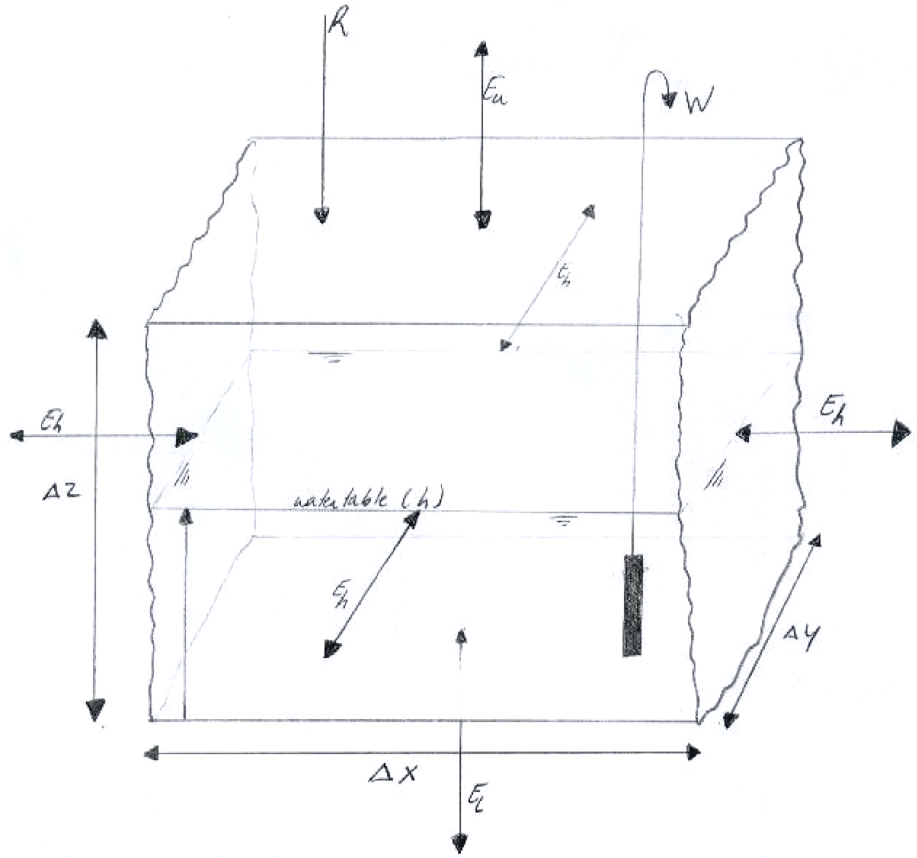
E_u Upper exchange in one area from one aquifer to another overlying aquifer

E_l Lower exchange in one area from on aquifer to another underlying aquifer

S Change in saturated storage. In Appendix 1 S is considered to be an “In”-component or an “Out”-component of the water balance (source or sink). In case S is “In”, water is released from storage into the model (source). This means a groundwater head decline. In case S is “Out”, water from the model “flows” into storage (sink). This means a rise of the groundwater head.

In Fig. 3.1 also D and H are given. D is called “drain discharge” and is a head-dependent flow component across the northern boundary of the model which affects the water balance of sub-catchments located at this boundary of the model. Physically, this represents a minor flow component out of the model and it can be interpreted as going “into fissures and cracks in the Amran Limestone”. D can be compared with E_l, which is exchange of water from one aquifer to the underlying aquifer.
H is flow across the W, E and S boundary of the model which affects the water balance of the sub-catchments located at the boundaries of the model. H can be compared with E_h, which is exchange (in the same aquifer) from one area to another.

The components of the water balance per sub-catchment can be generated in Processing Modflow Version 5 with the “Water Budget” option under the “Tools”-menu.



S = storage = h × Δx × Δy (m³)

E_h = horizontal exchange (m³) from one area to another (same aquifer)

E_u = exchange (m³) in one area from one aquifer to another overlying aquifer

E_l = exchange (m³) in one area from one aquifer to another underlying aquifer

W = abstraction (m³) in one area

D = drain discharge (m³); only on boundary of model

R = recharge (m³)

H = exchange (m³) from outside model boundary to one area, only on boundary of model

Fig.3.1: Explanation of water balance components used in Appendix 1 for a "chunk" of aquifer of the Sana'a Basin groundwater model

3.1.2 Abstractions for the year 2000

The water balance was determined for the year 1994 and the year 2000. As was already mentioned in the previous chapter, the model was not validated again for the year 2000 for the simple reason that no Sana'a Basin wide well-inventory has been carried out in the year 2000. To calculate the water balance in each sub-basin in the year 2000, the amount of abstraction per model-cell as measured in 1994 was extrapolated to the year 2000 by using a historical abstraction growth rate of 3.5% per year. This figure is based on an Irrigation Water Demand model made by the Technical Secretariat of the High Water Council (1992).

3.2 Results and Selection of Sub-basins

The results are given in Appendix 1, which should be read as follows. The zones for which the calculations have been carried out coincide with the sub-catchment map of the Sana'a Basin (Fig. 3.2). Sub-catchment or zone 1-6 are not modelled with the groundwater model since these sub-catchments are located in the northern Amran limestone area and the Amran limestone is considered to be impermeable from a modelling point of view.

In each zone, the waterbalance was determined for each aquifer. Sometimes this results in rows of zeros. Whenever all values for one layer are zero, it usually means that this layer is absent in the zone. An example is zone 7, layer 1, the area of Wadi Qasabah in the north-west part of the Sana'a Basin.

When looking at zone 11 layer 3 in 1994 for example, which is the Tawilah Sandstone in the subcatchment of Wadi As-Sirr in the north east part of the Sana'a Basin, around 17.42 million m^3 is released from storage into the model, around 2.14 million m^3 flows from the Tawilah sandstone outside the subcatchment into the Tawilah sandstone in Wadi As-Sirr and the 1.38 million m^3 flows into the sandstone from net precipitation. On the other hand, around 19.55 million m^3 is abstracted while around 1.39 million m^3 flows into the sandstone outside the subcatchment. The total amount of water flowing in the aquifer in Wadi As-Sirr is around 20.95 million m^3 which equals the amount of water flowing out of the aquifer. In the year 2000, groundwater abstraction has increased which is counterbalanced by release from storage (a groundwater head decline).

From Appendix 1it is clear that the dominant process is abstraction of water that is counterbalanced by release from storage (a groundwater head decline) and that this process is dominant in both 1994 and in 2000.

3.2.1 Where to implement demand-driven water management measures?

Water demand management is an alternative to increased water supply in order to meet growing demand (Stephenson, 2000). Therefore the relative and potential success of measures aimed at developing alternatives in order to meet growing demand as opposed to increasing water supply will be highest in sub-catchments where total amount of abstraction/km2 is relatively high and where recharge or other components of the "In"-term of the water balance are relatively low or, conversely, where total amount of abstractions is almost completely counterbalanced by storage depletion (second column of Table 3.1).

In order to assess these components of the water balance, the water balance calculations have been summarized per sub-catchment as a whole (the summation of the water balance of aquifer 1, aquifer 2 and aquifer 3) for the year 2000. On top of that, "exchange" in Table 3.1 is the summation of E_h (horizonal exchange from one area to another (in the same aquifer)), E_u (upper exchange in one area from one aquifer to another overlying aquifer), E_l (lower exchange in one area from on aquifer to another underlying aquifer), D (drain discharge), H (flow across the W, E and S boundary of the model).

Table 3.1: Summary of the water balance calculations for the year 2000 per sub-catchment

Managment Zone	**Wadi Catchment**	**Net (= In - Out) in Mm^3/year**			
		Storage depletion	**Exchange**	**Abstractions (incl. 20% Irr. Ret. Flow, see Table 2.1)**	**Recharge (from rain and sewage)**
D	7	0	-0.1	0	0.1
	8	1.3	-1.5	0	0.2
	13	1.6	0.1	-2.4	0.7
A	9	25.5	5.7	-32.2	1.0
P	10	0	0	0	0
I	11	20.6	0.9	-22.9	1.4
F	12	17.2	1.1	-18.7	0.4
K	14	7.6	-8.1	-5.9	7.1
E	15	10.6	-0.9	-10.8	1.1
B	16	15.6	3.6	-40.0	20.7
N	17	18.4	-4.5	-14.5	0.6
O	18	3.0	-1.7	-2.6	2.5
J	20	4.3	0.5	-7.0	2.2
L	19	3.5	-1.4	-4.7	2.6
	21	5.6	0.4	-11.1	5.1
	22	2.6	-0.6	-2.6	0.7

Based on Table 3.1 there are a number of zones that can be given a high priority to implement demand based measures to limit groundwater use. **These zones are no. 17, 15, 12, 11, 9 and 16 .** Highest chances of success in implementing demand based water management measures are in sub-catchment 17 (W. Sa'wan and Ar-Rawnah, east of Sana'a). Here abstractions are high and there is also a net negative exchange indicating flow out of the sub-catchment to neighbouring sub-catchments. So, storage depletion here is even higher than the total amount of abstractions! Almost the same applies to sub-catchment 15 (W. Hamdan and As-Sabarah, west of Sana'a).

3.2.2 Where to implement supply-driven water management measures?

Supply based measures should be implemented in those areas where there are reasonable chances for success in terms of extra amount of water that can be recharged in the aquifers. So, reasonable chances for success will be present in areas that have a relatively high component of recharge by precipitation and at the same time where storage depletion is relatively low. According to Table 3.1 these zones are no. 14, 21,19,18 and 20. The high recharge component due to domestic sewage of zone 16 has not been considered in this respect.

4. *Recommendations for Future Work*

Already in 1995 the following conclusions were drawn from the sensitivity analysis of the groundwater model:

"Although the model results look promising, there are still uncertainties concerning aquifer geometry and parameter estimates. The only way to minimize those uncertainties is to enhance the quality of the data. This means collecting data in the field. Especially the parameters:

- recharge;
- vertical permeability of the Tertiary Volcanics;
- horizontal permeability of the Cretaceous Sandstone;
- anisotropy of the Cretaceous Sandstone

need special attention from a modelling point of view".

Furthermore, it was concluded (in 1995) that:

- Top and bottom of the Cretaceous Sandstone needs to be mapped. Preferably this should be done by means of exploration drilling, since geophysical measurements in the Sana'a South area already indicated a poor geo-electrical contrast between the Tertiary Volcanics and the Cretaceous Sandstone.
- The groundwater monitoring network has to be expanded. To obtain a good understanding of direction of groundwater flow and groundwater level fluctuations the monitoring network should focus on the Cretaceous Sandstone throughout the Sana'a Basin.

In the space of 6 years (1995-2001) not a lot has happened with regard to data collection in the Sana’a Basin and therefore all conclusions mentioned above are still extremely valid. On top of that the following can be added:

- Large scale Sana’a Basin wide groundwater modelling is needed in order to update the 1995 MODFLOW groundwater model. Recently new data have become available indicating the “shallow” (around 900 m below the surface) presence of the Cretaceous Sandstone south of Sana’a. Also, the satellite study carried out by WEC and ITC (2000) has indicated the presence of “rift structures” in the west of the Sana’a Basin which has implications for the aquifer geometry of the groundwater model (limited areal extent of the Cretaceous Sandstone aquifer).
- Detailed groundwater modelling (fine grid) on sub-catchment scale is needed in order to evaluate measures aimed at demand-driven water water management or supply driven water-management. Boundary conditions for detailed groundwater modelling are taken from the large scale Sana’a Basin wide model.

Figure 3.2 : Location Map of Sub-Basins

Table 3.3: Results of the water balance calculations per zone per aquifer in 1994 and 2000

	1994	1994	1994	2000	2000	2000
	IN (M3/YEAR)	OUT (M3/YEAR)	IN-OUT (M3/YEAR)	IN (M3/YEAR)	OUT (M3/YEAR)	IN-OUT (M3/YEAR)
ZONE, LAYER	7	1		7	1	
(W. Qasabah)						
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	7	2		7	2	
STORAGE	35840	293	35547	37793	586	37207
HORIZ. EXCHANGE	127193	3892736	-3765544	106994	3973716	-3866722
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	100740	0	100740	100740	0	100740
HEAD DEP BOUNDS	4946798	1317747	3629051	5003433	1274510	3728923
SUM OF THE LAYER	5210570	5210777	-206	5248960	5248812	148
ZONE, LAYER	7	3		7	3	
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	8	1		8	1	
Yahis and Al-Huqqah						
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	8	2		8	2	
STORAGE	1072623	0	1072623	1264715	0	1264715
HORIZ. EXCHANGE	3305173	4576344	-1271171	3462330	4925656	-1463326
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	198560	0	198560	198560	0	198560
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	4576356	4576344	11	4925605	4925656	-51
ZONE, LAYER	8	3		8	3	
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0

	1994 IN (M3/YEAR)	1994 OUT (M3/YEAR)	1994 IN-OUT (M3/YEAR)	2000 IN (M3/YEAR)	2000 OUT (M3/YEAR)	2000 IN-OUT (M3/YEAR)
ZONE, LAYER	9	1		9	1	
Bani Hawat (northern central plain)						
STORAGE	7572688	1441658	6131030	5775323	2484168	3291155
HORIZ. EXCHANGE	228523	55702	172822	401321	35406	365915
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	177411	6579254	-6401843	12611	5332038	-5319427
WELLS	3308869	3850878	-542010	3982318	3155440	826878
DRAINS	0	17801	-17801	0	19456	-19456
RECHARGE	657730	0	657730	854830	0	854830
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	11945221	11945294	-73	11026402	11026508	-106
ZONE, LAYER	9	2		9	2	
STORAGE	447342	22943	424399	105324	45748	59576
HORIZ. EXCHANGE	3958129	441718	3516411	4106813	448664	3658149
EXCHANGE (UPPER)	6579254	177411	6401843	5332038	12611	5319427
EXCHANGE (LOWER)	141801	8347224	-8205423	0	7277757	-7277757
WELLS	255025	330508	-75482	298380	21353	277027
DRAINS	0	0	0	0	0	0
RECHARGE	164980	0	164980	164980	0	164980
HEAD DEP BOUNDS	0	2226936	-2226936	0	2201741	-2201741
SUM OF THE LAYER	11546531	11546739	-208	10007534	10007873	-339
ZONE, LAYER	9	3		9	3	
STORAGE	16825265	0	16825265	22148938	0	22148938
HORIZ. EXCHANGE	6033152	690144	5343008	5658757	872178	4786580
EXCHANGE (UPPER)	8347224	141801	8205423	7277757	0	7277757
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	28718092	-28718092	0	33352060	-33352060
DRAINS	0	1655769	-1655769	0	861350	-861350
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	31205641	31205806	-165	35085454	35085591	-137
ZONE, LAYER	10	1		10	1	
W. Thumah & Al-Mahajir & Shira						
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	10	2		10	2	
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	10	3		10	3	
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0

	1994 IN (M3/YEAR)	1994 OUT (M3/YEAR)	1994 IN-OUT (M3/YEAR)	2000 IN (M3/YEAR)	2000 OUT (M3/YEAR)	2000 IN-OUT (M3/YEAR)
ZONE, LAYER	11	1		11	1	
W. As-Sirr						
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	11	2		11	2	
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	11	3		11	3	
STORAGE	17425860	0	17425860	20565392	0	20565392
HORIZ. EXCHANGE	2143491	1398896	744595	2200886	1270639	930247
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	19558923	-19558923	0	22883939	-22883939
DRAINS	0	0	0	0	0	0
RECHARGE	1388460	0	1388460	1388460	0	1388460
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	20957811	20957818	-7	24154736	24154577	160
ZONE, LAYER	12	1		12	1	
W. Al-Furs & Rijam						
STORAGE	3260	131974	-128714	0	240042	-240042
HORIZ. EXCHANGE	0	4861	-4861	518	4747	-4229
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	137167	37157	100010	210685	0	210685
DRAINS	0	0	0	0	0	0
RECHARGE	33580	0	33580	33580	0	33580
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	174007	173992	14	244783	244789	-6
ZONE, LAYER	12	2		12	2	
STORAGE	12078	0	12078	5347	0	5347
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	12074	-12074	0	5348	-5348
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	12078	12074	3	5347	5348	-2
ZONE, LAYER	12	3		12	3	
STORAGE	16703827	0	16703827	17457420	0	17457420
HORIZ. EXCHANGE	2464433	1517940	946493	2472433	1396667	1075767
EXCHANGE (UPPER)	12074	0	12074	5348	0	5348
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	18091604	-18091604	0	18868579	-18868579
DRAINS	0	0	0	0	0	0
RECHARGE	429240	0	429240	329960	0	329960
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	19609575	19609545	30	20265162	20265246	-84

	1994 IN (M3/YEAR)	1994 OUT (M3/YEAR)	1994 IN-OUT (M3/YEAR)	2000 IN (M3/YEAR)	2000 OUT (M3/YEAR)	2000 IN-OUT (M3/YEAR)
ZONE, LAYER	13	1		13	1	
W. Al-Iqbal & ash Sha'b						
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	13	2		13	2	
STORAGE	2081973	5078	2076895	1633905	6250	1627655
HORIZ. EXCHANGE	1866908	2284663	-417755	2105124	2327842	-222717
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	48591	3068123	-3019532	36159	3292161	-3256002
WELLS	117493	1294443	-1176950	137467	756912	-619444
DRAINS	0	0	0	0	0	0
RECHARGE	708100	0	708100	642400	0	642400
HEAD DEP BOUNDS	1828827	0	1828827	1828591	0	1828591
SUM OF THE LAYER	6651892	6652308	-415	6383646	6383164	482
ZONE, LAYER	13	3		13	3	
STORAGE	2771	0	2771	1016	2031	-1015
HORIZ. EXCHANGE	281868	1141968	-860100	241761	1225053	-983291
EXCHANGE (UPPER)	3068123	48591	3019532	3292161	36159	3256002
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	1510516	-1510516	0	1767306	-1767306
DRAINS	0	651567	-651567	0	570066	-570066
RECHARGE	0	0	0	65700	0	65700
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	3352762	3352641	121	3600638	3600615	23
ZONE, LAYER	14	1		14	1	
W. Zahr & Harad & Al-Ghayl						
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	14	2		14	2	
STORAGE	1568902	71667	1497235	1730587	83225	1647362
HORIZ. EXCHANGE	1825000	0	0	2555000	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	6315775	-6315775	0	6341628	-6341628
WELLS	198305	1091277	-892973	232016	1244627	-1012611
DRAINS	0	0	0	0	0	0
RECHARGE	6447360	0	6447360	6447360	0	6447360
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	8585376	8585420	-44	8797882	8797827	55
ZONE, LAYER	14	3		14	3	
STORAGE	4744391	0	4744391	5926564	0	5926564
HORIZ. EXCHANGE	5121905	12736749	-7614844	4861086	12978959	-8117874
EXCHANGE (UPPER)	6315775	0	6315775	6341628	0	6341628
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	4143414	-4143414	0	4847797	-4847797
DRAINS	0	0	0	0	0	0
RECHARGE	697880	0	697880	697880	0	697880
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	16879951	16880163	-212	17827159	17826757	402

	1994	1994	1994	2000	2000	2000
	IN (M3/YEAR)	OUT (M3/YEAR)	IN-OUT (M3/YEAR)	IN (M3/YEAR)	OUT (M3/YEAR)	IN-OUT (M3/YEAR)
ZONE, LAYER	15	1		15	1	
W. Hamdan & As-Sabarah						
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	15	2		15	2	
STORAGE	646963	3354	643608	676924	97001	579923
HORIZ. EXCHANGE	258079	5402	252677	342555	94196	248358
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	755820	-755820	0	958981	-958981
WELLS	24236	747973	-723737	28356	875128	-846772
DRAINS	0	0	0	0	0	0
RECHARGE	583270	0	583270	977470	0	977470
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	1512548	1512549	-1	2025305	2025306	-1
ZONE, LAYER	15	3		15	3	
STORAGE	9312562	0	9312562	10015782	0	10015782
HORIZ. EXCHANGE	2365071	3960845	-1595774	2663535	3790648	-1127114
EXCHANGE (UPPER)	755820	0	755820	958981	0	958981
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	8538372	-8538372	0	9913380	-9913380
DRAINS	0	0	0	0	0	0
RECHARGE	65700	0	65700	65700	0	65700
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	12499154	12499217	-63	13703996	13704028	-31
ZONE, LAYER	16	1		16	1	
W. Al-Mawrid & Al-I'shash & Al-Hayd						
STORAGE	1305524	1089463	216061	1226551	3311940	-2085389
HORIZ. EXCHANGE	78284	222257	-143973	78256	412636	-334381
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	7954202	-7954202	27542	8781842	-8754301
WELLS	7949624	691697	7257926	1408778	2290705	-881927
DRAINS	0	0	0	0	0	0
RECHARGE	624150	0	624150	12055950	0	12055950
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	9957581	9957618	-37	14797077	14797123	-46
ZONE, LAYER	16	2		16	2	
STORAGE	7014522	22675	6991847	3004263	1449692	1554571
HORIZ. EXCHANGE	946062	905191	40871	1024790	1390759	-365969
EXCHANGE (UPPER)	7954202	0	7954202	8781842	27542	8754301
EXCHANGE (LOWER)	4189	4993604	-4989415	24278	5518257	-5493979
WELLS	142029	11223612	-11081583	157983	12195286	-12037302
DRAINS	0	0	0	0	0	0
RECHARGE	1084050	0	1084050	7588350	0	7588350
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	17145055	17145082	-27	20581507	20581535	-27
ZONE, LAYER	16	3		16	3	
STORAGE	15655536	0	15655536	16219729	0	16219729
HORIZ. EXCHANGE	6139409	2731214	3408195	6907489	2601945	4305544
EXCHANGE (UPPER)	4993604	4189	4989415	5518257	24278	5493979
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	24282937	-24282937	0	27037623	-27037623
DRAINS	0	0	0	0	0	0
RECHARGE	229950	0	229950	1018350	0	1018350
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	27018498	27018338	160	29663824	29663847	-23

	1994 IN (M3/YEAR)	1994 OUT (M3/YEAR)	1994 IN-OUT (M3/YEAR)	2000 IN (M3/YEAR)	2000 OUT (M3/YEAR)	2000 IN-OUT (M3/YEAR)
ZONE, LAYER	17	1		17	1	
W. Sawan & Ar-Rawnah						
STORAGE	61567	60524	1043	32832	56071	-23239
HORIZ. EXCHANGE	26770	33745	-6975	48919	61194	-12275
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	113758	-113758	0	150200	-150200
WELLS	119691	0	119691	185713	0	185713
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	208027	208027	0	267464	267465	-1
ZONE, LAYER	17	2		17	2	
STORAGE	2135	45255	-43120	0	17809	-17808
HORIZ. EXCHANGE	9764	9730	34	11798	27231	-15433
EXCHANGE (UPPER)	113758	0	113758	150200	0	150200
EXCHANGE (LOWER)	0	384096	-384096	0	461330	-461330
WELLS	182026	0	182026	212970	0	212970
DRAINS	0	0	0	0	0	0
RECHARGE	131400	0	131400	131400	0	131400
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	439083	439081	1	506369	506369	-1
ZONE, LAYER	17	3		17	3	
STORAGE	16351204	40938	16310267	18449182	9531	18439650
HORIZ. EXCHANGE	1962640	6488870	-4526229	2006252	6456695	-4450442
EXCHANGE (UPPER)	384096	0	384096	461330	0	461330
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	12661746	-12661746	0	14944033	-14944033
DRAINS	0	0	0	0	0	0
RECHARGE	493480	0	493480	493480	0	493480
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	19191422	19191553	-131	21410244	21410258	-14
ZONE, LAYER	18	1		18	1	
W. Shahik						
STORAGE	35732	0	35732	2441	0	2441
HORIZ. EXCHANGE	0	3690	-3690	0	592	-592
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	88982	-88982	0	69931	-69931
WELLS	24090	0	24090	35232	0	35232
DRAINS	0	0	0	0	0	0
RECHARGE	32850	0	32850	32850	0	32850
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	92672	92673	-1	70522	70523	0
ZONE, LAYER	18	2		18	2	
STORAGE	1301894	0	1301894	1605399	0	1605399
HORIZ. EXCHANGE	134968	448469	-313501	152684	527674	-374991
EXCHANGE (UPPER)	88982	0	88982	69931	0	69931
EXCHANGE (LOWER)	0	1519463	-1519463	0	1554421	-1554421
WELLS	1110877	-1105556	0	1299727	-1293500	0
DRAINS	0	0	0	0	0	0
RECHARGE	1547600	0	1547600	1547600	0	1547600
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	3078766	3078809	-43	3381840	3381822	18
ZONE, LAYER	18	3		18	3	
STORAGE	1369257	13984	1355273	1423628	5703	1417925
HORIZ. EXCHANGE	2336643	3676495	-1339852	2512140	3814228	-1302088
EXCHANGE (UPPER)	1519463	0	1519463	1554421	0	1554421
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	2525457	-2525457	0	2595140	-2595140
DRAINS	0	0	0	0	0	0
RECHARGE	990610	0	990610	924910	0	924910
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	6215973	6215937	36	6415099	6415071	28

	1994	1994	1994	2000	2000	2000
	IN (M3/YEAR)	OUT (M3/YEAR)	IN-OUT (M3/YEAR)	IN (M3/YEAR)	OUT (M3/YEAR)	IN-OUT (M3/YEAR)
ZONE, LAYER	19	1		19	1	
W. Ghayman						
STORAGE	52703	0	52703	0	699	-699
HORIZ. EXCHANGE	2207	0	2207	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	83799	-83799	0	56488	-56488
WELLS	16644	53436	-36792	24342	0	24342
DRAINS	0	0	0	0	0	0
RECHARGE	65700	0	65700	32850	0	32850
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	137254	137235	19	57192	57187	5
ZONE, LAYER	19	2		19	2	
STORAGE	3702078	0	3702078	3424816	0	3424816
HORIZ. EXCHANGE	783773	846501	-62728	766739	946135	-179396
EXCHANGE (UPPER)	83799	0	83799	56488	0	56488
EXCHANGE (LOWER)	0	1269262	-1269262	1400	1235007	-1233607
WELLS	0	4238760	-4238760	0	4674400	-4674400
DRAINS	0	0	0	0	0	0
RECHARGE	1784850	0	1784850	2606100	0	2606100
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	6354499	6354523	-24	6855544	6855543	1
ZONE, LAYER	19	3		19	3	
STORAGE	46770	0	46770	48937	0	48937
HORIZ. EXCHANGE	1576935	2843743	-1266808	1769514	3007763	-1238249
EXCHANGE (UPPER)	1269262	0	1269262	1235007	1400	1233607
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	49275	-49275	0	44348	-44348
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	2892967	2893018	-52	3053459	3053511	-52
ZONE, LAYER	20	1		20	1	
W. Al-Mulaikhy & Hamal						
STORAGE	0	0	0	0	0	0
HORIZ. EXCHANGE	0	0	0	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	0	0	0	0	0	0
ZONE, LAYER	20	2		20	2	
STORAGE	5270317	0	5270317	4289681	0	4289681
HORIZ. EXCHANGE	1531906	831933	699973	1826841	792195	1034646
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	14279	612092	-597814	47095	593568	-546473
WELLS	0	6216370	-6216370	0	7001471	-7001471
DRAINS	0	0	0	0	0	0
RECHARGE	843880	0	843880	2223580	0	2223580
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	7660382	7660396	-14	8387197	8387235	-38
ZONE, LAYER	20	3		20	3	
STORAGE	9851	0	9851	6114	0	6114
HORIZ. EXCHANGE	2723809	3331474	-607665	2632290	3184881	-552592
EXCHANGE (UPPER)	612092	14279	597814	593568	47095	546473
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	3345752	3345753	-1	3231971	3231976	-5

	1994 IN (M3/YEAR)	1994 OUT (M3/YEAR)	1994 IN-OUT (M3/YEAR)	2000 IN (M3/YEAR)	2000 OUT (M3/YEAR)	2000 IN-OUT (M3/YEAR)
ZONE, LAYER	21	1		21	1	
W. Hizyaz						
STORAGE	207016	4947	202070	0	301668	-301668
HORIZ. EXCHANGE	0	48	-48	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	437770	-437770	0	1317476	-1317476
WELLS	224920	210342	14578	337994	0	337994
DRAINS	0	0	0	0	0	0
RECHARGE	221190	0	221190	1281150	0	1281150
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	653127	653107	20	1619144	1619145	-1
ZONE, LAYER	21	2		21	2	
STORAGE	9015805	0	9015805	5913025	40562	5872463
HORIZ. EXCHANGE	1507154	961597	545558	1805976	971571	834405
EXCHANGE (UPPER)	437770	0	437770	1317476	0	1317476
EXCHANGE (LOWER)	6904	495871	-488968	32041	440902	-408861
WELLS	0	10647180	-10647180	0	11437396	-11437396
DRAINS	0	0	0	0	0	0
RECHARGE	1136975	0	1136975	3821915	0	3821915
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	12104608	12104649	-41	12890431	12890430	1
ZONE, LAYER	21	3		21	3	
STORAGE	11357	0	11357	7355	0	7355
HORIZ. EXCHANGE	2328047	2828373	-500327	2415120	2831337	-416217
EXCHANGE (UPPER)	495871	6904	488968	440902	32041	408861
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	2835275	2835277	-1	2863377	2863378	-1
ZONE, LAYER	22	1		22	1	
W. Akhwar						
STORAGE	33075	0	33075	3241	0	3241
HORIZ. EXCHANGE	0	2159	-2159	0	0	0
EXCHANGE (UPPER)	0	0	0	0	0	0
EXCHANGE (LOWER)	0	63763	-63763	0	36090	-36090
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	32850	0	32850	32850	0	32850
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	65925	65922	3	36091	36090	1
ZONE, LAYER	22	2		22	2	
STORAGE	2301234	0	2301234	2570605	0	2570605
HORIZ. EXCHANGE	330324	470008	-139684	317638	338340	-20702
EXCHANGE (UPPER)	63763	0	63763	36090	0	36090
EXCHANGE (LOWER)	0	632757	-632757	0	610931	-610931
WELLS	0	2250940	-2250940	0	2633601	-2633601
DRAINS	0	0	0	0	0	0
RECHARGE	658460	0	658460	658460	0	658460
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	3353781	3353705	76	3582793	3582872	-79
ZONE, LAYER	22	3		22	3	
STORAGE	6911	0	6911	5274	0	5274
HORIZ. EXCHANGE	2533100	3172765	-639665	2733037	3349244	-616207
EXCHANGE (UPPER)	632757	0	632757	610931	0	610931
EXCHANGE (LOWER)	0	0	0	0	0	0
WELLS	0	0	0	0	0	0
DRAINS	0	0	0	0	0	0
RECHARGE	0	0	0	0	0	0
HEAD DEP BOUNDS	0	0	0	0	0	0
SUM OF THE LAYER	3172768	3172765	3	3349241	3349244	-3