

The Preliminary Study of the Stampriet Transboundary Aquifer in the South East Kalahari/Karoo Basin

By

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May 2009

DECLARATION

I declare that The Preliminary Study of Stampriet Transboundary Aquifer in the South East Kalahari/Karoo Basin is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

Hadjira Peck

May 2009

Signed:

ABSTRACT

The Preliminary Study of the Stampriet Transboundary Aquifer in the South East
Kalahari/Karoo Basin

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The Auob transboundary aquifer (TBA) is located in the SE Kalahari/Karoo Basin and has previously been individually managed by its member states i.e. Botswana, Namibia and South Africa.

The main recharge area is situated in the north western area of the Namibian Stampriet Artesian Basin (SAB). The groundwater flow direction is from the north west to south east. Recharge is calculated as one percent of the average rainfall (150 - 300mm per year) (JICA, 2002). However, the role of episodic rainfall events which occur every ± 20 years also takes place and is believed to be the main source of recharge to the semi-confined Auob transboundary aquifer.

The main objectives were to conceptualize the Auob aquifer system; verify conceptualization with a groundwater flow simulation and allow a “what-if” scenario model to be produced. A pertinent objective of this study is to simulate the groundwater flow to determine the potential groundwater flux towards Namibia’s neighbouring states. In this way, the necessary research in identifying the groundwater flow and its flow mechanisms will be accomplished to successfully manage such a vital resource in an equitable manner.

A conceptual model of the Auob aquifer in the SAB has been modelled and forms a basis for the subsequent numeric simulation. The groundwater flow patterns were simulated with the use of the Modular Finite-Difference Ground-Water Flow Model (MODFLOW). The normal and episodic recharges were placed into the groundwater flow simulation to examine the significance of these two types of recharge. The simulation time was also extended to a period of twenty years correlating with the time of the episodic rainfall event.

The significance of this study investigates the groundwater flow across political boundaries and through the use of the water balance method and geological linkages in existing data the Auob aquifer is proven to be a legitimate TBA. The episodic recharge events and the representation of flow patterns under these conditions identifies that overabstraction is possible in Namibia and can change flow patterns across the border.

The determination of the Auob TBA characteristics has definite socio-economic implications which affect all water users of the Auob aquifer in all member states. The sharing of data and multilateral cooperation is essential for the management of the aquifer. Furthermore, the future research within the aquifer system and governmental legislature must also have a holistic approach to incorporate all countries.

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LIST OF ACRONYMS

CEDARE- Centre for Environment and Development for the ARab Region and Europe

IAEA – International Atomic Energy Agency

IGRAC – International Groundwater Resources Assessment Centre

JICA – Japanese International Cooperation Agency

MMEWR – Ministry of Minerals, Energy and Water Resources (Botswana)

SAB – Stampriet Artesian Basin

SADC – South Africa Development Community

TBA – Transboundary Aquifer

Chapter 1 – Introduction

1.1. Purpose

Southern Africa is known for its semi-arid to arid conditions and its subsequent water resource variability. Many of the countries that fall in this region have turned to its groundwater potential to offer a solution to the ever increasing demand on this vital resource. There are twenty official transboundary aquifers (TBAs) delineated within the Southern African Development Community (SADC) Region alone (Vasak & Kukuric, 2006). The Stampriet TBA lies within the South East Kalahari Artesian Basin which traverses the political borders of Botswana, Namibia and South Africa. Recharge of the aquifers is mainly known to take place in Namibia and groundwater flows in a NW to SE direction.

This study will determine the resultant groundwater flux into these member states which will establish the significance of the Stampriet TBA; influence the equitable management of the aquifer system in the recharge state; and produce a conceptual model and a ‘what-if’ scenario model of the Stampriet TBA. In terms of significance, the research will broaden the understanding of the aquifer system and provide stepping stones for further numerical modelling of the aquifer to take place.

1.2. Location of the study area

The Stampriet Artesian Basin (SAB) refers to the transboundary groundwater system located in Namibia (Alker, 2008) and is assumed to extend into Botswana and South Africa. The SAB occupies 71,000 km² in Namibia. The boundaries of the SAB along the NE, E and SE directions are not clearly defined. However, it is estimated that the extent of the SAB into Botswana is approximately 70, 000 km² with its extent into South Africa as yet being undetermined (Puri, 2001).

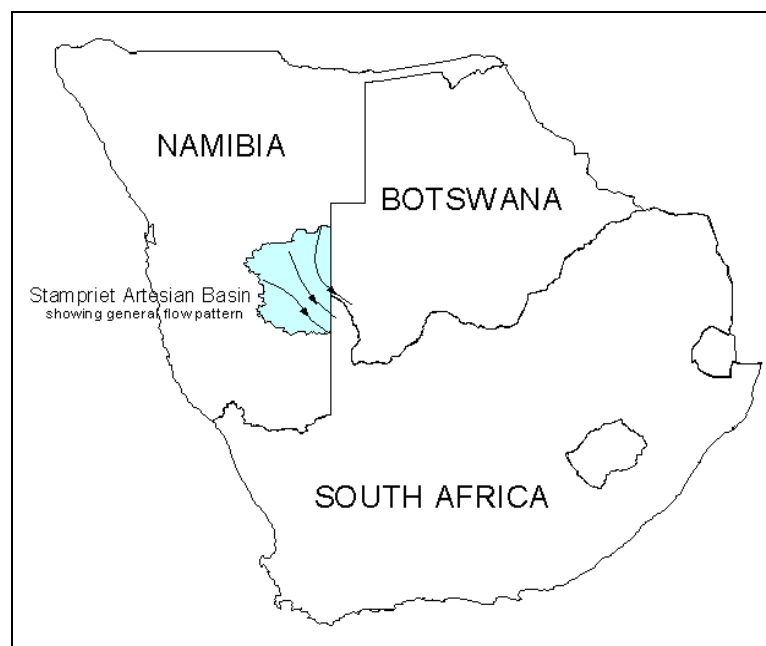


Figure 1: Karoo aquifer in Namibia and generalized flow directions (Puri, 2001)

1.3. Study Rationale

Transboundary groundwater commonly implies a body of groundwater intersected by a political border with the attendant potential threat of dispute over a shared resource.’ (Cobbing et al 2008). In its entirety the transboundary aquifers in the SAB does not fall under such a definition. However, the mismanagement of the aquifer by one or all of the governing countries will impact on the entire aquifer system. Therefore the scientific processes governing the aquifer system should be researched in a holistic view and its subsequent management and co-operation of the involved member states are essential. For this reason, the thesis is vital in its capacity to contribute towards the challenging goal of managing such an essential resource between very different countries.

The TBAs that lie within the project area of the SAB have been individually managed by the three member states. The independent research that has occurred within the SAB thus far has been exclusive to the section of the aquifer system located in the specific member state. Its objectives founded on water usage and population in the area.

Though these countries have similar climatic conditions, their water usage is in no way identical. In Namibia, the main water use is irrigation which accounts for approximately 46% of its total groundwater abstraction within the study area (JICA Report, 2002), whilst Botswana mainly uses its groundwater supply for pastoral farming and domestic use (MMEWR Bokspits Report, 2003).

Water usage as well as its quantity and quality differ not only in each country but also within various locales dependent on the geological structures and population that will be further discussed in the next chapter.

A holistic approach is used in that the numeric modelling assumes that the Auob aquifer system is not restricted by political boundaries. Evidence of the extension of the aquifer system is discussed within the dissertation and data has been drawn from two of the member states.

The study will further conceptualize the Stampriet TBA and calculate the groundwater flux from Namibia to both Botswana and South Africa. Moreover, the study will serve to increase the understanding of the system in the recharge member state and assist in the multi-lateral management of the aquifer system.

Lastly, it endeavours to produce an interactive ‘what-if’ scenario model of the Stampriet TBA which allows the user to modify inputs and outputs in order to predict quantity estimates within the system.

1.4. Research approach and thesis structure

The research approach:

- INTRODUCTION- Critique of significant reports which researched the groundwater potential within the identified study area- chapter 1.
- OVERVIEW OF THE STUDY AREA- Background information of the study area- chapter 2.
- LITERATURE REVIEW- A desktop study gathering sources and significant articles identifying the various methodologies and studies completed on transboundary aquifers. With special attention dedicated to the relevant parameters e.g. recharge estimation techniques- chapter 3.
- METHODOLOGY- Acquisition of modelling software and known literature where conceptual modelling and/or MODFLOW was similarly utilized to further understand an aquifers system's groundwater flow patterns, macro water balance and groundwater flux - chapter 4.
- RESULTS- Data analysis and interpretation of results in order to answer set objectives of study - chapter 5.
- CONCLUSION AND RECOMMENDATIONS- The main conclusions and resultant recommendations as a result of the research - chapter 6.

1.5. Previous investigations

The JICA Report of 2002 undertook the significant task of quantifying the groundwater potential and investigating the flow regime of the SAB. Whilst formulating a comprehensive groundwater management plan for the SAB in Namibia. Though this study was comprehensive and included a conceptual model of the three aquifers within the Stampriet Basin, it can now be seen as incomplete in respect to the transboundary status it now boasts.

The report provides extensive data on the groundwater potential of the SAB, including its rainfall amounts; recharge evaluation and geochemical analysis within Namibia. This data, in addition to other reports from the individual countries, has enabled a conceptual model to be formulated within the Namibian study area.

Through the data given in this report, the use of MODFLOW was used to calculate the groundwater flux and the overall water balance of the Auob aquifer. The events of episodic recharge over time, which is evidently reported in the area (Schalk, 1961), will be incorporated into the model to show its overall effect on the aquifer as a stress element

The MMWER (2003) has a similar objective of identifying the zones of greatest groundwater potential in respect to its current needs within their study area in Botswana. These reports form the foundation needed to readily determine the extent of the aquifer. Furthermore, these reports are used to link the geology and water chemistry across political borders proving that the Auob aquifer is indeed a TBA.

Research in South Africa has been completed on a large scale with data (e.g. water levels) being acquired from the Department of Water Affairs and Forestry's extensive database.

Chapter 2 – Overview of the Study Area

2.1. Introduction

The Stampriet Artesian Basin (SAB) is located within the southeast area of Namibia covering an expanse of 71 000km². The following information on the study area was compiled with the use of the JICA Report on the SAB (2002), the Department of Water Affairs (Namibia) data and the research paper titled: ‘The Stampriet Artesian Aquifer Basin’ by Marianne Alker (2008). The study area has a fairly flat topography with a large amount of sand dunes covering the underlying bedrock.

The various stratigraphic units shape the geomorphology into two distinct zones discussed further below. The area has an annual rainfall of 150mm-200mm/year with the exception of episodic rainfall events that occur approximately every 20 years in the study area.

There are two ephemeral rivers known as the Auob and Nossob Rivers, within the semi-arid region. The main aquifers located are known as the unconfined Kalahari Aquifer and the confined Auob and Nossob aquifers. These confined aquifers are located in the Prince Albert Formation in the Ecca Group within the Karoo Sequence.

2.2. Physiography

2.2.1. Topography

The topography of the study area is relatively flat with an elevation of 1500m – 950m from the northwest and southeast (see Figure 2 below). The north western part of the SAB has an elevation of 1,350m above mean sea level and is reported to drop 500m to 850m in the southeast (Alker, 2008).

2.2.2. Geomorphology

The study area is divided into two distinct zones which follows the geology that lies beneath it. The western and southwest part of the study area has noticeable cliffs and slopes formed by the protruding bedrock. The bedrock in the central and eastern parts of the study area are overlain by sand dunes produced by the NW-SE directional winds. The geomorphology map of the study area (Figure 3) was achieved using LANDSAT/TM images and monochromic aerial photographs (JICA Report, 2002).

Table 1: Geomorphologic Interpretation Chart. Adapted from JICA Report (2002)

Unit Name	General Altitude	Geomorphology	Other Ground Surface Characteristics
Hh	High	Hill	Even and inclined with smooth surface
Hm	Moderate	Hill	Even and very smooth surface
Hi	Low	Hill	Rough texture
Sd	-	Sand Dune	Yellow coloured linear texture with N-S direction
Bd	Low	Bed Rock	Colours and geomorphology depending upon their geology
Vg	-	(Vegetation)	Generally sparse

2.2.3. Rainfall

The average rainfall for the study area is 150mm - 300mm per annum (see Figure 4). There is a decrease of rainfall when moving from north to south. Systematic episodic rainfall takes place in ± 20 year cycles. These heavy rainfall events can produce the annual rainfall within a few days, resulting in flooding in many areas. The highest rainfall event documented was 774mm in 1977-78 in Owingi located along the Black Nossob River. This heavy rainfall event is believed to be the main source of recharge to the “confined” Auob and Nossob aquifers.

2.2.4. Climate

The climate of Namibia is a subtropical country. However, due to the influence of the ocean currents, topography and air circulation, most of the country experience semi arid to arid conditions. Rainy season starts from October to April with most rainfall occurring from December onwards. The average maximum temperature is 30°C and minimum of 2°C within the study area. The annual potential evaporation ranges between 3,200mm - 3,800mm and daily evaporation rate within the study area is 9,7mm in December and 4,7mm in July (see Figure 5 below).

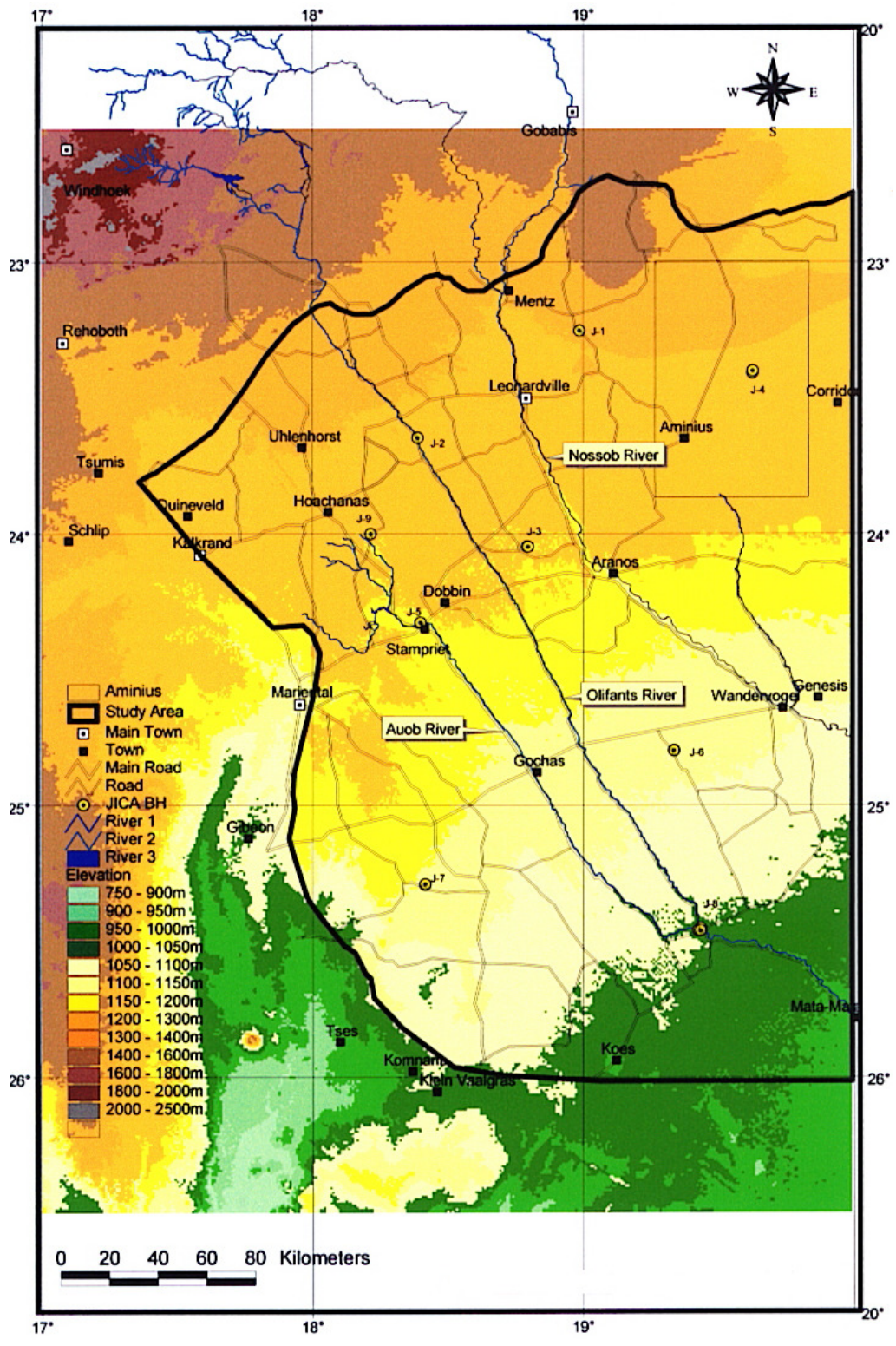


Figure 2: Topographic Map of the Study Area. (JICA, 2002).

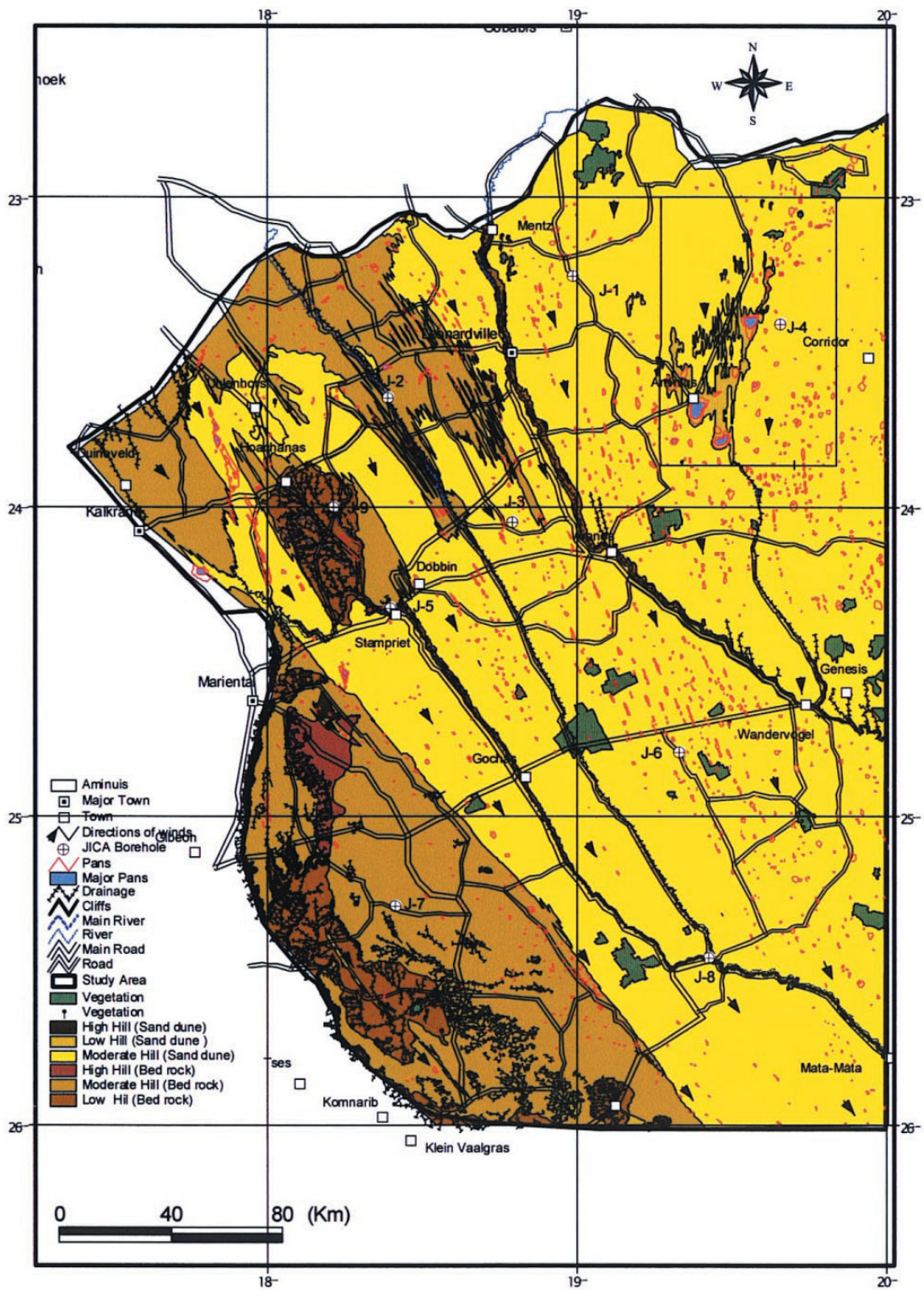


Figure 3: Geomorphology of the Study Area. (JICA, 2002).

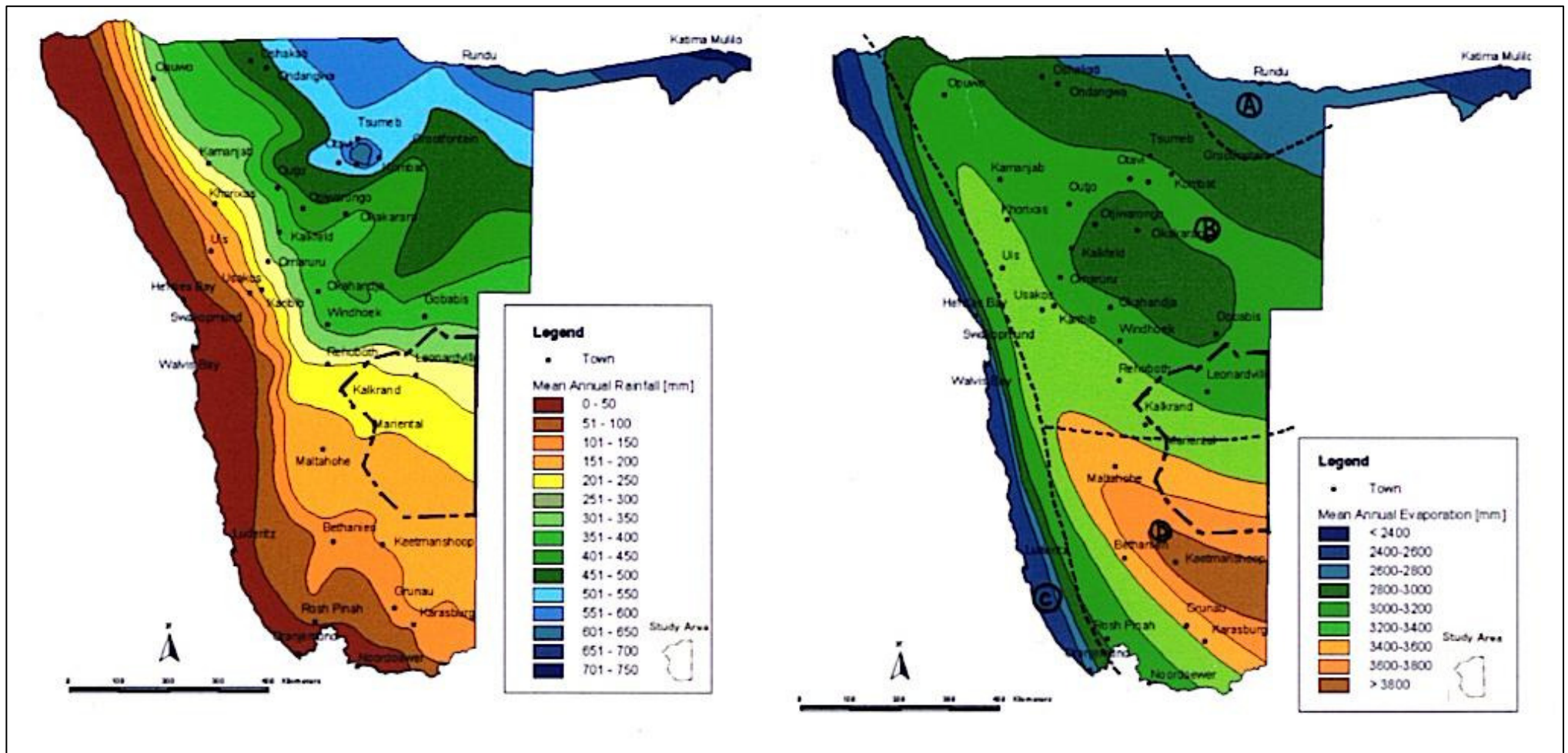


Figure 4: Mean annual Rainfall and Evaporation for Namibia (JICA, 2002).

2.2.5. Drainage Systems

The study area lies within the Auob and Nossob river catchments. As these two rivers are ephemeral, they flow only few short periods during the rainy season. The upper part of the Nossob River is divided into the Black and White Nossob tributaries. They originate in a savannah area, northeast of the capital city of Windhoek 2,000 m above sea level. The Auob River originates northwest of the central town of Stampriet, 1,200m above sea level.

2.3. Water Usage

Within the study area there are several sectors that are supplied with water. Villages are supplied with water through Namwater, and beneficiaries pay a water fee for maintenance of facilities of N\$2.35-N\$2.96/m³. There is only one abattoir located within the study area and it is reliant on the Hardap Scheme for its water supply. Water use for the tourism sector is determined by using the capacity of the 11 lodges that lie within the study area. As seen in Table 2 below the main sector for water use is irrigation. The main crop is lucerne, which comprises of half of the total irrigated areas in the study area. Other crops are maize and various vegetables. Irrigation is closely followed by stock watering.

Table 2: Estimated Water Usage in March 2000 (JICA Report, 2002).

Sectors	Water Usage (million m3/year)	Proportion (%)
1. Domestic water		
1.1 Village centers	0.635	4.26
1.2 Commercial farms	1.594	10.69
1.3 Communal land	0.127	0.85
Sub-total	2.356	15.80
2. Industries	0	0.00
3. Tourism	0.004	0.03
4. Stock watering	5.678	38.07
5. Irrigation	6.876	46.10
Total	14.914	100.00

2.4. Geology

2.4.1. Stratigraphy

The Dwyka Group, Nama Group and Damara Sequence forms the basement rocks in the study area. It serves as an impermeable barrier for the confined Auob and Nossob aquifers. The Kalahari beds host the overlying unconfined aquifer known as the Kalahari Aquifer. The Kalahari beds were deposit on the 'African surface' where a 'Pre-Kalahari Valley' was eroded in the late Cretaceous period. The confined aquifers are located in the Prince Albert Formation consisting of non-marine sediments in the Eccca Group, which lies in the Karoo Sequence. The Auob (Stampriet) aquifer is further located in the Auob Member and upper Mukorob Member within the Prince Albert Formation. The stratigraphy of the Auob aquifer is divided into five permeable and impermeable layers (see Table 3). The Auob aquifer is confined by the Rietmond member above and the lower Mukorob shale layer below.

2.4.2. Geological Structures

There are many NE-SW directional faults within the study area that are shown on Figure 7 as lineaments as they are covered with Kalahari beds. A lineament identified as a linear or curved structure on the surface of assumed to indicate the subsurface geological structures. As seen on Figure 7, there are many lineaments in the western and southern areas which follow a N-S trend. The following geological cross-sections are derived from the geological information collected at pre-existing boreholes from the JICA Report (2002), the DWA and Namwater boreholes.

The cross-sections shown below (Figures 9 -16) are positioned on the locality map in Figure. 8. The cross-sections clearly indicate the three main aquifers known as the Auob; Nossob and Kalahari Aquifers within their geological structure.

It also illustrates the:

- confining layers of the confined aquifers;
- the positions of the faults cutting through the aquifers and stratigraphy;
- the displacement of stratigraphy along fault lines;
- dolerite intrusions and erosional surfaces.

STRATIGRAPHY OF THE STAMPRIET ARTESIAN BASIN

(W = water strikes)

KALAHARI	Sand, gravel, calcrete Calcrete-cemented conglomerate W
KALKRAND	Basalt
RIETMOND	(isopach) Dolerite (W at U & L contacts)
AUOB	U Ss; coarse grained; medium to fine grained W U coal, black shale M Ss; medium to fine grained L coal, black shale L Ss; coarse grained; med. to fine grained W
MUKOROB	U Muk. sandstone; medium to fine grained W? U Muk. sandstone-siltstone-shale, bioturbated Mukarob shale, grey to black
NOSSOB	U Nossob sandstone; medium to coarse W U Nossob sandstone; fine grained U Nossob siltstone-shale L Nossob sandstone; medium to coarse W L Nossob sandstone; fine grained L Nossob siltstone-shale
DWYKA	Mudstone, grey, with dropstones Tillite
PRE-KAROO	U Nama - Red sandstone, shale L Nama - grey shales, sandstones Kamtsas - pink arkoses

Figure 5: Stratigraphic Column of Geology in the Study Area (IAEA Report, 2002)

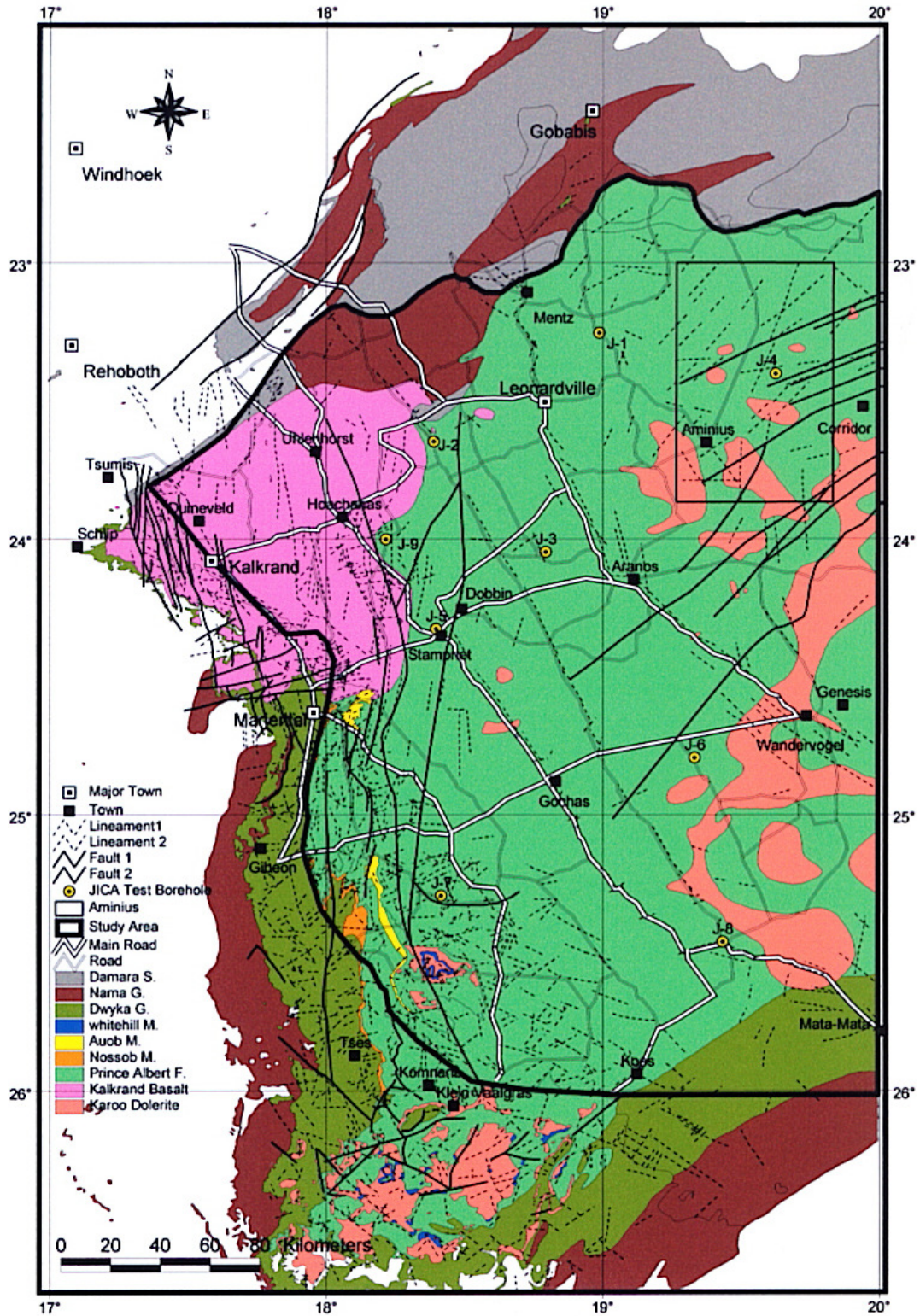


Figure 6: Geological Map of Study Area (JICA, 2002).

Table 3: Lithological Description of Auob Member. Modified from JICA, 2002.

Formation		Thickness (m)	Lithology
Auob	Upper Sandstone (A5)	0-61	White, massive sandstone weathering light yellow. Coarse-grained to locally gritty; high porosity and permeability; accessory biotite; cross beds and clay pellets up to 13 mm. Common brownish black, calcareous concretions up to 3.6 mF, in places coalescing to form a continuous layer.
	Upper Bituminous Shale and Coal (A4)	1-36	
	Middle Sandstone (A3)	-	Light grey to light brown, well bedded, fine to medium-grained sandstone; sand grains well rounded and well sorted; accessory biotite; isolated clay pellets. Petrified wood, often inside elongate, calcareous concretions in a layer of red, Fe-rich or yellowish white clayey sandstone; logs up to 50 cm, 23 m long.
	Lower Bituminous Shale and Coal (A2)	-	
	Auob Member Lower Sandstone (A1)	5-30	Medium to coarse-grained, white to cream-coloured, thick bedded, faintly cross bedded channel sandstones. Mainly multi-story channel sands up to 30 m thick. Thickness 5 to 30 m.

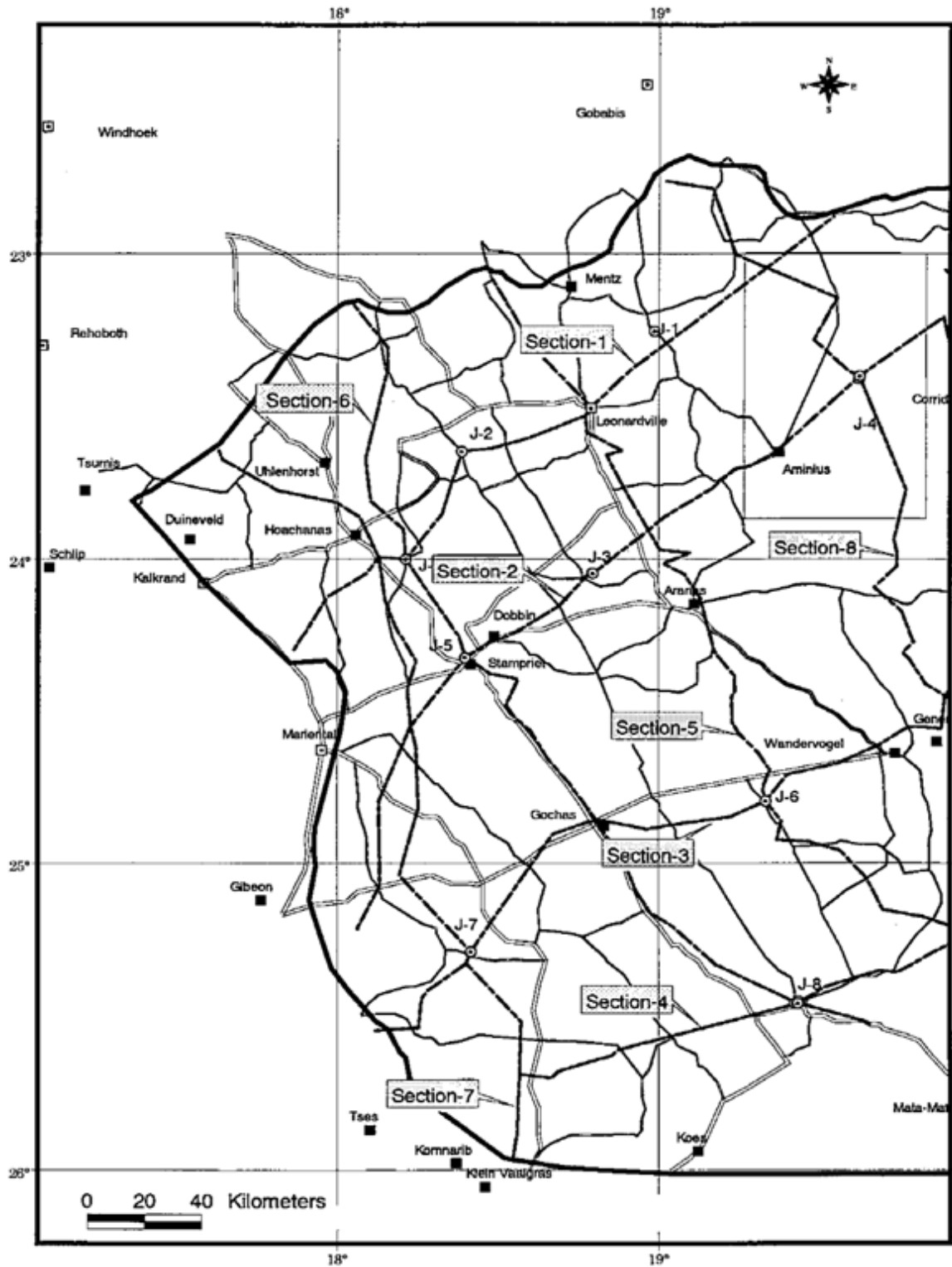


Figure 7: Location Map of Geological Cross-sections (JICA, 2002).

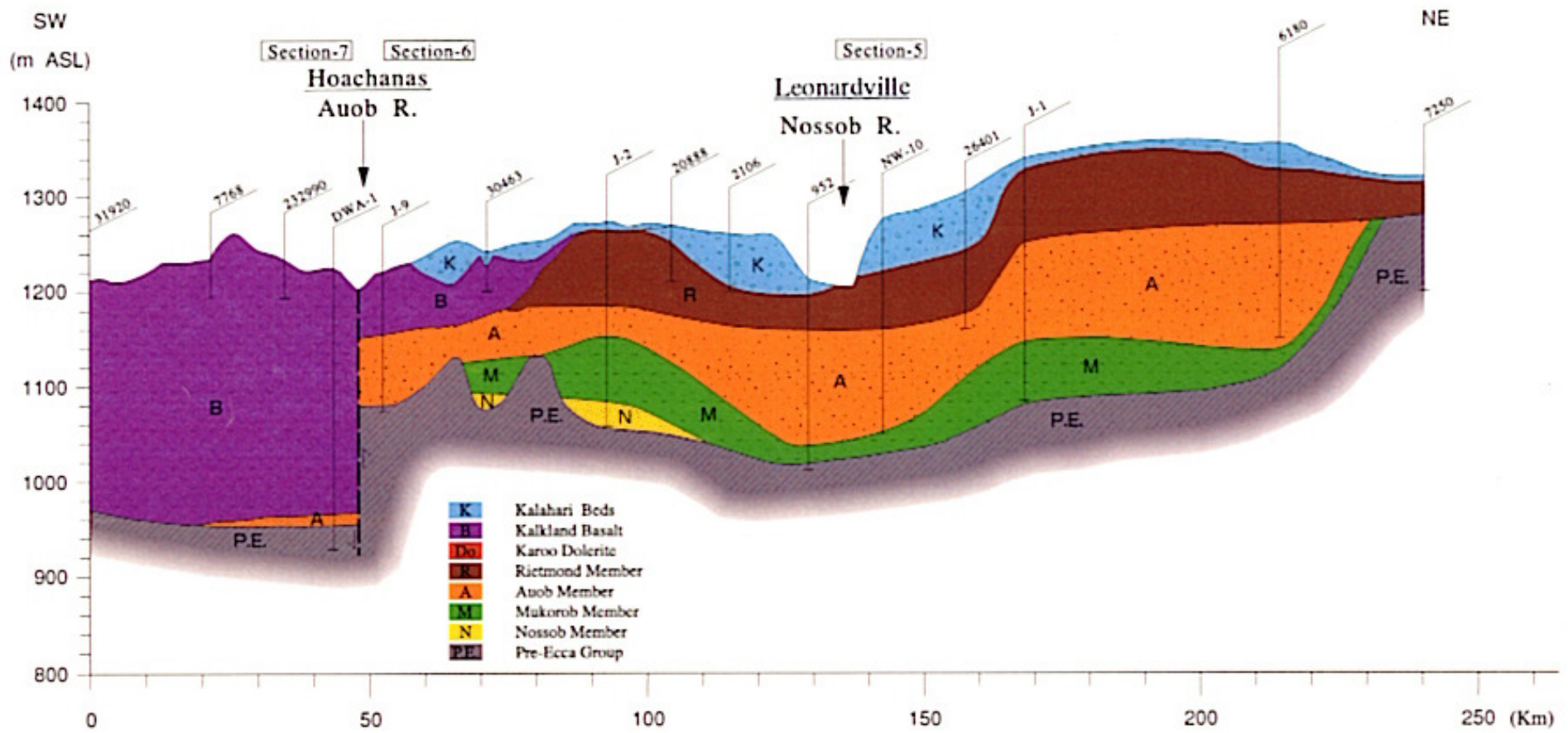


Figure 8: Geological Cross Section of Section 1(JICA, 2002)

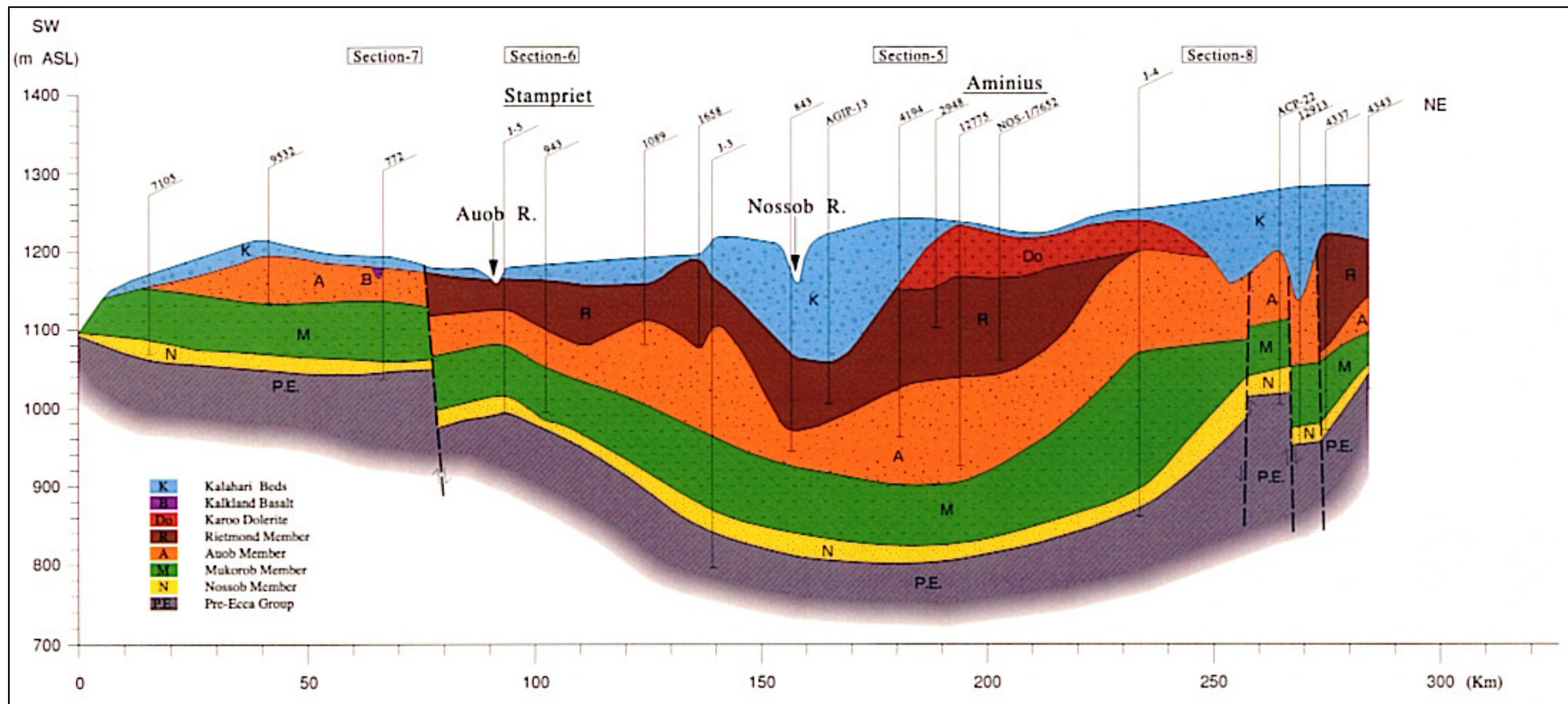


Figure 9: Geological Cross Section of the SAB- Section 2(JICA, 2002)

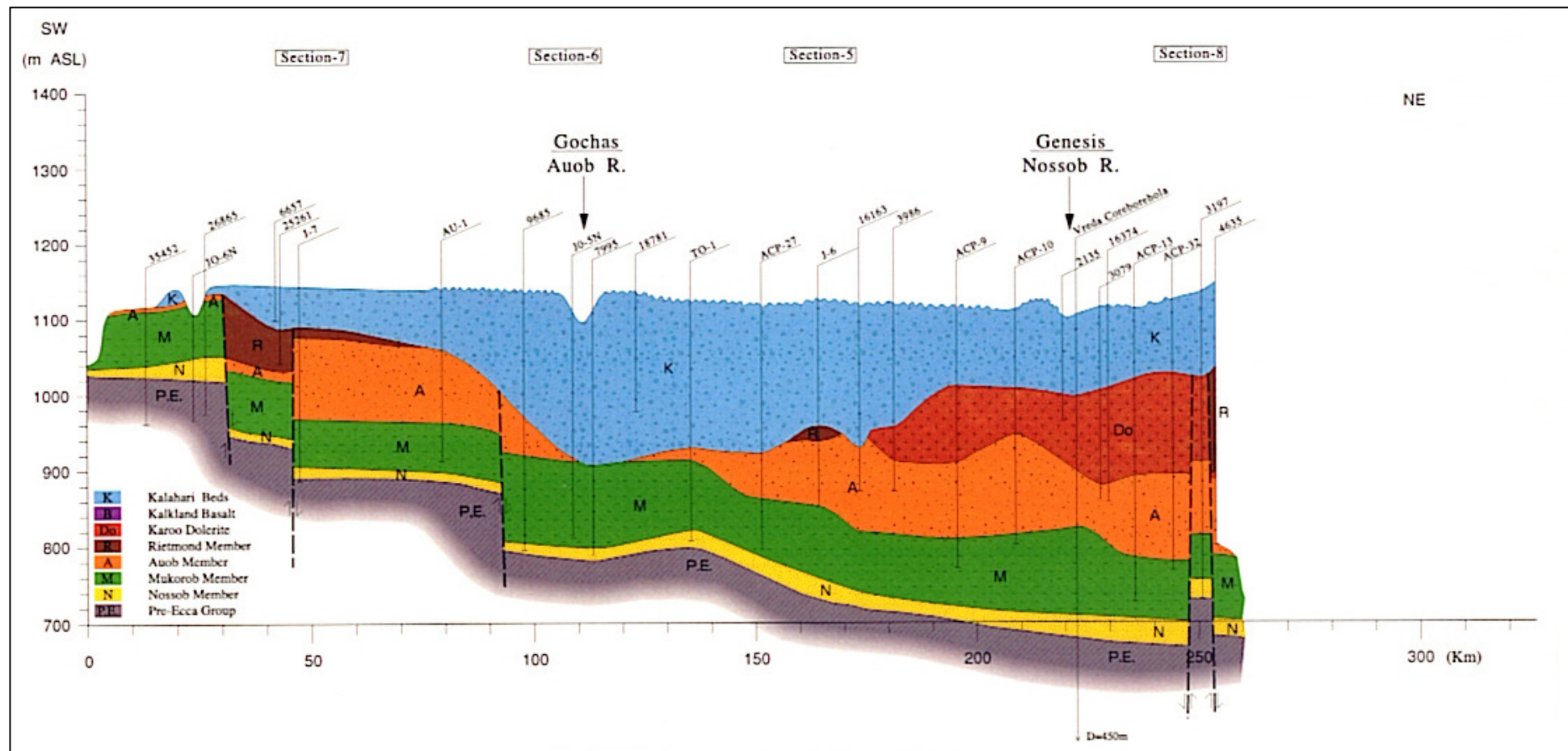


Figure 10: Geological Cross-sections of the SAB- Sections 3 (JICA, 2002)

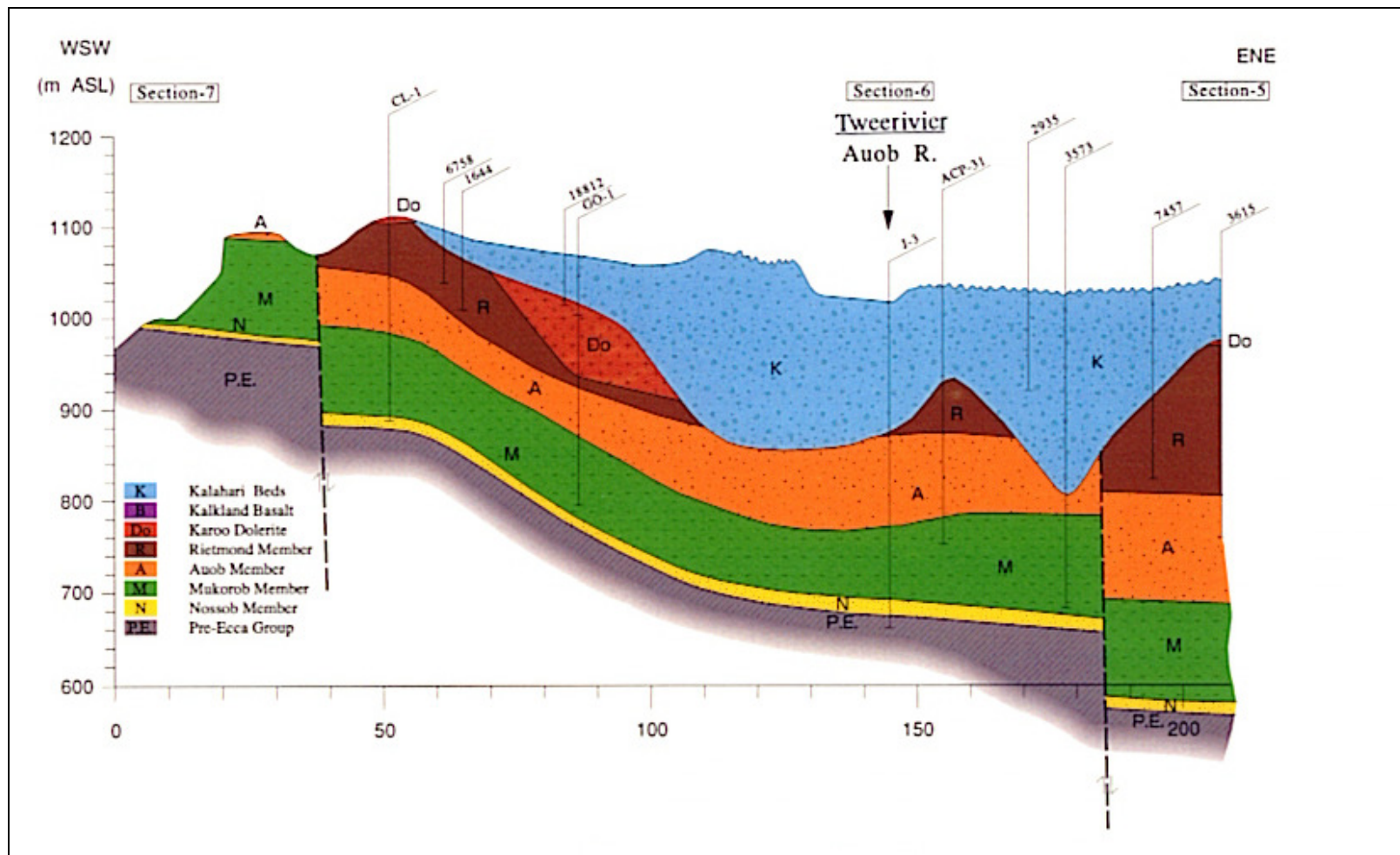


Figure 11: Geological Cross Section of the SAB- Section 4 (JICA, 2002)

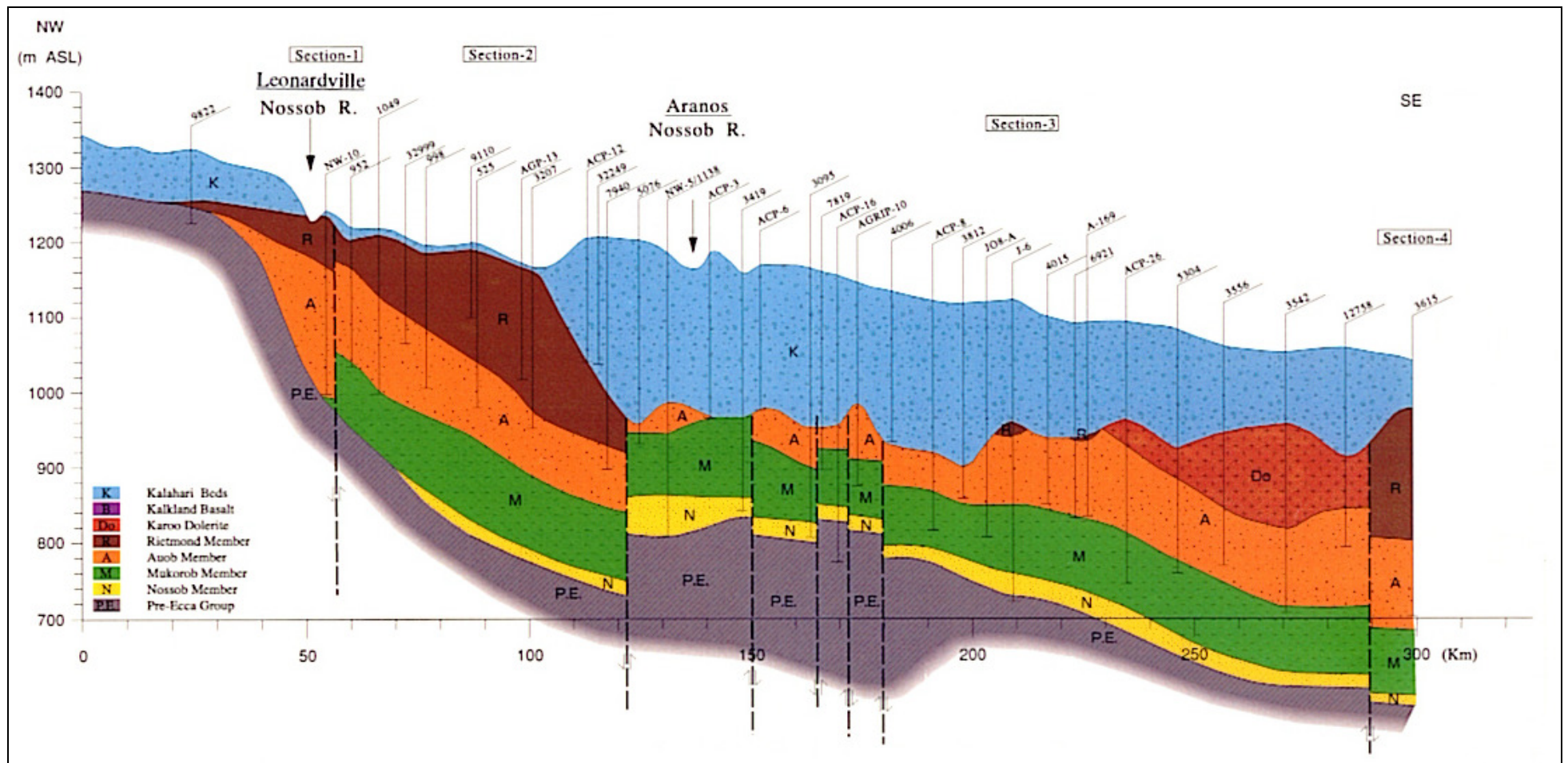


Figure 12: Geological Cross Section of the SAB- Section 5 (JICA, 2002)

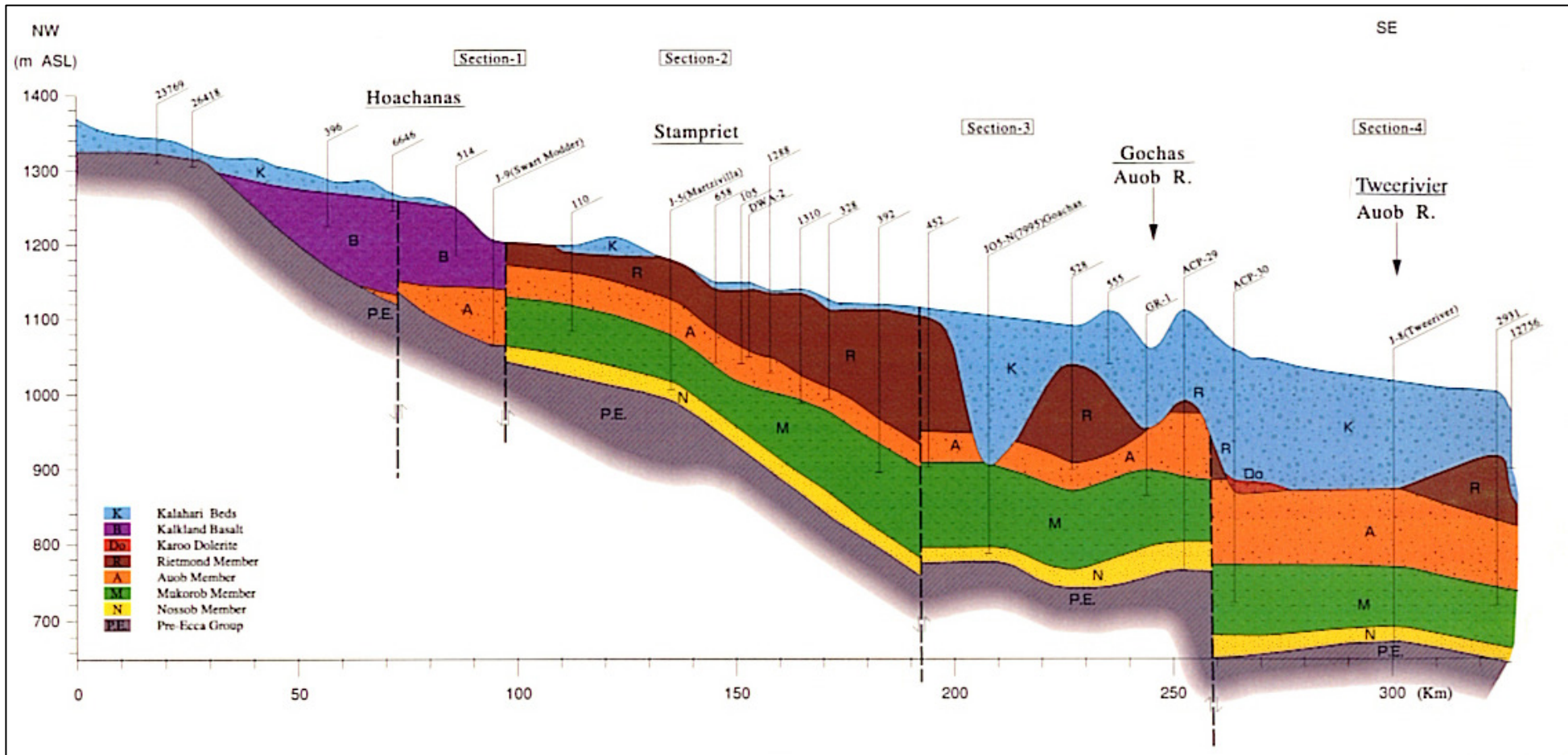


Figure 13: Geological Cross-sections of the SAB- Sections 6 (JICA, 2002)

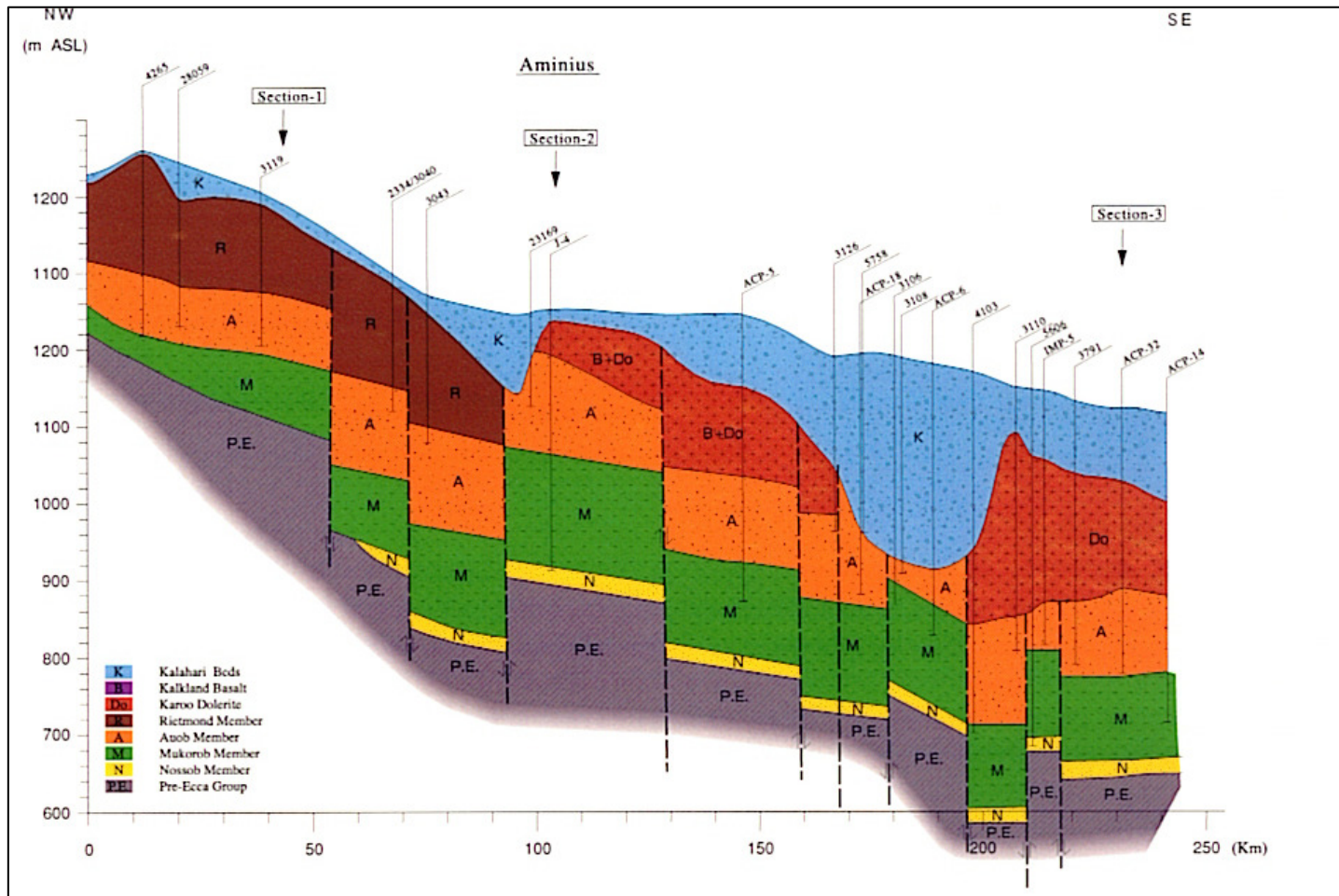


Figure 14: Geological Cross Section of the SAB- Section 7 (JICA, 2002)

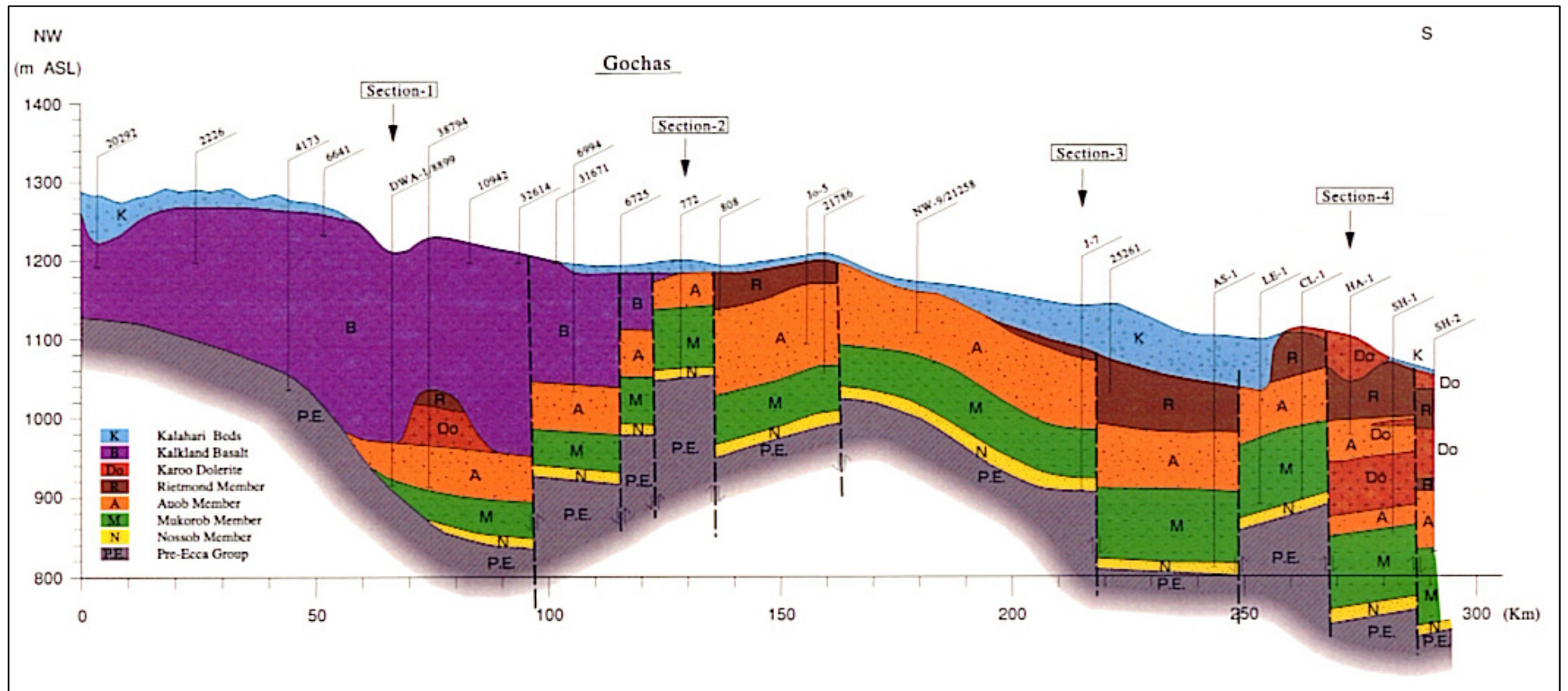


Figure 15: Geological Cross-sections of the SAB- Sections 8 (JICA, 2002)

2.5. Hydrogeology

2.5.1. Aquifer Type and Distribution

As previously stated elsewhere, there are three main aquifers located in the SAB, namely the Kalahari (unconfined) aquifer; Auob (confined) Aquifer and the Nossob (confined) aquifer. The Kalahari aquifer lies within the Kalahari beds and includes the upper part of the Rietmond member below. The bottom surface of the Kalahari aquifer is known as the “African Surface”. The impermeable part of the Rietmond is eroded in the in the central and southern part of the basin. The absence of the Rietmond member allows the Kalahari aquifer to lie directly on the Auob aquifer in these regions as is seen in many of the geological cross-sections (see Figures 9-11).

The Auob aquifer is positioned between the Kalahari aquifer and Nossob aquifer. Though it is geologically divided into five individual layers it is seen as one hydrogeological unit. The upper Mukorob member is also considered part of the Auob aquifer and it is then confined by the lower impermeable Mukorob member. A portion of the Auob aquifer is cropped out in the western part of the study area near the town of Mariental. The thickness of the Auob aquifer is approximately 100m-150m, though it can be more that 150m in some areas.

The Nossob aquifer lies between the lower Mukorob layer and the Pre-Ecca Group. The aquifer has an average thickness of 25m in most of the SAB, though there is an increase of thickness from the west to the eastern regions. The maximum thickness is 125m.

2.5.2. Recharge

The recharge area in Namibia is located in the NW area of the SAB. It is calculated to be one percent of the average rainfall which is in the range of 150 - 300mm a year (JICA report, 2002). However, episodic rainfall events occur once in approximately 20 years also takes place. This heavy rainfall event is believed to be the main source of recharge to the “confined” Auob and Nossob aquifers. The methods used to calculate recharge and the Auob water balance is thus recalculated over a 20 year period in order to identify the importance of these episodic recharge events. Recharge in Botswana and South African, has to be considered as well as a critique of any episodic rainfall events and preferential pathways that may be present.

2.5.3. Recharge mechanisms

The karstic sinkholes in the NW on the study area are the primary recharge mechanism during episodic rainfall events. As reported in the JICA Report, the major recharge into the Auob aquifer occurs via these fractures and karstic sinkholes that are situated on the rim of the basin. It is assumed that the recharge of the Auob and Nossob aquifers can only occur during these heavy rainfall events. In some areas the Kalahari aquifer lies directly over the Auob aquifer without the presence of the impermeable Rietmond member. In these areas, it is considered that recharge could take place through the Kalahari aquifer or that some interaction would be taking place.

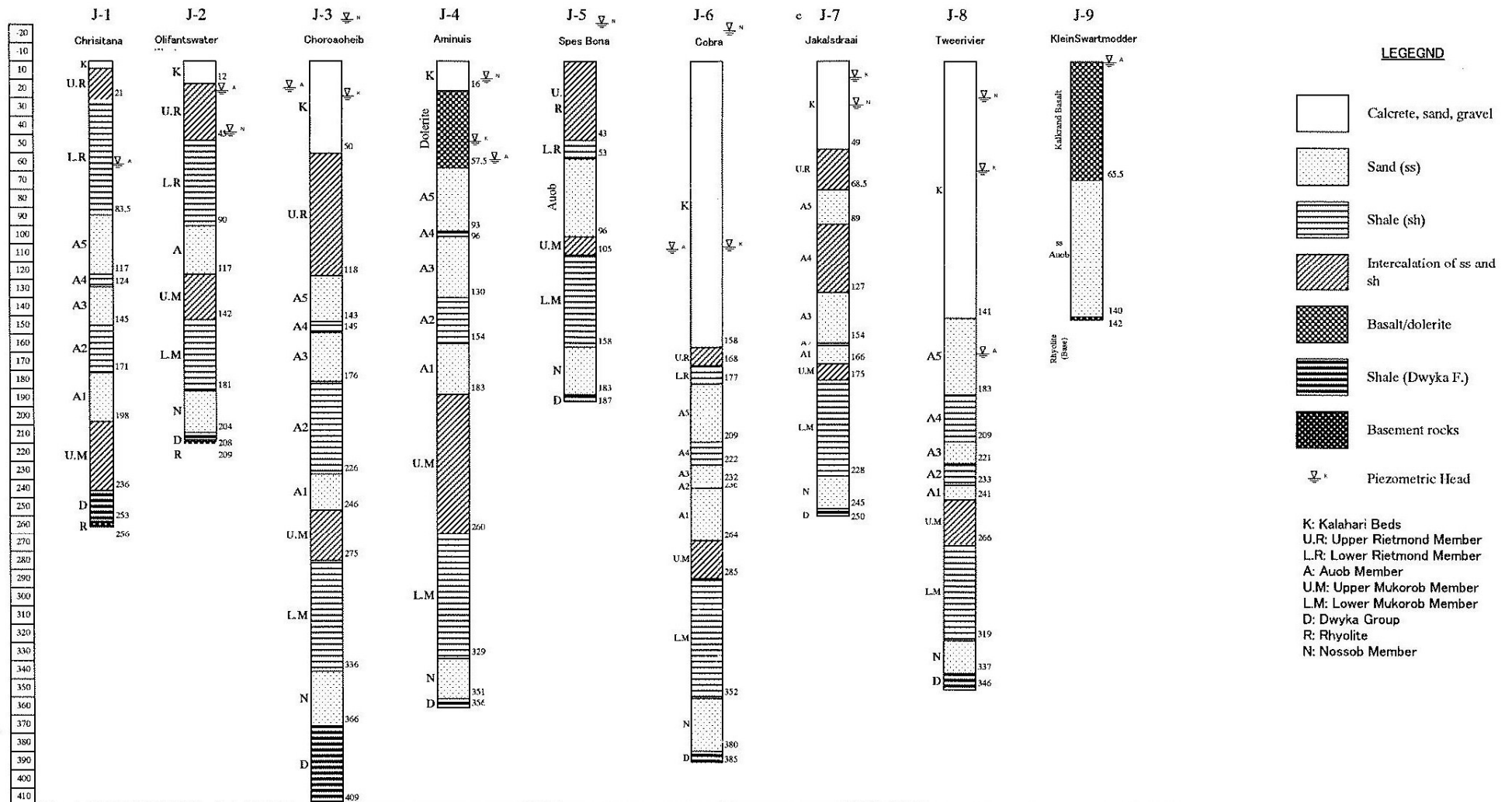


Figure 16: Geological Logs of JICA Boreholes (J1-J9). Modified from JICA (2002).

	J-1	J-2	J-3	J-4	J-5	J-6	J-7	J-8	J-9							
Kalahari	WL	-	WL	19.08 m	WL	49.40 mBGL	WL	-	WL	102.14 mBGL	WL	9.72 mBGL	WL	59.75 mBGL	WL	-
	WL	-	WL	1188.97 mAS	WL	1208.66 mAS	WL	-	WL	1000.53 mAS	WL	1138.47 mAS	WL	961.5 mASL	WL	-
	T	-	T	6.4 m ³ /day	T	0.1 m ³ /day	T	-	T	6.2 m ³ /day	T	30.0 m ³ /day	T	0.13 m ² /day	T	-
	EC	-	EC	330 mS/m	EC	227 mS/m	EC	-	EC	2,310 mS/m	EC	103 mS/m	EC	351 mS/m	EC	-
	TDS	-	TDS	2157 mg/L	TDS	1481 mg/L	TDS	-	TDS	14874 mg/L	TDS	670 mg/L	TDS	2282 mg/L	TDS	-
	pH	-	pH	7.2	pH	7.2	pH	-	pH	8.6	pH	7.40	pH	8.70	pH	-
Auob	Temp	-	Temp	21.9°C	Temp	29.3°C	Temp	-	Temp	26.9 °C	Temp	27.0 °C	Temp	27.0 °C	Temp	-
	WL	57.72 mBGL	WL	15.01 mBGL	WL	13.62 mBGL	WL	-	WL	102.8 mBGL	WL	-	WL	183.8 mBGL	WL	2.3 mBGL
	WL	1274.00 mAS	WL	1260.25 mAS	WL	1194.44 mAS	WL	-	WL	999.66 mASL	WL	-	WL	831.18 mASL	WL	1207.9 mASL
	T	25.2 m ³ /day	T	3.4 m ³ /day	T	194.0 m ³ /day	T	-	T	8.4 m ³ /day	T	-	T	0.3 m ³ /day	T	1240 m ³ /day
	EC	85 mS/m	EC	90 mS/m	EC	116 mS/m	EC	-	EC	187 mS/m	EC	-	EC	1,039 mS/m	EC	101 mS/m
	TDS	564 mg/L	TDS	605 mg/L	TDS	775 mg/L	TDS	-	TDS	1248 mg/L	TDS	-	TDS	6754 mg/L	TDS	656 mg/L
Nossob	pH	7.6	pH	7.8	pH	7.5	pH	-	pH	8.6	pH	-	pH	9.66	pH	7.70
	Temp	25.0°C	Temp	25.8°C	Temp	29.8°C	Temp	-	Temp	26.9 °C	Temp	-	Temp	28.0 °C	Temp	28.6 °C
	WL	-	WL	39.45 mBGL	WL	-30.91.0 mBGL	WL	6.23 mBGL	WL	-19.64 mBGL	WL	21.65 mBGL	WL	20.46 mBGL	WL	-
	WL	-	WL	1236.15 mAS	WL	1238.96 mAS	WL	1250.15 mAS	WL	1197.90 mAS	WL	1126.50 mAS	WL	1000.8 mASL	WL	-
	T	-	T	2.9 m ³ /day	T	1.3 m ³ /day	T	7.01 m ³ /day	T	1.2 m ³ /day	T	0.01 m ³ /day	T	0.02 m ³ /day	T	-
	EC	-	EC	91 mS/m	EC	460 mS/m	EC	100 mS/m	EC	136 mS/m	EC	431 mS/m	EC	5,030 mS/m	EC	-
Basalt	TDS	-	TDS	616 mg/L	TDS	3303 mg/L	TDS	665 mg/L	TDS	6955 mg/L	TDS	2743 mg/L	TDS	33,500 mg/L	TDS	-
	pH	-	pH	8.3	pH	8.2	pH	8.9	pH	8.5	pH	9.10	pH	8.64	pH	-
	Temp	-	Temp	30.0°C	Temp	24.9°C	Temp	30.3°C	Temp	28.5°C	Temp	27.8°C	Temp	29.1°C	Temp	-
	WL	-	WL	-	WL	-	WL	-	WL	-	WL	-	WL	-	WL	-
	T	-	T	-	T	-	T	-	T	-	T	-	T	-	T	-
	EC	-	EC	-	EC	-	EC	-	EC	-	EC	-	EC	-	EC	-

Figure 17: The hydrogeological characteristics of the JICA boreholes (J1-J9)

2.6. Groundwater Quality

The hydrochemistry of the Auob aquifer is invaluable in linking the aquifer across borders, as well as identifying the boundaries of the aquifer in South Africa and Botswana. There is an area identified with high salinities which is unsuitable for irrigation. This area is known as the “Salt Block” located in the south eastern part of the SAB and also consists of a high fluoride concentration which can lead to fluorosis in many of the animals. The representative boreholes (J1-J9) have been highlighted on the locality map on Figure 13. An example of the hydrogeological characteristics of these boreholes can be seen on Figure 12 above.

The Total Dissolved Solids (TDS) in each aquifer were used as a hydrogeological tool to identify the water quality in each aquifer. The TDS values have been evaluated from the JICA boreholes highlighted in Figure 13. The Kalahari aquifer has a high concentration around J-6, located in the south-east part of the SAB. The maximum TDS values are 14,874 mg/l, passed the 1,000 mg/l permitted for potable water.

The Auob aquifer has high TDS values around borehole J-8 which lies further SE with a maximum value of 6,574 mg/l. The overall water quality in the north eastern part of the SAB has the best quality water, exceeding the water quality of the Kalahari aquifer.

The Nossob aquifer has the worst quality of water, with similar values at J-8. Most of the Nossob aquifer is not suitable for human consumption.

Chapter 3- Literature Review

3.1. Summary of literature reviewed

3.1.1 Transboundary aquifers

Introduction

Transboundary groundwater can be defined as “continuous ground water reservoir ... that underlies or whose water flows beneath two or more political jurisdictions and can be exploited by each jurisdiction” (Campana, 2005). Another definition from Cobbing (2008) highlights the potential water conflict that will arise if multilateral management does not take place.

The importance of transboundary aquifers (TBAs) cannot be denied. However, it is a multifaceted subject that not only takes into account all hydrological factors, but also has many significant social and economic implications.

There are 263 transnational watersheds currently known which cover 45.3% of the land surface on earth (Jarvis, *et al* 2005). More than half the world rely on groundwater for basic human needs (Eckstein, 2005). According to Jarvis *et al* (2005), these basins affect approximately 40% of the world’s population and consist of 60% of the global fresh water supply. Furthermore, the importance of cooperation between relevant countries hosting these basins have been indicated by the number of water treaties signed concerning their shared groundwater resource. The number of treaties signed according to continent (Jarvis *et al*, 2005) are as follows:

- Europe: 35
- Africa: 13
- Middle East and Asia: 10
- North America: 4
- South America: None

The transboundary aquifers within Southern Africa are seen in Figure 18 (adapted from Vasak, S., 2008). The SE Kalahari/Karoo Basin is listed as number 13 in the diagram. A short summary of TBAs shared by Namibia has been summarised by Ndengu (2002) with the inclusion of the SAB and its aquifer systems. The summary focuses on the basin within Namibian borders.

However, more holistic discussion can be seen in the framework document by Puri (2001), which incorporates the other member states in a succinct summary of the hydrogeological information in each country and its known extent. A further study into the SAB and the research completed within these member states is derived from Alker (2008). Alker's study discusses the studies carried out within each member state, its groundwater flow patterns and institutional arrangements for groundwater management and transboundary cooperation.

3.1.2. Management and Law

The equitable multilateral management and subsequent groundwater policies of a transboundary aquifer is not an easy accomplishment. Spatial variation, groundwater rights of stakeholders within each member state, and the potential groundwater conflict is discussed by Matthews (2005). In this publication it is understood that no law or policy can be implemented without the correct scientific knowledge verifying the reasoning behind such a policy. Conflicts may arise not only from water quantity reduction due to over abstraction in one member state, but also due to water quality degradation.

The optimal management plan of any transboundary aquifer would be a cooperative model. A cooperative model is defined as a management plan that is executed for all parts of the aquifer which yields the highest level of net social welfare (Chermack *et al*, 2005). The use of a cooperative model ensures that the relevant data and stresses on an aquifer system is taken into account. This method can also establish multilateral cooperation between institutions from member states during the research and planning stages.

In respect to the subsequent laws of a the Auob TBA system, the conceptual model E (see figure 19 below) within the documentation of Eckstein (2005) is the best fit. The model description is a confined aquifer that is unconnected to a surface body of water (excluding the recharge zone). Model E illustrates that this confined aquifer does traverse one or more political borders. Reversed natural flow can take place if overabstraction occurs within this conceptual model.

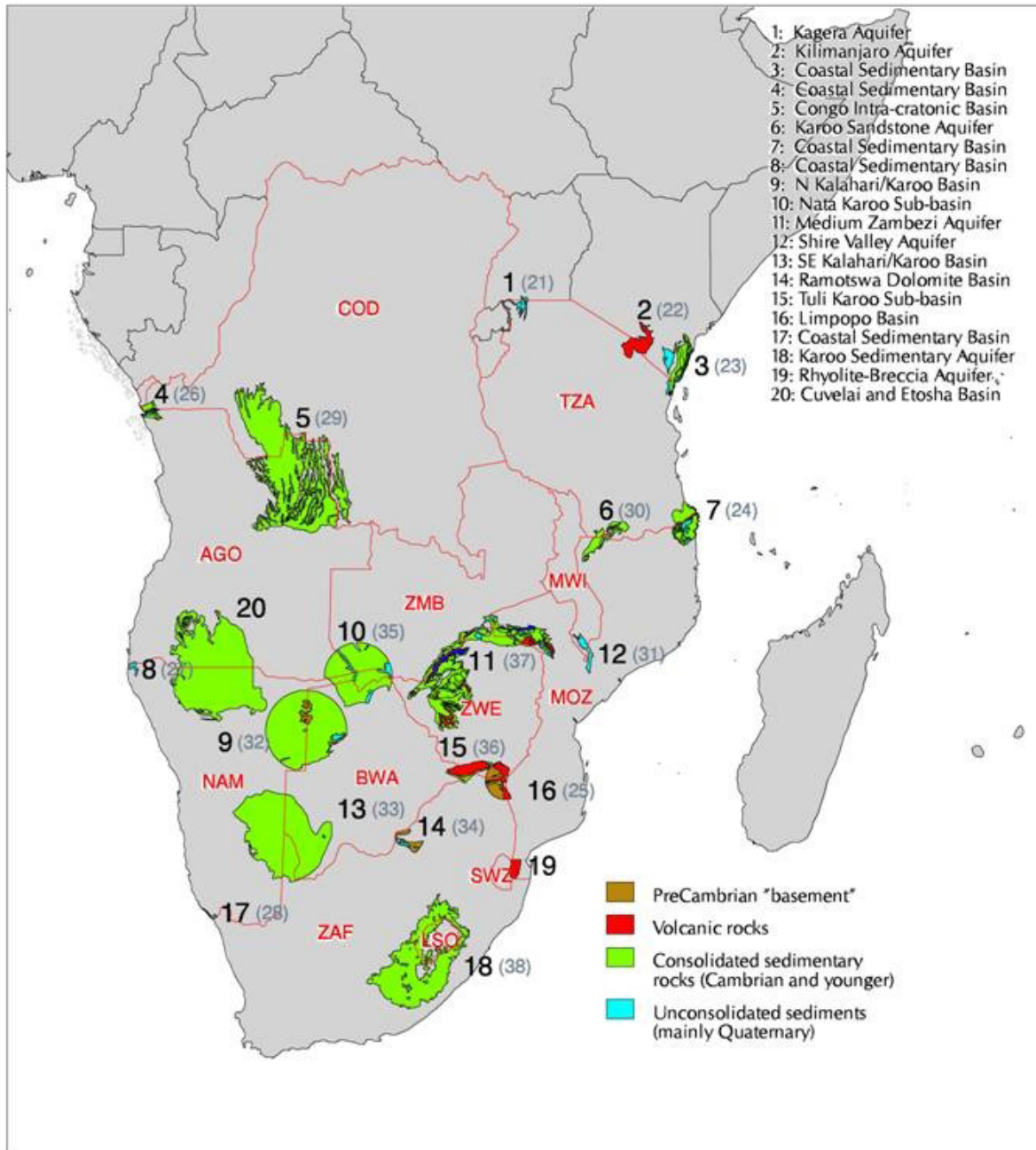


Figure 18: Transboundary aquifers in Southern Africa. Adapted from (Vasak S. , 2008)

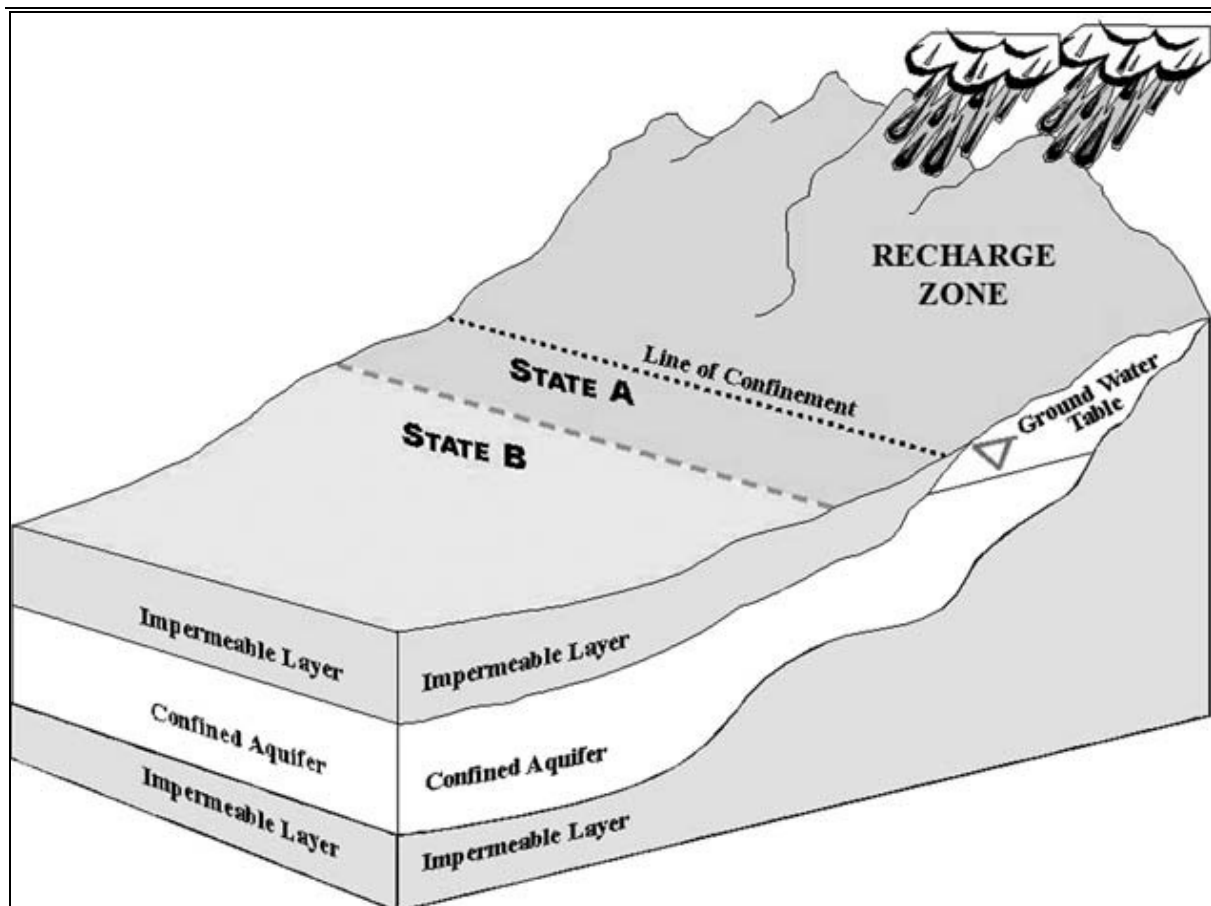


Figure 19: Conceptual Model E. Reproduction of Eckstein (2005).

A few examples of TBAs consistent with the parameters of conceptual model E is derived from Eckstein (2005) listed below:

- ‘Mountain Aquifer’ between Israel and Palestine in the West Bank
- Guarani Aquifer beneath Argentina, Brazil, Paraguay and Uruguay

A regional programme for the management of the Nubian TBA was completed and documented. The Nubian TBA is considered successfully managed with regional cooperation between Chad, Egypt, Libya and Sudan (Abu-Zeid & Abdel-Meguid, 2002).

3.1.3. Climate change

Climate change is a highly controversial topic. Despite the ongoing debates, the climatic variation is evident and the resultant course of action to ensure water for all is essential. According to Dragoni & Sukhija (2008), climate change will ensure an 'increase in the amount of precipitation at high latitudes, whereas decreases are likely in most subtropical land regions.' Surface water is more susceptible to climate change than groundwater due to the high evaporation rates that can take place. Groundwater is the only viable option for good quality water storage during climatic changes.

A main concern involving the impact of climate change is the affect of recharge within the hydrological aquifer systems. Concerning the study area, the precipitation rates in the semi-arid region will most likely decrease with climatic change.

Episodic and normal recharge takes place within the SAB over a twenty year cycle. The last few decades clearly shows the trend and will be discussed further in this dissertation. This increase in precipitation during an episodic rainfall events has been simulated in this study.

A case study on the impact of climate change with regards to the uncertainties of groundwater recharge can be seen in an article written by Holman (2006), and determines that the direct impact of climate change is not only dependent on hydrological research. Therefore, an integrated approach to various necessary aspects, such as socio-economic and agricultural factors, must be considered. The impact of climate change within the SAB is still uncertain, however, it will have a definite impact on recharge estimation in the future. Climatic change may also lead to groundwater flow changes, as reported in Dragoni & Sukhija (2008).

3.1.4. Recharge

Recharge has been defined as “the entry into the saturated zone of water made available at the water-table surface, together with the associated flow away from the water table within the saturated zone” (Freeze & Cherry, 1979). Rainfall and recharge relationships have been previously studied. One example is by Wu *et al* (1996). Their research revealed that there are different relationships depending on the water table (shallow, intermediate and deep).

The IAEA Report (2002) completed a study on environmental and radioactive isotopes to enhance the knowledge of the hydrogeological cycle of the aquifer systems within the SAB, This research also delineated the recharge areas and identified the recharge mechanisms of the aquifer systems.

As previously mentioned in Chapter 2, the recharge within the Auob aquifer system is divided into normal recharge and episodic recharge events. A high rainfall event, which drives the occurrences of episodic recharge, occurs approximately every 20 years. The first documented case of the high rainfall events included the identification of the preferential pathways to the Auob aquifer. This article, written by Schalk (1961), accurately summarised the data from the high rainfall event into:

- Morphological features
- Distribution of rainfall
- Formation of pools
- Supply to groundwater

The JICA Report (2002) had a similar high rainfall documented during the high 1999 – 2000 rainfall event. Though more advanced methods were used, ultimately this data was used for the same purposes as 40 years prior. The attempt was to determine the water balance and a comparison was made between the episodic and normal recharge events. The 1999 – 2000 data values were incorporated into the groundwater flow simulation of the Auob aquifer system as seen further in Chapter 4.

3.1.5. Conceptual modelling and Groundwater Flow Simulation

The conceptual modelling of the Auob system was a diagram of the hydraulic behaviour of the aquifer, its stresses, flow directions and assumed fluxes. The conceptual model is used as a stepping stone for the groundwater flow simulation (see Figure 20 below).

The three-dimensional-finite-difference-model (MODFLOW) (McDonald & Harbaugh, 1988) is used to simulate the groundwater flow patterns within the Auob aquifer system. Groundwater flow is simulated using a block-centred finite difference approach (Gomez, *et al*, 2006). The main text used for the simulation of groundwater flow patterns was the Processing Modflow User Guide produced by Chiang & Kinzelbach (1998).

Similar studies using MODFLOW have been documented and reviewed by Gomez *et al* (2006) for the correct application of software stated as follows:

- Finite difference model for evaluating the recharge of the Guarani aquifer system on the Uruguayan-Brazilian border (Gomez *et al*, 2006)
- A Regional-scale groundwater flow model for the Leon-Chinandega aquifer, Nicaragua (Palma & Bentley, 2007).

The main literature utilized in this dissertation is from JICA (2002), MMWER (2003) and the MODFLOW user guides for numerical simulation. The *Groundwater in Namibia, an explanation to the Hydrogeological Map* (Christelis, 2001) has also provided a summary of the hydrological characteristics of the SAB.

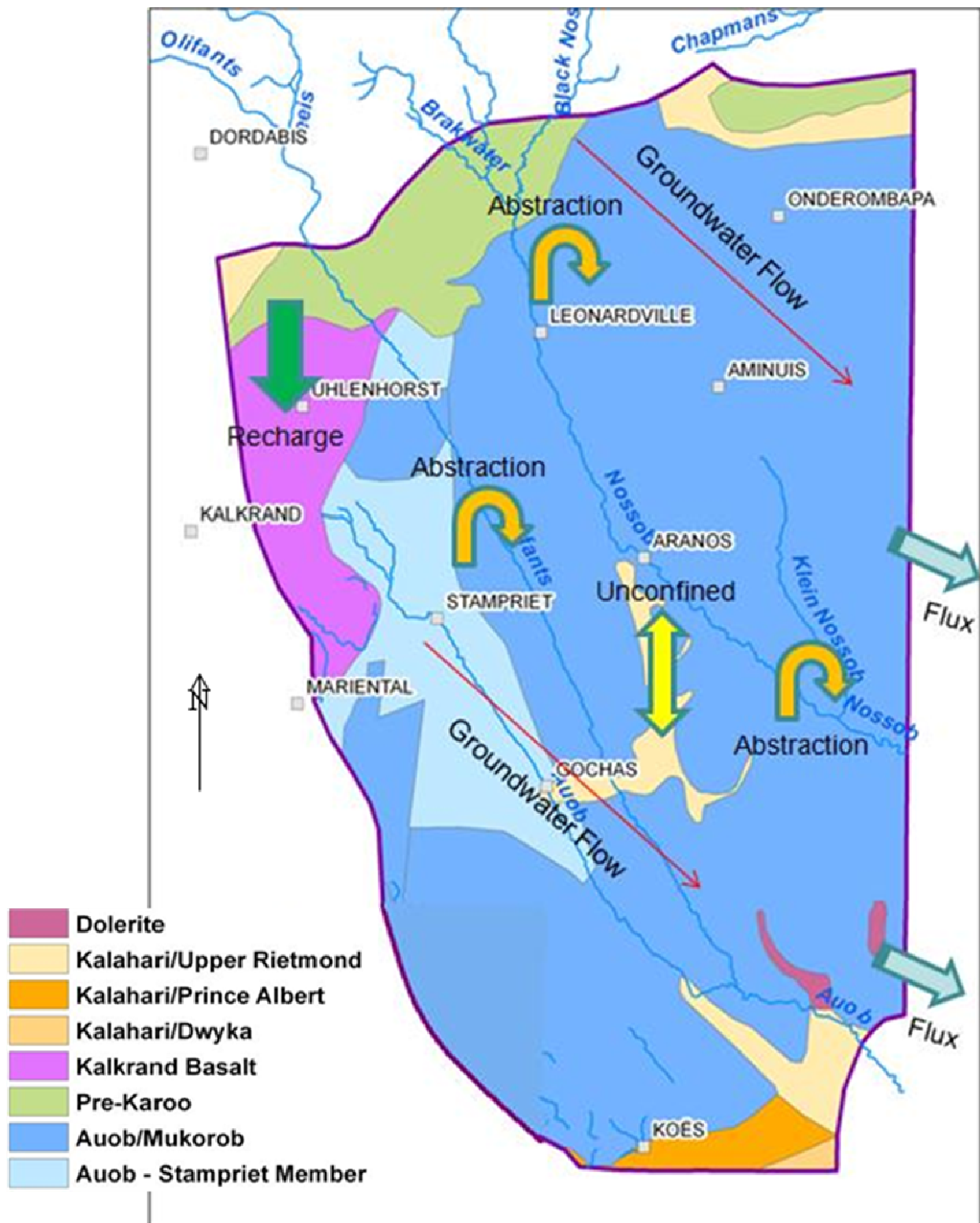


Figure 20: Conceptual model of Auob aquifer system (plan view).

Chapter 4- Methodology

4.1. Introduction

The research in this dissertation was achieved using a few methodologies such as the groundwater flow simulation and conceptual modelling. These methods are used to verify the conceptualization of the Auob aquifer system. The groundwater flow simulations are not dependent on the accuracy of the water balance calculations and does not quantify outflow through this simulation. However, these methods are used to enhance the understanding of the interactions within the system. As well as simulate the recharge conditions of the Auob aquifer system over a twenty year cycle.

The research study consists of three techniques which serve successfully to 1) construct a conceptual model of the aquifer system 2) simulate the groundwater flow in the system; and 3) model the data within separate recharge estimate scenarios.

A comparison is completed between the proposed conceptual model and the groundwater flow simulation resulting in an extension of the conceptual model (Figure 33). The conceptual model is then compared to the groundwater flow simulation conducted using the Modular Finite-Difference Ground-Water Flow Model (MODFLOW) (McDonald & Harbaugh, 1988). The groundwater flow system uses the known hydrological conditions placed under assumed conditions. As a result, a simulation of the groundwater flow and serve as a base for subsequent numerical modelling of the aquifer system. The vital study of the annual rainfall and episodic rainfall events that occur within the study area has been simulated within specific scenarios.

A numerical model of the three aquifers i.e. Kalahari, Auob and Nossop Aquifer Systems has been completed in 2002 by Japan International Cooperation Agency (JICA) and The Department of Water Affairs-Namibia.

The groundwater flow simulation studies assumed the boundary conditions to have a no flux eastern border. The following excerpt taken from the Summary Documents of the JICA Report (Chapter 12-12) states why the eastern border connecting the aquifers to South Africa and Botswana was seen as a no-flux condition.

“On the eastern side, the aquifers are continuous to the territory of Botswana and South Africa. Since groundwater level contours are almost perpendicular to the boundary, it was considered to be no flux condition.”

The Darcy method was utilized to quantify the outflow from the Auob aquifer system using data from the year 2000 acquired from the JICA Report (2002). The results of the outflow and hydrological data acquired have been used to formulate a conceptual model of the Auob aquifer system. The numeric simulation with the use of MODFLOW enables the preliminary ‘what-if’ scenario model to be constructed for the Auob aquifer system.

4.2. Water Balance Method

The water balance method has been used to calculate the potential outflow of the Auob aquifer, with the use of geological maps and hydrological data from the JICA Report. The area of the Auob aquifer was calculated using the geological map of the top layer of the Auob aquifer system (see Figure 14). The Auob upper layer map was then overlain by the grid to calculate the approximate area of the aquifer. The thickness was averaged using the known thicknesses (see Table 5) at the selected JICA boreholes and the volume calculated.

The initial data of elevation and thickness of the aquifer were located in the seven JICA boreholes (see Figure 15). The effective porosity of 5% was calculated in the JICA Report and utilized in the study to quantify the storage capacity of the aquifer. The abstraction amount of 13, 622m³/day was then calculated over a full year and subtracted by the total quantity of groundwater within the Auob system. All the above information was then incorporated into the revised Darcy Method to calculate outflow from the Auob aquifer system.

The revised Darcy equation was used to quantify groundwater flow leaving the aquifer. The following equation was used:

$$Q = T \cdot E \cdot i$$

Q - outflow

T - transmissivity

i - hydraulic gradient

E – width of aquifer

The transmissivity values ranging from 0.006-1.240 m³/day/m (see Table 4 below) of seven boreholes from the JICA Report were identified; subsequently its lowest four values were used in the equation. Based on the data from seven boreholes, extracted from the JICA Report, the transmissivity values range from 0.006-1.240 m³/day/m (see Table 4 below); subsequently its lowest four values were used in the equation.

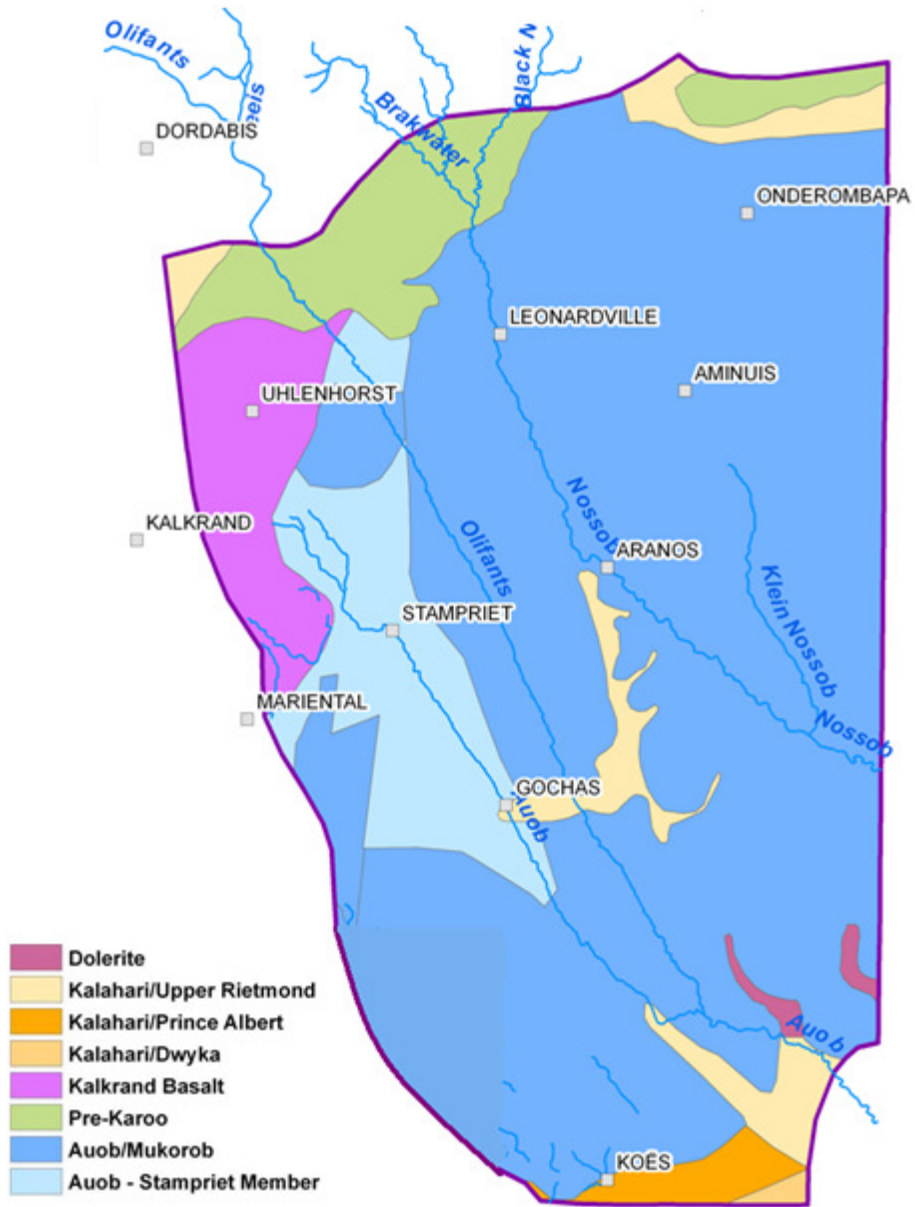


Figure 20: Geological top layer of the Auob aquifer system.

As there are only seven transmissivity values over the SAB, the boreholes with the least transmissivity (highlighted in Figure 15 below) which is clearly seen from the NW to SE correlates with the groundwater flow. These values are used in the above equation to ensure that the outflow is rather undervalued than overestimated.

Table 4: Transmissivity values of seven boreholes located in the Auob aquifer. Modified from the JICA Report, 2002.

Borehole Name	Transmissivity (m³/day/m)
J8	0.006
J2	3.42
J6	8.44
J1	25.2
J4	87.6
J3	194
J9	1,240

Locality Information							Borehole Structure				Pumping Data									
Location		Borehole Number		Coordination			Depth drilled (m)	Screen Pipe			Static water level			Yield (m ³ /h)	Dynamic water level (mbgl)	Specific yield (m ³ /h/m)	EC (mS/m)	TDS (mg/lit.)	pH	Temp. °C
No.	Farm Name	JICA Ref. No.	WW No.	Latitude (d:m:s)	Longitude (d:m:s)	Elevation (masl)		from (mbgl)	to (mbgl)	Thickness (m)	(mbgl)	(masl)	Date							
				Latitude (decimal)	Longitude (decimal)															
J1	Christiana	J1A	39839	23°15'14.9"	18°59'12.0"	1331.71	256.00	84.00	180.55	30.55	57.49	1274.22	2000/05/06	8.00	68.29	0.741	85	553	7.62	25.0
J2	Olifantswater West	J2A	39840	23°38'50.9"	18°23'19.4"	1275.26	130.51	95.05	127.51	26.41	16.94	1258.32	2000/03/07	3.40	54.94	0.089	90	585	7.78	25.8
		J2N	39841	23°38'53.1"	18°23'19.4"	1275.60	209.00	181.07	204.47	23.40	39.72	1235.88	2000/02/07	2.90	73.93	0.085	91	592	8.34	30.0
J3	Steynsrus	J3K	39842	24°02'45.3"	18°47'36.2"	1208.05	102.00	44.23	76.90	17.52	19.35	1188.7	2000/10/07	1.50	29.84	0.143	330	2 145	7.17	21.9
		J3A	39843	24°02'52.5"	18°47'35.2"	1205	253.00	121.34	247.74	32.15	15.77	1189.23	2000/04/07	19.88	20.26	4.428	115	771	(7.5)	29.3
		J3N	39844	24°02'54.9"	18°47'46.1"	1205	409.00	336.80	363.40	14.60	-24	1229	2000/07/09	0.15	-	-	461	3 089	8.41	14.4
J4	Okanyama (Aminuis)	J4K	39845	23°24'03.5"	19°37'29.6"	1258.05	53.20	30.00	50.30	20.30	45.1	1212.95	2000/02/10	0.10	50.71	0.018	227	1 476	8.58	29.3
		J4A	39846	23°24'01.8"	19°37'32.8"	1256.39	204.00	59.60	175.97	56.05	59.13	1197.26	2000/08/09	19.70	79.54	0.965	646	2 119	7.47	23.8
		J4N	39847	23°24'03.8"	19°37'34.4"	1256.38	356.00	328.00	351.35	23.35	10	1246.38	2000/10/07	11.80	65.31	0.213	100	650	8.89	30.3
J5	Maritzville	J5N	39848	24°19'41.7"	18°23'52.6"	1168.33	187.00	158.00	179.23	20.46	-20	1188.33	21/8/2000	0.80	26.46	0.017	139.5	904	8.27	31.1
J6	Cobra	J6K	39849	24°48'00.3"	19°20'05.4"	1102.67	168.50	108.50	165.00	17.50	101.98	1000.69	2000/05/08	3.00	122.7	0.145	2 310	15 015	9.09	29.8
		J6A	39850	24°48'02.1"	19°20'06.7"	1102.47	273.00	237.90	264.00	26.10	104.41	998.06	31/7/2000	3.96	128.29	0.166	188	1 216	8.54	26.9
		J6N	39851	24°47'58.7"	19°20'04.5"	1103.18	385.00	350.18	373.58	23.40	-16	1119.18	Oct-00	-	-	-		0		27.8
J7	Jackalsdraai	J7K	39852	25°17'29.9"	18°25'00.4"	1144	55.00	27.60	51.00	23.40	10.04	1133.96	21/8/2000	7.15	19.44	0.761	103	670	7.44	27.0
		J7N	39853	25°17'28.2"	18°24'59.4"	1144	250.00	226.83	241.33	14.50	22.45	1121.55	2000/05/08	0.30	88.33	0.005	431	2 743	9.08	29.1
J8	Tweerivier	J8K	39854	25°27'40.4"	19°25'57.6"	1021.25	129.00	84.60	114.00	23.40	60.31	960.94	21/7/2000	0.24	75.2	0.016	351	2 282	8.74	27.0
		J8A	39855	25°27'42.3"	19°26'01.4"	1021.13	250.00	234.10	242.80	8.70	172.32	848.81	Oct-00	-	-	-	1 039	6 754	12.19	28.0
		J8N	39856	25°27'41.3"	19°25'59.7"	1021.26	346.00	320.15	337.55	17.40	20.77	1000.49	Oct-00	-	-	-	>5,000	33 500	8.64	21.8
J9	Klein Swart Modder	J9A	39857	24°00'06.5"	18°12'55.0"	1210.16	141.50	65.43	135.33	69.90	2.23	-2.23	30/8/2000	45.00	5.05	15.957	101	656	7.69	28.6

Table 5: Selected JICA boreholes used in groundwater simulation. All three aquifers are represented on table as K- Kalahari; A-Auob and N- Nossob.

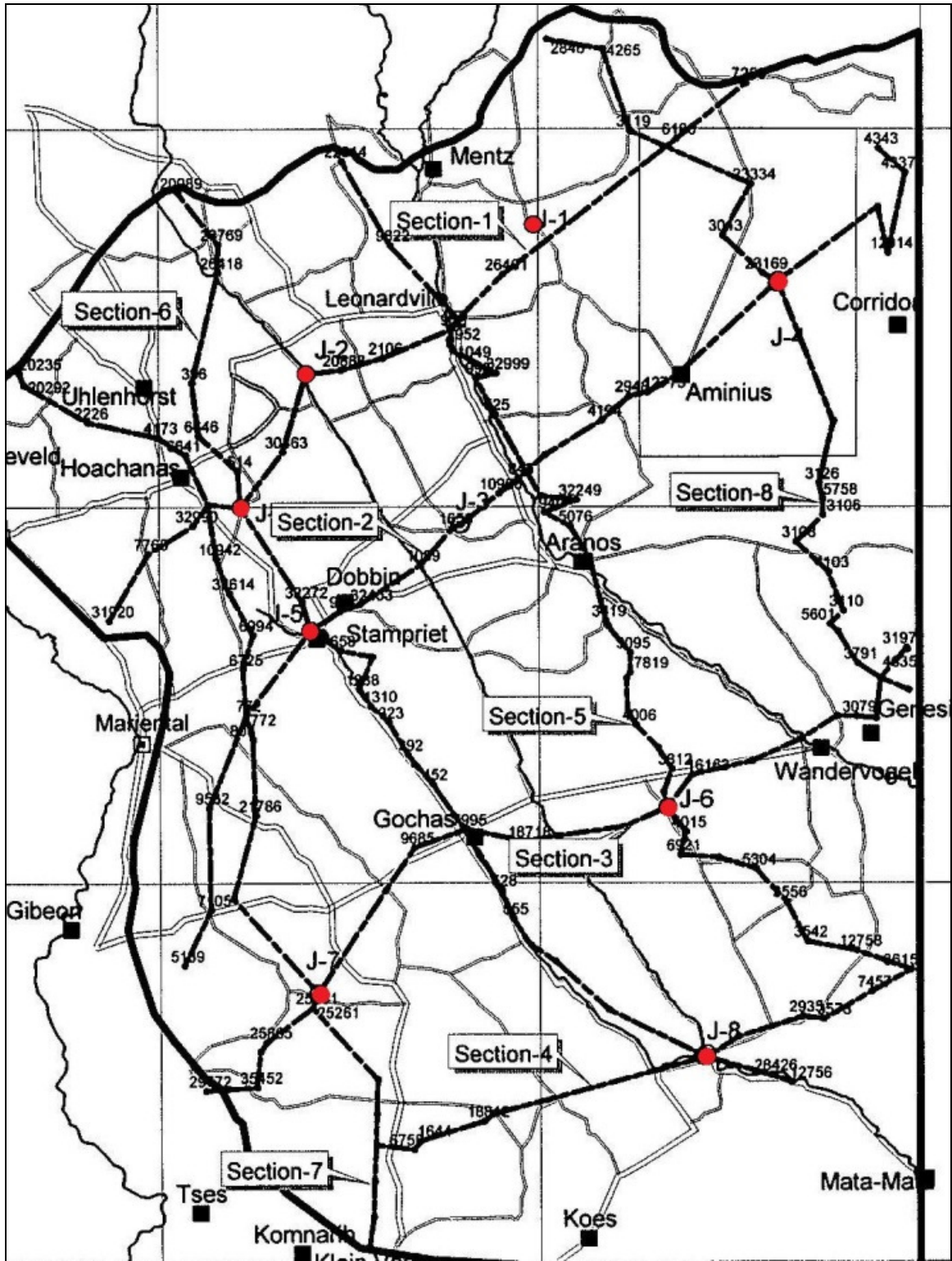


Figure 21: Borehole positioning with boreholes J1; J2; J3; J4; J5; J6; J7; J8 and J9.

Modified from JICA Report (2002).

4.3. Conceptual Modelling

The conceptual model (Figure 20) is set in a plan view with the lithological units distributed as found in the top layer of the Auob Aquifer. The Auob member is represented in light blue whilst the main episodic recharge zone which host preferential flowpaths, Kalkrand Basalts, is seen in purple. This conceptual model also highlights cluster areas of high abstraction points and the unconfined area within the Auob aquifer system. The groundwater flow direction, determined by JICA Report (2002), is also represented and the groundwater flux zones proposed.

The revised conceptual model (Figure 33) is a simplified three dimensional model which represents the Auob Aquifer within its distinct lithological units in further detail. As well as the proposed recharge zone; basic structural features and the potentiometric surfaces determined by groundwater flow simulation. The annual and episodic recharge zones are also shown.

4.4. Groundwater Simulation

4.4.1. Introduction

The Modular Finite-Difference Ground-Water Flow Model (MODFLOW) (McDonald & Harbaugh, 1988) software is utilized to model the regional-scale groundwater flow in the Auob aquifer (see Palma & Bentley 2007 for a similar study). A simplified model of the Auob aquifer in transient state conditions has been accomplished using the JICA Report data of Auob hydraulic properties and nine JICA boreholes.

The Auob aquifer system was modelled as one layered unconfined aquifer across the SAB, following the Auob lithological unit's top layer. The chosen boreholes from the JICA (2002) contain valuable data which includes detailed description of the locality information; borehole structure and pumping data (see Table 5). These boreholes were used to simulate the conditions and set parameters such as hydraulic conductivity. Other points were defined in the most accurate cell across the model to indicate simplified abstraction points within the study area. These abstraction amounts and recharge values are obtained from JICA (2002).

The initial groundwater flow simulation of the Auob Aquifer system to determine possible groundwater flux has been completed using the following method adopted from Xu *et al* (2002). The study area was divided into finite-difference cells using the MODFLOW software. With the use of the Kriging method and Surfer Version 8.02, an interpolated groundwater level and hydraulic conductivity value was assigned to each cell. A high storage value was assigned to the area and the model was run in a transient state for one second (Figure 25).

The simulation thereafter has been divided into two distinct modelling scenarios as follows:

Scenario 1: The annual recharge values for one year was placed within the modelled area.

Scenario 2: The episodic recharge occurring within the zone of preferential pathways is represented. As well as the 'normal' or annual recharge occurring at all other places due to proposed infiltration in unconfined zones. The simulation takes place over 20 years with only one such episodic recharge event taking place.

Within both scenarios the effect of a normal rainfall year (permitting 1.5- 3mm/year recharge) and those of a episodic rainfall event (10- 15mm/year recharge) has been successfully modelled taken from JICA (2002). The modified recharge amounts were modelled over the a yearly basis as well as the 20 year high rainfall cycle.

The following assumptions are taken into account in the preliminary modelling of this aquifer, 1) Recharge takes place within the NW corner of the modelled area within the Kalkrand Basalts and 2)The selected wells positioned within the study area can represent the total abstraction that takes plays within the Auob aquifer

4.4.2. Input Parameters

The grid design for the worksheet for the model has been placed using the geographic coordinates 17-20° E and 22-26° S. The entire modelled area within these geographic coordinates has been set as the worksheet size of 336.724km E and 448.96km S which amounts to 151176km². The study area was divided onto grid intervals of 7km longitudinal and 7.48km in the latitudinal directions. The cells totals 60 and 48 cells respectively (see Table 6).

The elevation of the top and bottom layers were digitised using the top of the Auob aquifer map (see Figure 23). The averaged thickness (100m) of the Auob aquifer was placed within the digitised zones and served as the bottom layer of the aquifer.

The boundary conditions of the model area has been adopted from JICA (2002). The boundary conditions (Figure 24) are divided into the no flow condition (grey cells); and calculated cells in green or blue shades. The basement rocks to the north and south bounds the model area, whilst the western border of the study area restricts the Auob aquifer.

The eastern border remains a represented by a drain. The geology of the Auob aquifer system is known to traverse the political border into Botswana and South Africa. The JICA boreholes are positioned on the base map within the study area and the abstraction points are represented by the red cells. These abstraction points are clumped over the study area in a few positions in the study area where there is a conglomerate of urban/irrigational water use is being cultivated. These points where calculated via the JICA study to be 13.622m³/day.

The abstraction wells were then placed within the model to approximate the cumulative abstraction amounts of the immediate area.

The aquifer hydraulic properties such as groundwater levels and abstraction was adopted from the JICA Report (2002). The hydraulic conductivity was calculated using the transmissivity values located in the selected JICA boreholes with the exact thickness allocated. The model itself was run in a transient state over different time periods. Borehole data and other input parameters can be seen in Table 6 below.

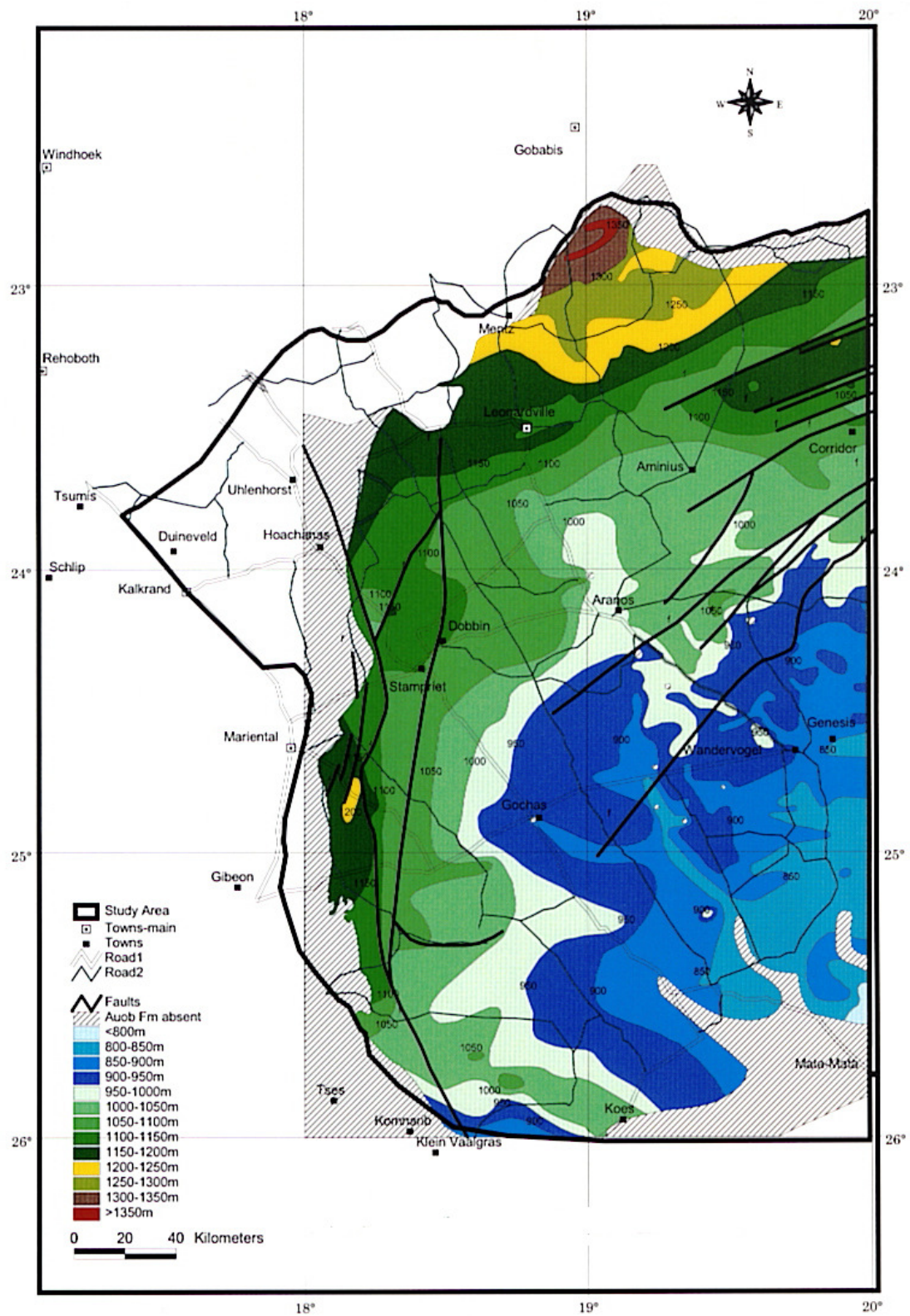


Figure 22: The top layer of the Auob aquifer system (m.A.S.L).

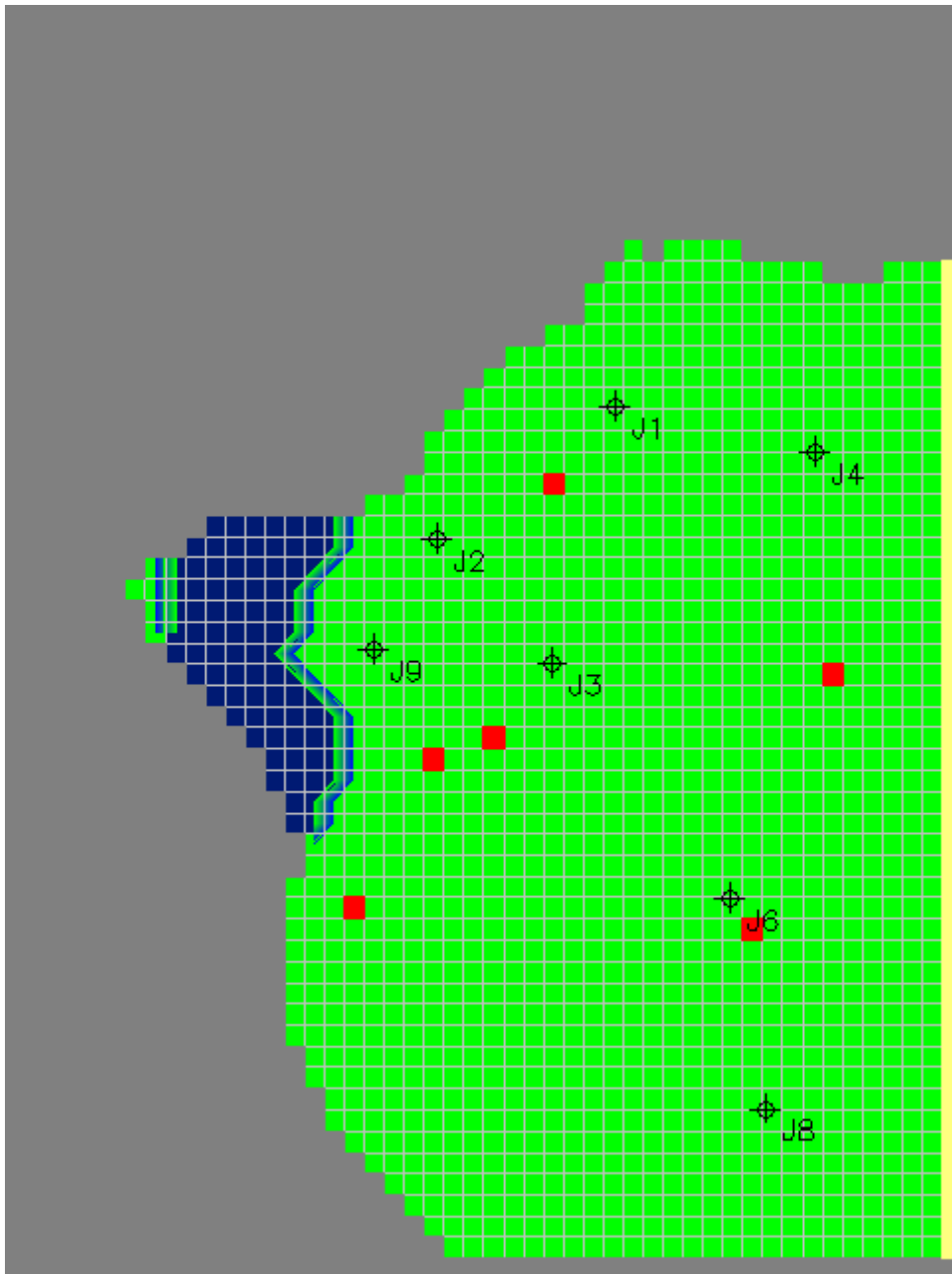


Figure 23: The boundary conditions of the groundwater flow simulation of the Auob aquifer system.

The no flow area (grey cells); annual infiltration (green cells) and episodic recharge zone (blue cells). The averaged yearly abstraction amounts within the surroundings (red cells). As well as, the drain along the Namibia-Botswana border to the east (yellow cells).

Input Parameters					
Parameter			Value	Unit	Description
Mesh Size (columns; rows)			48; 60		
Cell Size			7,7.5	Km	
X2			336724	M	X axis on map used
Y2			448960	M	Y axis on map used
Layer Type			-	-	Confined
Amount of Layers			1	-	-
Simulation Flow Type			-	-	Transient state
Initial Hydraulic Head			-	-	Interpolated
Boreholes	Easting	Northing			
J1	21478.28	303708.3	Calc	-	Active
J2	15173.37	258225.4	Calc	-	Active
J3	19261.77	214943.3	Calc	-	Active
J4	28476.04	290244.5	Calc	-	Active
J6	25496.79	132780.7	Calc	-	Active
J8	26743.92	56486.8	Calc	-	Active
J9	12956.25	22205.88	Calc	-	Active
Observations Wells					
J1	21478.28	303708.3	1274	m	
J2	15173.37	258225.4	1260.25	m	
J3	19261.77	214943.3	1194.41	m	
J4	28476.04	290244.5	1197.25	m	
J6	25496.79	132780.7	999.66	m	
J8	26743.92	56486.8	831.18	m	
J9	12956.25	22205.88	1207.9	m	
Initial Hydraulic Conductivity					
J1	21478.28	303708.3	0.22300885	m/day	
J2	15173.37	258225.4	0.065769231	m/day	
J3	19261.77	214943.3	1.243589744	m/day	
J4	28476.04	290244.5	0.415165871	m/day	
J6	25496.79	132780.7	0.078148148	m/day	
J8	26743.92	56486.8	0.000048	m/day	
J9	12956.25	22205.88	16.75675676	m/day	
Recharge					
Normal year			1.5	mm	Rest of study area
Episodic year			10	mm	Kalkrand Basalts
Well	Column	Row			
W1	28	23	-500	L ³ /T	Leonardville
W2	42	32	-500	L ³ /T	Below Section 8
W3	25	35	-3000	L ³ /T	Dobbin
W4	22	36	-8400	L ³ /T	Stampriet
W5	18	43	-800	L ³ /T	Below Mariental
W6	38	44	-500	L ³ /T	Below J6

Table 6: Input Parameters for groundwater simulation of Scenario 1 and 2.

As the Auob aquifer is a semi-confined aquifer, the episodic recharge mainly takes place along preferential flow paths located within the Kalkrand Basalts in the north west. The recharge within an average rainfall period is calculated to be approximately 1.5-3mm/year. The high rainfall episodic events allow for approximately 10mm/year of recharge to take place.

The model therefore simulates both instances where a normal rainfall year and an episodic rainfall event takes place. The changes in the hydraulic head contoured maps are shown in Figures 19-26. The model allows for such a comparison not only between these two rainfall events, but also the 20 year cycle in which these episodic rainfall events occur.

4.4.3. Groundwater Flow Simulation of Scenario 1 and 2

The Auob aquifer system lying within the SAB is plotted from 17-20° E and 22-26° S. The entire modelled area within these geographic coordinates has been set as the worksheet size which amounts to 151176km².

The elevation of the Auob aquifer has been digitised using the elevation maps from JICA (2002) and the averaged thickness of 100m has been placed over the digitised zones. The parameters for both Scenario 1 and 2 has been kept constant, except for the recharge values within the different time periods.

Scenario 1:

The model has been run under transient conditions using a normal rainfall year, with abstraction amounts for the Auob aquifer (for the year 2000, adopted from JICA, 2002) with calculated hydraulic conductivity.

Scenario 2:

Case 1: The model uses the episodic rainfall amounts for the year 2000 (10mm) within the Kalkrand Basalts whilst keeping the other parameters constant. Recharge through infiltration from the Kalahari Beds are represented as 1.5mm over the rest of the study area.

Case 2: The model was then run using the episodic rainfall event of the year 2000 in a 20 year cycle which included the yearly abstraction amounts and the one episodic event. The comparison between these models can be seen in Figures 30-32 below.

Chapter 5- Transboundary Aquifer Characteristics and Simulation

5.1. Transboundary Aquifer Determination

The Auob aquifer system as mentioned earlier in the text has the highest yield of the best quality water compared to the Kalahari and Nossob aquifers within the SAB. Thus, its water usage is in great demand and the continued management of the resource is imperative.

The hydrogeological and structural boundaries of any aquifer system do not follow political borders. It is documented that the Auob aquifer system extends into Botswana and South Africa (JICA, 2002). The understanding of the Auob aquifer within the 'recharge' member state as well as the quantification of the amount of outflow (groundwater flux) is essential to equitable management by all stakeholders. The extent of this aquifer system is important to ascertain the significance of the Auob aquifer system as a transboundary aquifer.

The JICA (2002) shows three aquifers in the SAB, namely the Kalahari unconfined aquifer system, Auob and Nossob confined aquifer systems. The data acquired from MMWER (2003) also known as the Bokspits Report, show three individual aquifers, namely the Olifantshoek quartzite, Otshe Sandstone (formation found in the Eccca Group) and the Kalahari Group aquifer.

The Otshe sandstone consists of interbedded layers of sandstone, mudstone and shale (MMWER, 2003). Similar to the Auob and upper Mukorob members found in the JICA (see Figure 5). There is a linkage between the Auob sandstone and the Otshe Sandstone. It has been concluded that the Auob and Otshe aquifer systems are the same aquifer system due to the same lithological units present (MMWER, 2003).

This linkage in lithology and the comprehension of the aquifer systems located within the study area indicates that the Auob aquifer system is indeed a transboundary aquifer. However, resulting from the research completed in this study, it is determined that this aquifer does not have sufficient groundwater flow into neighbouring countries.

5.2. Water Balance Method (Outflow)

Table 7: Initial Auob outflow results using the revised Darcy method.

Auob Outflow					
Borehole	Transmissivity (m³/day/m)	Q-Outflow		Abstraction	Outflow minus
Name		(m³/day)	(m³/year)	(m³/year)	Abstraction (m³/year)
J8	0.006	8.58	3130.94	4970000	-4966869
J2	3.42	4889.41	1784635.09	4970000	-3185365
J6	8.44	12066.27	4404187.18	4970000	-565813
J1	25.2	36027.24	13149942.78	4970000	8179943
Average value	9.2665	13247.87	4835473.99	4970000	-134526

The Auob outflow results (Table 8 above) endeavoured to determine if there was sufficient water within the system to create a groundwater flux into neighbouring countries. The borehole data available for such an equation was scarce, as only seven JICA boreholes had a transmissivity value for the Auob aquifer system.

The results show negative values for the potential amount of outflow from the Auob aquifer system. With the exception of J1, however, this amount would still indicate a very little potential outflow across the political borders.

5.3. Conceptual Model

5.3.1. Plan view model

The conceptual model endeavours to give a graphical representation of the Auob aquifer system and enhance the understanding of the stresses within this system. The model is a useful tool that identifies the conditions of the aquifer system which can be compared or verified by the groundwater simulation process.

The conceptual model of the Auob aquifer system (Figure 20) uses the geological delineation in the top layer of the Auob aquifer as a base map. This is in order to accurately represent the Auob aquifer and not the entire basin. The model illustrates the recharge area within the Kalkrand Basalts where the sinkholes act as the main recharge mechanism for this unconfined part of the Auob aquifer system (see Chapter 2).

There are three main abstraction points located on the map which corresponds to the main clusters of abstraction delineated in the JICA Report for the Auob aquifer system. Though these orange arrows are a general representation of the main abstraction clusters, the largest abstraction amounts takes place at Stampriet.

The position of the yellow arrow in the centre of the study area represents the unconfined section within the aquifer system due to the absence of the confining lower Rietmond member. This area is believed to be an area of recharge, through the Kalahari Sands into the system. However, it could also be argued to be discharge area dependent on the hydrogeological structures found in the area. This area and other unconfined regions within the cross sections of the SAB compelled the numerical simulation to regard the Auob aquifer system as unconfined. In terms of recharge, the area where episodic recharge does not occur, which is most of the study area, infiltration of the normal recharge has been utilised.

The groundwater flow pattern determined by previous studies is reported to be in a NW-SE direction and arrows within the study area represent this flow patten. Lastly, the flux arrows located at the Namibian/Botswana border is assumed due to evidence described above.

5.4. Groundwater Flow Simulation

The initial groundwater flow simulation is utilised to ascertain the amount of potential outflow from the Auob aquifer system. The resulting map (Figure 16 below) represents the corresponding hydraulic head within the aquifer system. The groundwater level decreases from green to blue on the map. There is a uniform flow observed across the study area as green cells. There are certain points towards the north of the study area that are a darker shade of green indicating the lower groundwater level. The zone around the J4 borehole in the NE of the study area shows an increase of stress on the aquifer in dark blue. The white cells within the study area indicate areas where no hydraulic head value has been formulated.

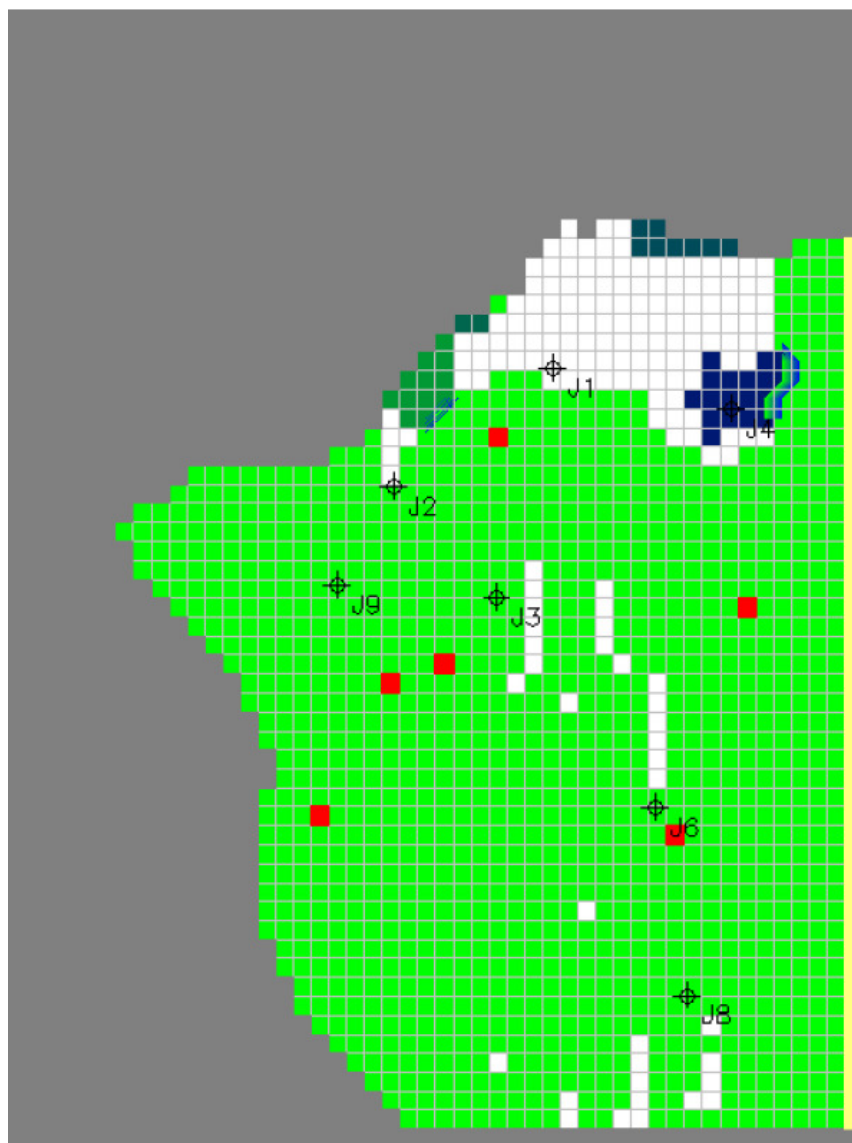


Figure 24: Initial groundwater flow simulation of the Auob aquifer system.

The groundwater flow simulation of the Auob aquifer system is divided into Scenario 1 and 2. Scenario 1 simulates the groundwater flow of the Auob aquifer system in a transient state for one year (as described in Chapter 4). The boundary conditions of the SAB have been set with no-flow (grey) cells surrounding the study area. The position of a drain within the model is seen at the eastern border represented as yellow cells on the map. The scenario simulates a normal recharge year which was placed at 1.5mm/year across the study area. This value has been utilised from JICA (2002) whereby 1% of the annual rainfall is concluded to have the potential recharge within the area.

Scenario 2 is an extension of the recharge in the area which includes the episodic recharge within the Kalkrand basalts. The recharge rate is estimated to be 10mm, 10% of the annual rainfall, as estimated within the JICA (2002). The normal rainfall has been distributed across the rest of the study area as proposed infiltration from the Kalahari beds to the Auob aquifer. This is substantiated by the unconfined zones observed in the geological cross sections in Chapter 2. Scenario 2 simulates the Auob aquifer system over a twenty year cycle. There is one episodic rainfall event in the first year and continued normal recharge over the study area for all other years.

The groundwater flow simulation serves five distinct purposes as follows:

1. To understand the groundwater flow patterns under the known conditions to determine if there is any potential groundwater flow across political borders.
2. Simulate the impact of the normal and episodic rainfall events that takes place within the 20 year cycle;
3. Enable the model to be used as a basis for further numerical modelling of the Auob aquifer system;
4. To enable the 'what-if' scenario modelling of the Auob aquifer system to be accomplished

The study area is known as an arid to semi-arid area and for approximately 19 years of the 20 year cycle, the rainfall reflects this observation with very low amounts ranging from 150-300mm per year (see Figure 28). However, with the addition of episodic rainfall events the amount of recharge on an annual basis elevates the status from the presumably arid area. As seen in Figure 26, a substantial increase in the recharge amounts can be observed, from 1.5mm to 80mm per year.

The impact and importance of the episodic recharge has been documented Braune *et al* (2008) within the study area. Figure 20 shows a schematic diagram on the importance of episodic recharge in regards to the geological formations located within the study area and presumably in the other member states. The possibility of recharge areas within other member states are not only determined through the rainfall amounts, but also the proposed recharge mechanisms for this ‘confined’ aquifer system.

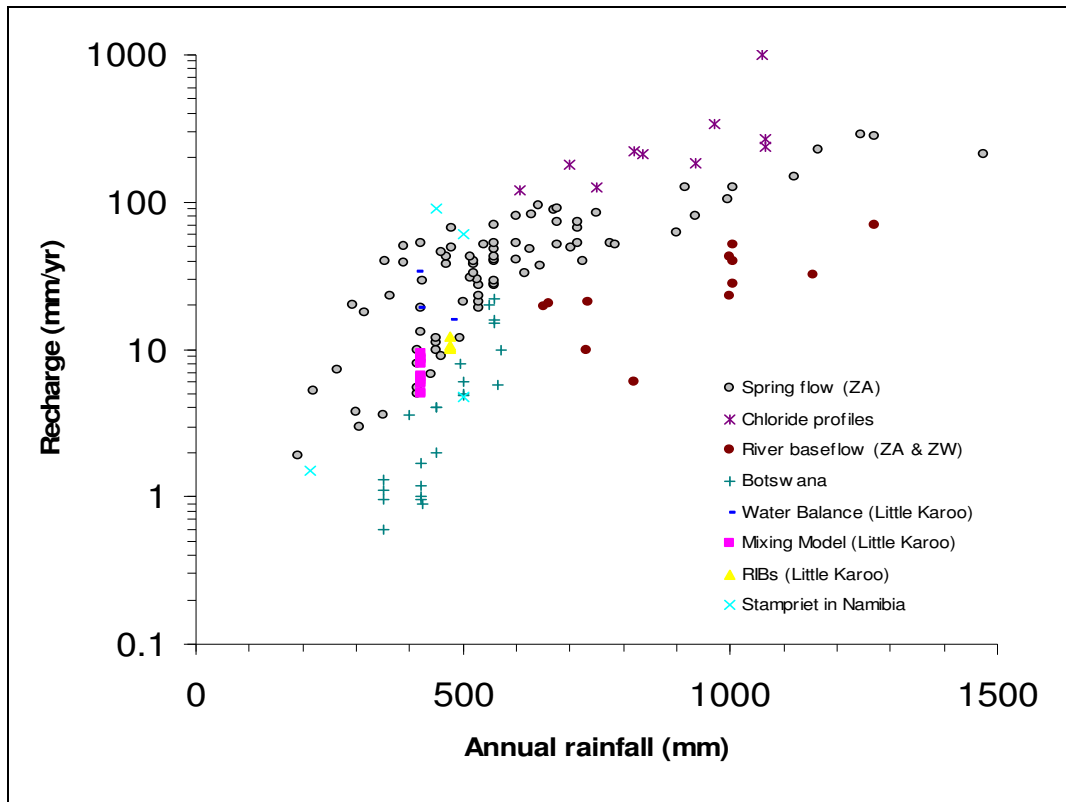


Figure 25: Recharge VS annual rainfall graph. Reproduced from Xu (2000).

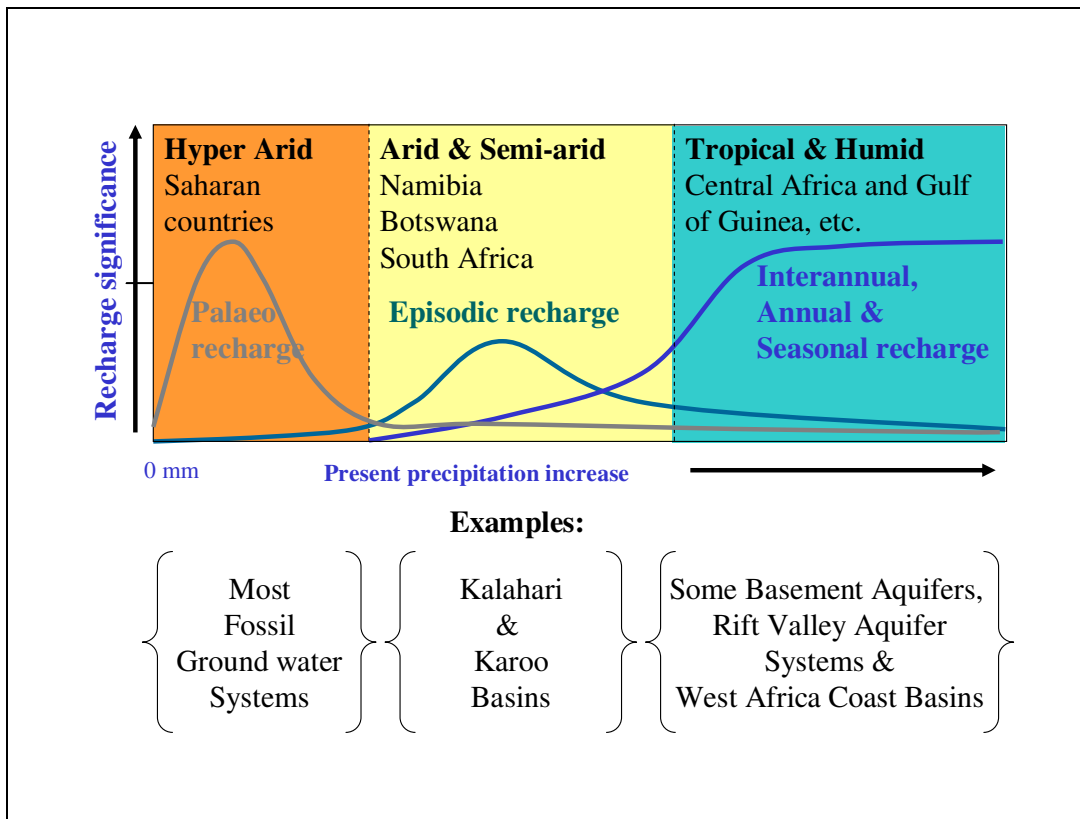


Figure 26: Schematic diagram of recharge within geological formations Adapted from (Braune & Xu, 2008).

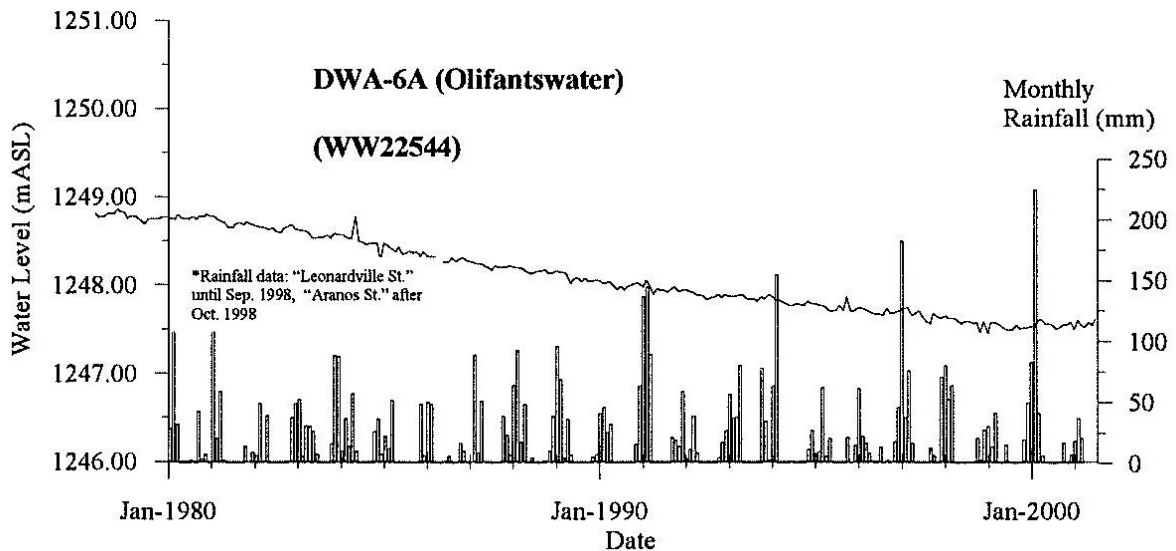
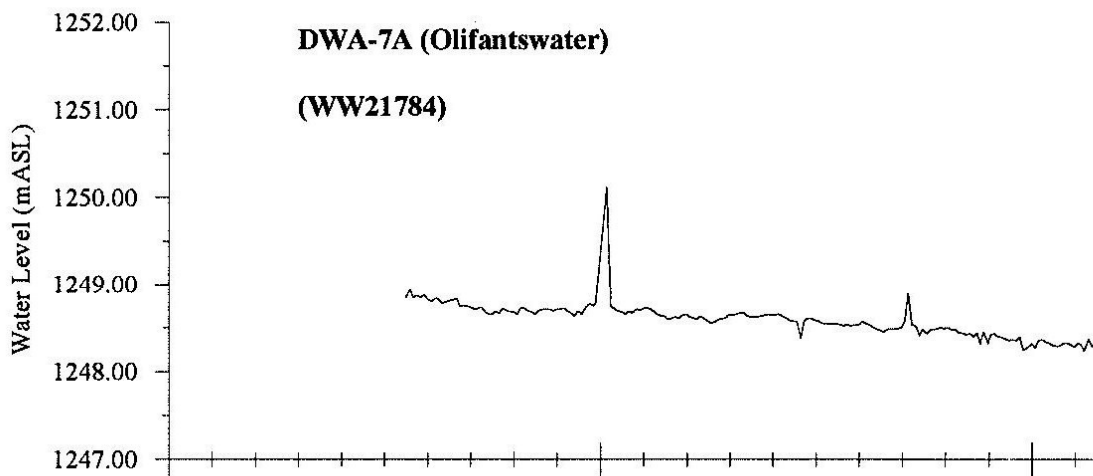
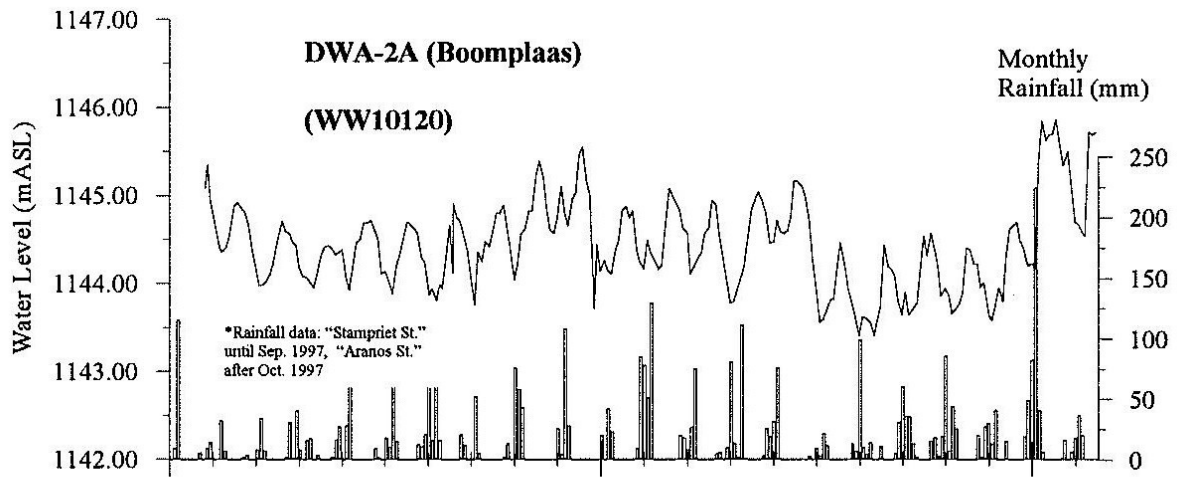


Figure 27: Examples of rainfall peaks over the 20 year cycle in three JICA boreholes with the corresponding water levels. Reproduced from JICA, 2002.

5.5. Scenario 1

This groundwater flow simulation models the Auob aquifer system with its normal recharge values of 1% of rainfall across the study area. The model is run in a transient state over a period of one year. The resulting groundwater flow map (Figure 29) follows the protocol of the initial groundwater flow simulation in terms of colour coding and visual characteristics. Scenario 1 has a similar pattern to the initial groundwater flow map (Figure 20), with the exception of the decrease in water level to the northern parts. There are very little intermediate values visible on the map, with a constant value across most of the study area.

There are heightened areas of stress which correlates with the areas of greatest abstraction, which is close to the town of Stampriet. This is seen as two very close red cells representing abstraction zones in the centre of the map. As seen in the initial groundwater flow simulation, the uncalculated hydraulic head (white cells) to the north of the study area remains unchanged.

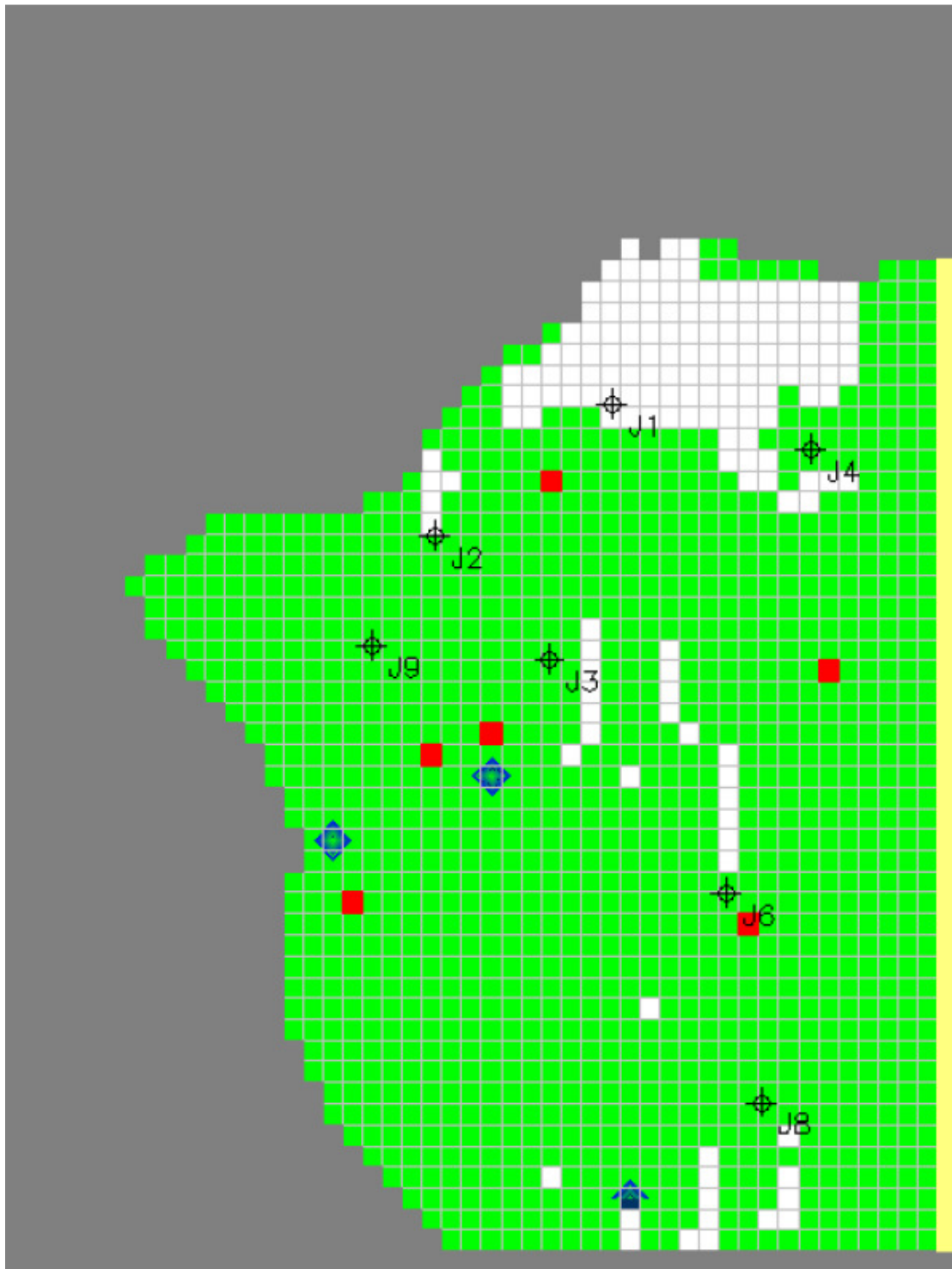


Figure 28: Scenario 1 depicting annual recharge (1.5mm) over the study area for one year.

5.6. Scenario 2

As stated previously, Scenario 2 simulates the Auob aquifer system in a twenty year cycle, specifically following the reoccurrence of the episodic rainfall event noted in Figure 19 above. The resultant groundwater flow maps are divided into year 10 and year 20. This objective here was to represent the increase stress on the aquifer as the abstraction continues and the aquifer system is depleted.

The simulation was run over 20 years with an episodic recharge event occurring in the first year (Figure 31). The unconfined areas which link the Kalahari aquifer system to the Auob aquifer system at certain areas are represented as a normal recharge zone across the study area.

Figure 21 represents the first year which contains both the episodic and normal recharge over the study area. The zones of abstraction points out where excessive stress to the aquifer occurs and can be seen as red cells at four distinct points on the map. These points of stress to the aquifer are magnified for each passing year. Figure 32 and 33 are the groundwater flow maps for year ten and year twenty within this cycle.

The tenth year of abstraction within the cycle (Figure 32) retains the similar groundwater flow pattern as the previous simulations. The uncalculated head cells remains mainly to the north with some scattering of these values over the central area. There is a decrease in the water level around the abstraction zones as well as in the western border of the area. The final year of the cycle (Figure 33) expands the position of the four stressed zones of the aquifer laterally across the study area.

Table 8: Hydraulic heads for Scenario 2, case 1.

Borehole	Observed heads (m)	Calculated heads (m)
J1	1274	0
J2	1260.25	1177.1
J3	1194.41	1168.39
J4	1197.25	993.98
J6	999.66	928.1
J8	831.18	888.88
J9	1207.9	1237.5

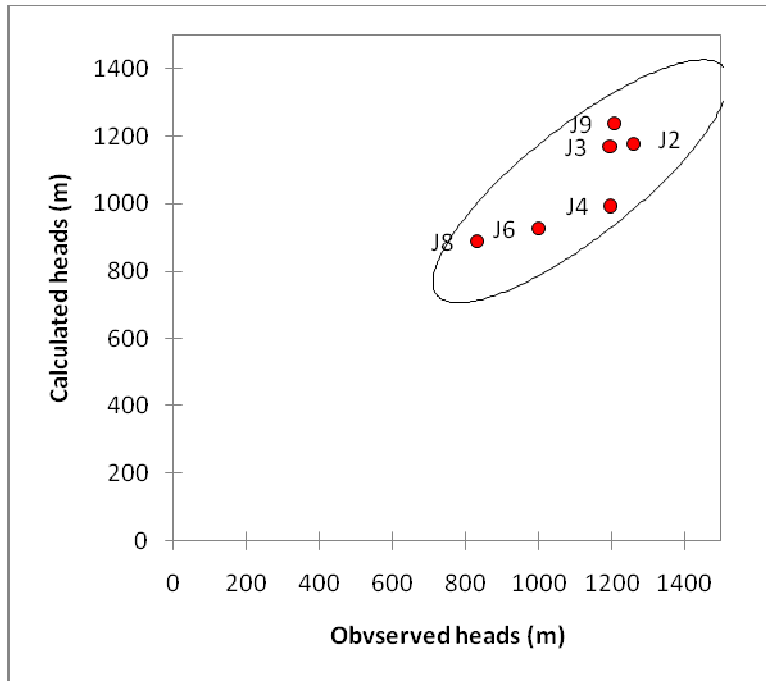


Figure 29: Calculated VS Observed heads for Scenario 2, case 1.

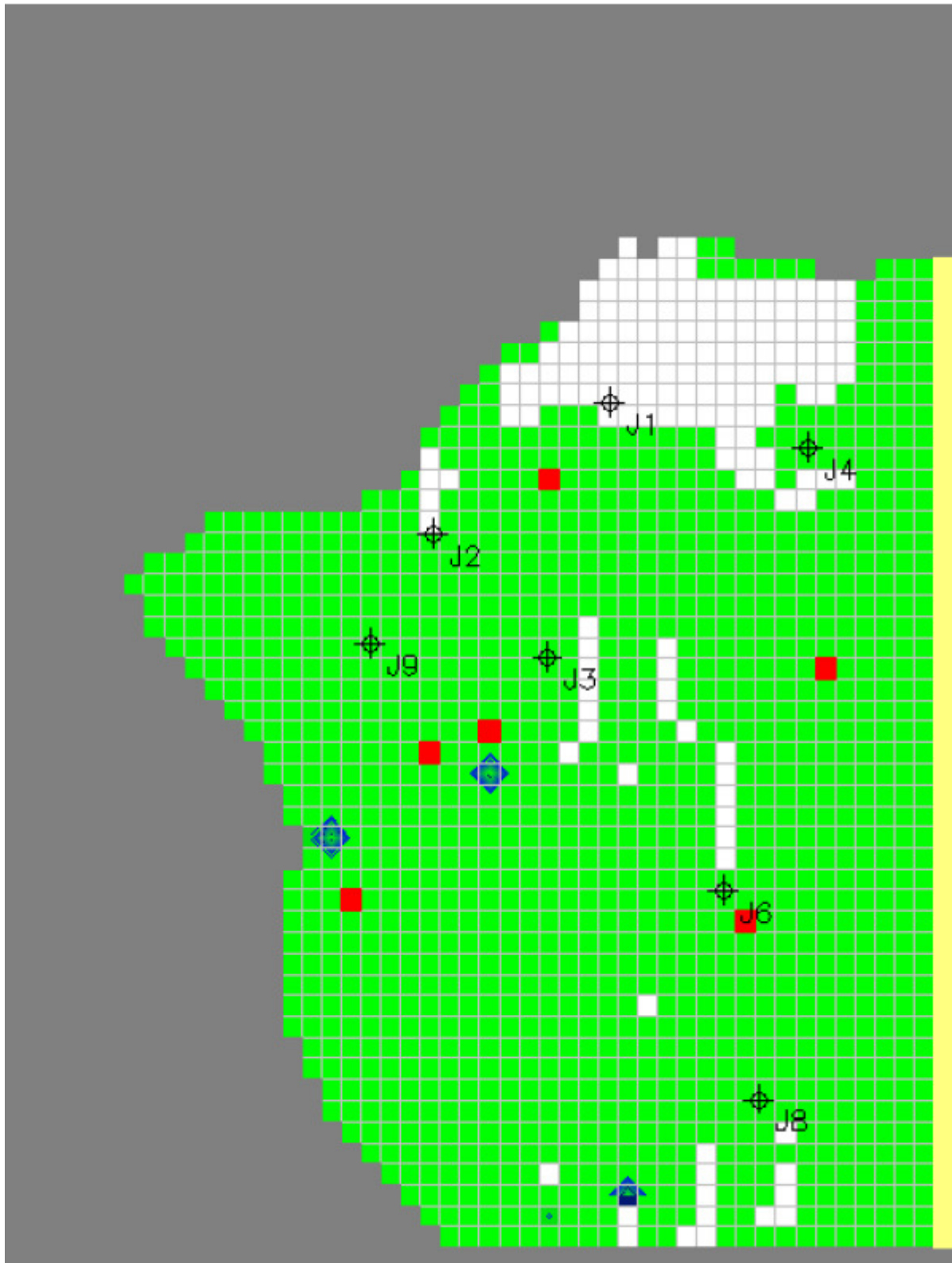


Figure 30: Scenario 2, depicting year one with episodic recharge within the Kalkrand Basalts and normal recharge across the other parts of the study area.

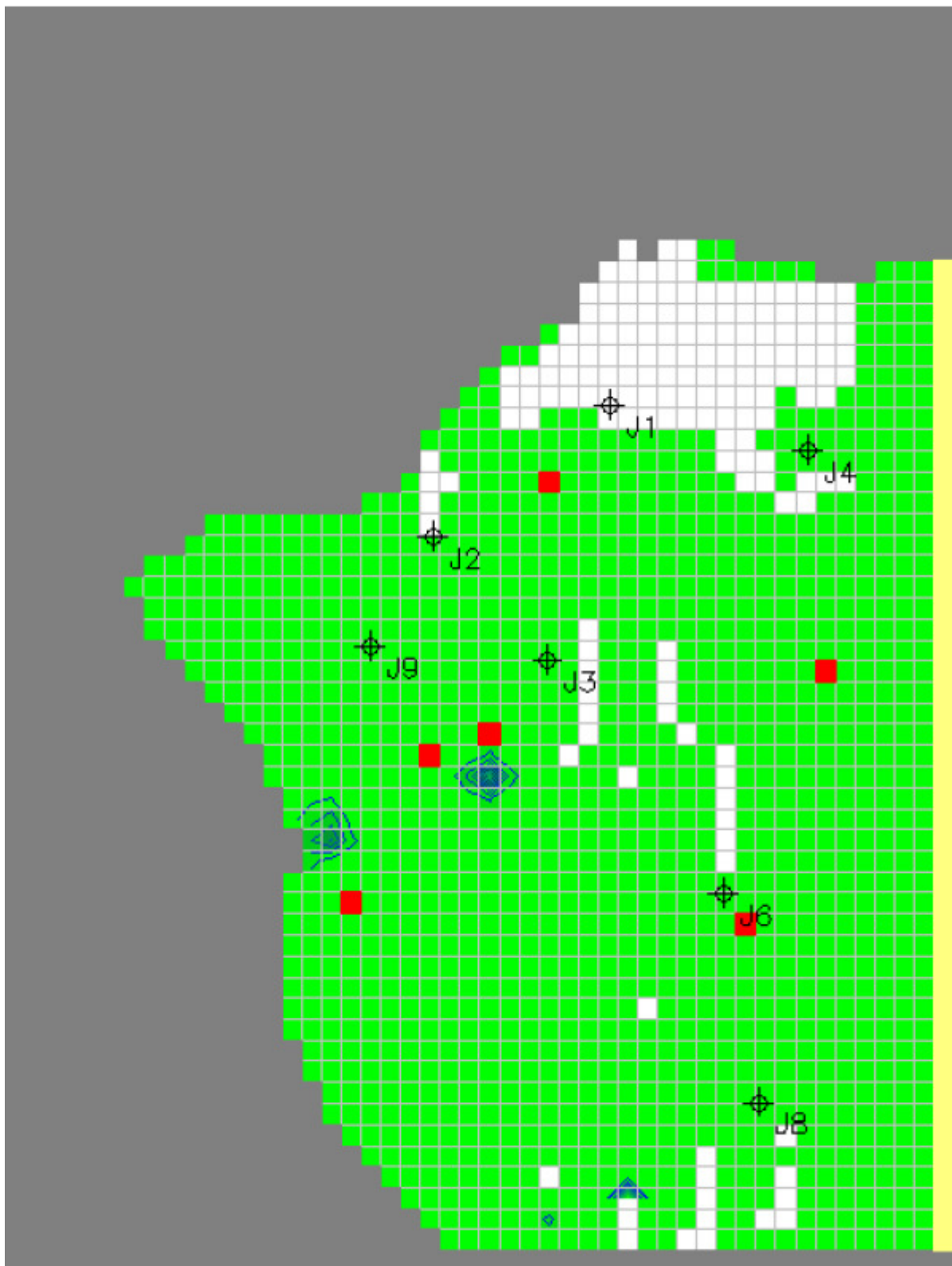


Figure 31: Scenario 2, depicting year ten in the episodic recharge cycle.

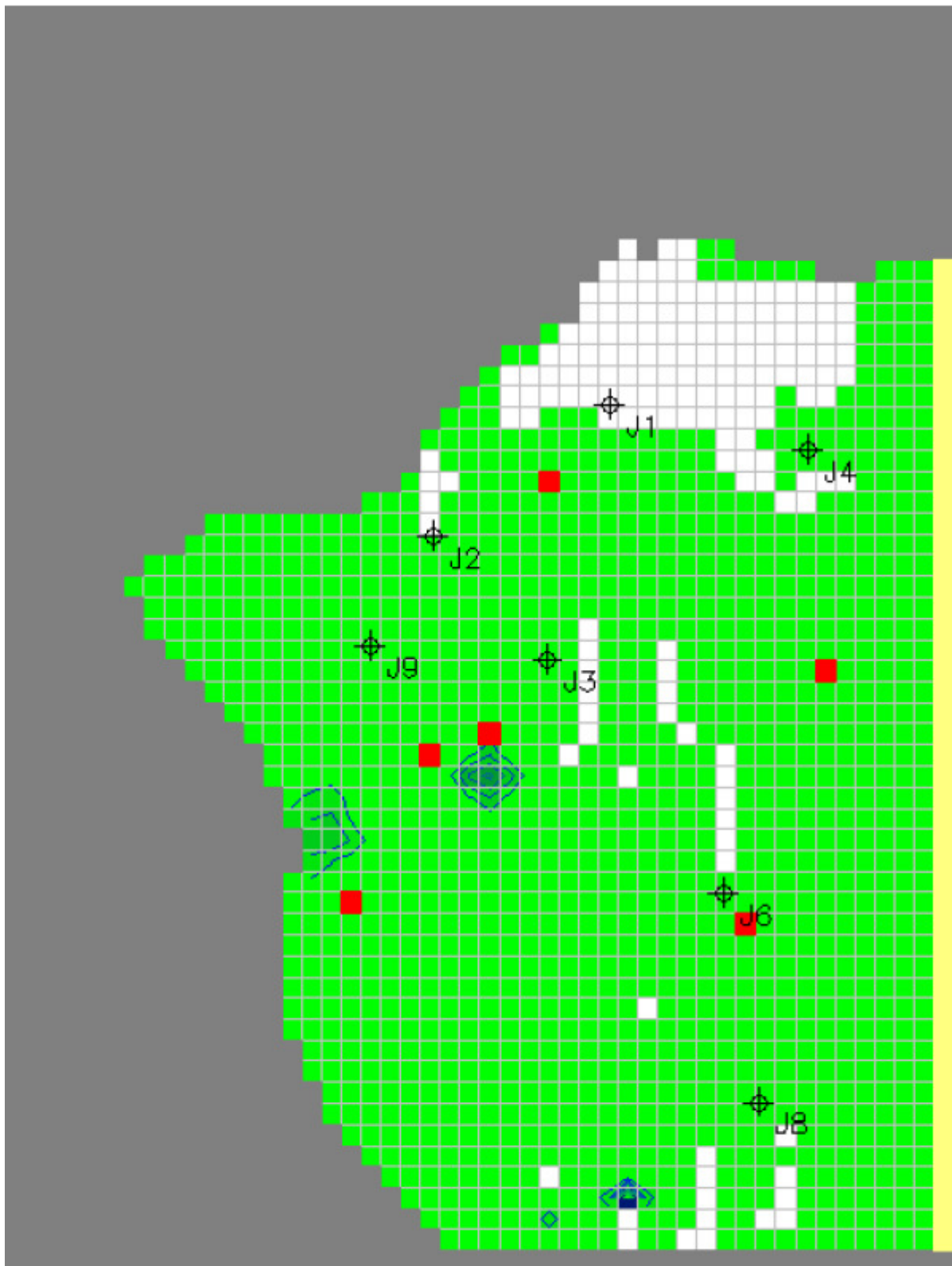


Figure 32: Scenario 2, depicting groundwater flow of year twenty of the recharge cycle.

5.7. Three-dimensional revised conceptual model

The revised conceptual model (Figure 34 below) endeavours to demonstrate the effect of episodic recharge into the Auob aquifer system. The model is very similar to the initial conceptual model with regards to the recharge zones and abstraction points. Though not to scale, the revised model represents a more detailed lithology of the Auob member and highest abstraction points. The preferential pathways in the form of sinkholes are displayed within the Kalkrand Basalts. These pathways have been discussed in previous literature such as the JICA (2002) and the resultant 'pool formation' in Schalk (1961).

As a result of the groundwater flow simulation, the understanding of the aquifer system has changed. The initial concept of the confined conditions of the Auob aquifer system which resulted in artesian flow at certain points is not constant within the twenty year cycle. The abstraction amounts from the Auob aquifer is based on quantities from the year 2000 abstraction records JICA (2002). The groundwater flow simulation clearly shows a steadily decrease in water level around areas where large quantities of water is abstracted e.g. Stampriet area.

These large-scale abstraction amounts are ever increasing as the need for irrigation continues. The understanding that the Auob aquifer system is fully recharged only during a heavy rainfall event supports the concept that at the later stage of the cycle, the groundwater flux would not be possible.

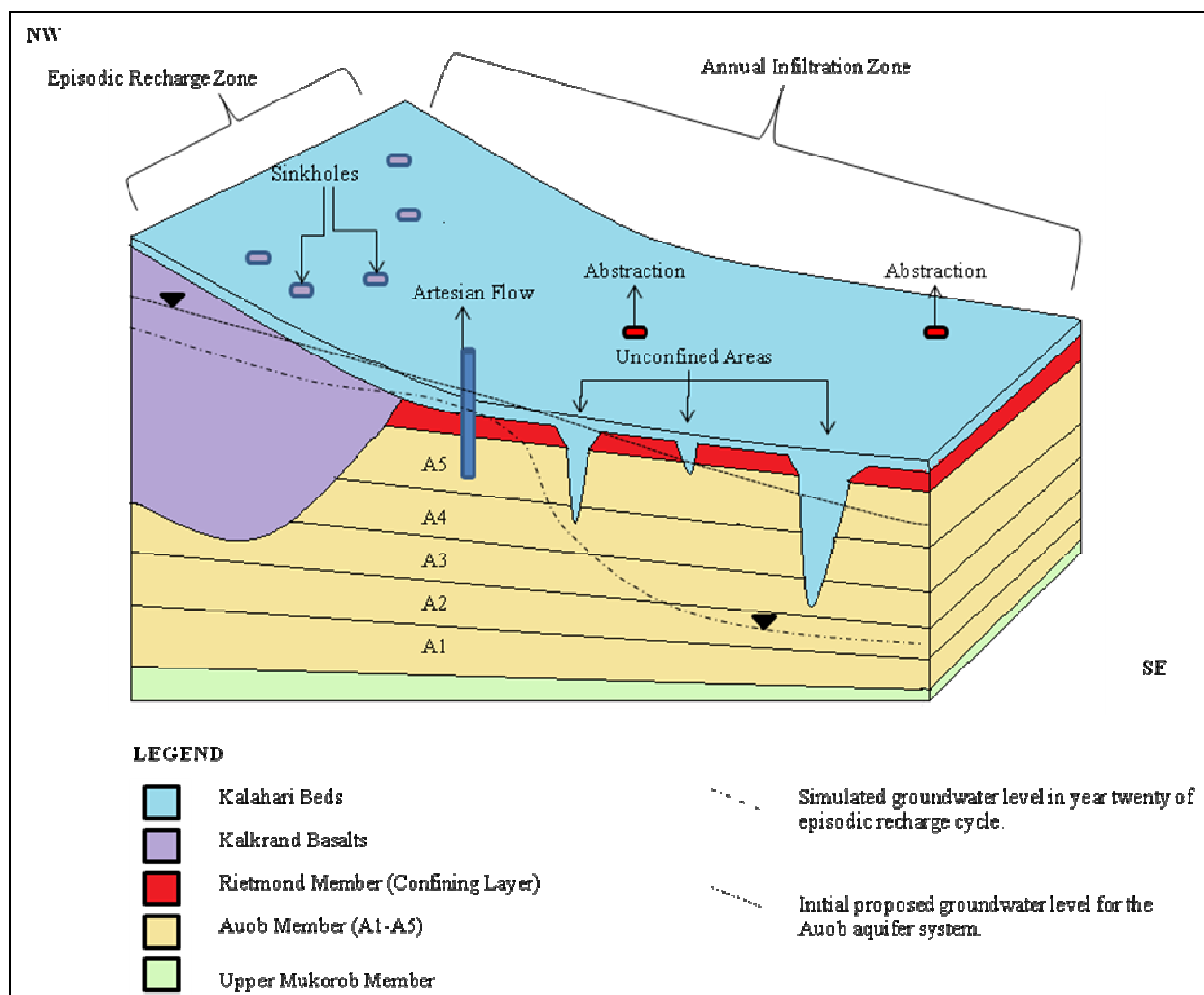


Figure 33: The three dimensional revised conceptual model for the Auob aquifer system.

5.8. Interpretation

The Auob aquifer system has been documented as a transboundary aquifer. The JICA (2002) and MMWER (2003) have discussed the similarities in lithology and the extension into its neighbouring counterparts. The potential outflow from Namibia has been researched (JICA, 2002) and to a lesser extent in Botswana as well. South Africa has had exploration completed within its part of the extended study area. However, due to the groundwater salinity in the area and the limitation of this study, the data on South Africa's portion of the Auob TBA is not commented on in this study.

The groundwater flux (outflow) calculated in Table 8 illustrate the potential amount of abstraction taking place in the Auob aquifer in the year 2000. The four transmissivity values used have resulted in four possible amounts of outflow. There is a very low possibility of outflow from the Auob system. Negative outflow values are primarily seen with this equation. This equation is not utilized for its accuracy, but for enhancing the conceptualization of groundwater cross flow to the neighbouring countries.

The research undertaken can conclude the Auob aquifer as a TBA. A further step was taken to determine the potential outflow of the Auob aquifer system in Namibia. This was completed to determine if there was sufficient supply of groundwater for cross flow into Botswana and South Africa.

The initial groundwater flow simulation (Figure 25) indicates a very similar hydraulic head over most of the study area observed as shades of bright green. The green shade though similar has a change in hydraulic head by approximately 100m across the study area. This initial groundwater flow simulation included both the episodic and annual rainfall event of the year 2000. Utilizing the method discussed (see page 60) from Xu *et al* (2002), the groundwater flow map was produced (Figure 23).

The Auob aquifer system was then simulated under the two different recharge conditions. The importance of the recharge events is the dependence of the Auob system on the episodic recharge event. This event, occurring every twenty years, is the main recharge event for the Auob aquifer system. The rise in groundwater levels after these high rainfall events is indicated in Figure 28 at the DWA-2 Borehole.

There are confined and unconfined zones that are present in the Auob aquifer system. The latter is mainly due to the areas where the confining Rietmond Member has been eroded and the Kalahari Beds are in contact with the Auob aquifer. This has ensured that the groundwater flow simulation has modelled the Auob aquifer system as an unconfined layer.

Scenario 1 indicates a similar hydraulic head over most of the study area. The abstraction areas located in red has an effect on the main stressed areas located in blue shaded cells. Scenario 2 follows a similar pattern as Scenario 1 with regards to its main stress areas. Case 1 has simulated the values of episodic and annual recharge and the abstraction amounts for the year 2000. The calculated heads are plotted against the observed heads of the year in Figure 30. The resultant calculated hydraulic head is similar to the observed with the exception of J1 that cannot be seen on the graph. This is due to the zero values for hydraulic head (white cells) to the north. Through the Auob aquifer system there is a potential for outflow to the neighbouring countries in Case 1, but the potential outflow steadily decreases over the twenty year cycle.

Case 2 simulates the twenty year cycle and the increase of the stress zone is indicated on the maps in Figures 32 and 33. The water budget of the whole domain (see Addendum A) indicates the decrease in groundwater availability over this time period. The Auob aquifer system is a TBA, but utilizing the data of the year 2000, there is a very slight chance of cross flow. This is mainly due to the high abstraction amounts across the study area.

As literature accurately predicts the episodic rainfall plays a vital role in combating the increasing abstraction rates within the study area. As well as being the main recharge source for the Auob aquifer system through sinkholes located in the Kalkrand Basalts.

Approximately ninety-six percent of the South African border is underlain by low-yielding aquifers (Cobbing et al, 2008). Though seen as low yielding at present, the need for water will further enhance the economic viability of deeper boreholes. The Auob aquifer transboundary system can in this respect increase the yield available if the system is managed multilaterally.

The revised conceptual model (Figure 34) represents this trend of decreasing groundwater levels over the twenty year cycle. The understanding of the importance of the episodic recharge is not reflected in the management plan as abstraction is constant or more likely increases over this time frame.

The groundwater flow pattern of the Auob aquifer system is from the north west to south east. In 2002 the JICA has calculated thirty percent overabstraction of the aquifer system's in the SAB. The current situation of increased irrigation and water supply in the SAB is causing an increase in the abstraction rates. At this rate, overabstraction in Namibia can not only cause depletion of the aquifer system, but possibly the reversal of flow patterns from Botswana and South Africa.

Chapter 6- Conclusions and Recommendations

6.1. Conclusions

The importance of this preliminary research is vast and can be seen when looking at the many socio-economic implications for its three member states. Through this research, the transboundary Auob aquifer system's status is confirmed. This means that the management and responsibility of the Auob aquifer system needs to be equitably divided between the member states. The intergovernmental management and cooperation of the Auob aquifer system is necessary in order to ensure that all stakeholders in will have access to this vital resource..

It is evident that the study of a transboundary aquifer such as the Auob aquifer system needs to be undertaken through a holistic approach. The holistic approach was particularly necessary in establishing the aquifer system as a transboundary aquifer with flow across the political borders of Namibia. A plan view of a conceptual model is shown in Figure 35.

This research shows that the groundwater flow patterns simulated within the twenty year cycle has a large decrease in water supply. It is evident that the episodic recharge within the study area is clearly the main source of recharge and plays a vital role within this system. To this end, it is plausible that potential overabstraction within the recharge member state creates a possibility to lessen groundwater flow across the border and halt this flow all together.

6.2. Recommendations

Following the research that has been completed for the Auob aquifer system, the following recommendations are suggested:

1. The Auob aquifer system should be researched as a transboundary aquifer and the entire study area within all member states should be taken into consideration.
2. Further numerical modelling of the Auob aquifer system should be undertaken within all three member states.
3. The use of current hydrogeological data should be used within the modelling process and a comparative analysis produced from the year 2000 data.
4. Conceptual modelling should be enhanced further with the addition of geological structures within the entire aquifer system.
5. Enhanced management within Namibia is advised as the increase in irrigation and possible absence of an episodic rainfall event can have detrimental effects for the other member states.
6. A recommendation of decreasing abstraction rates in the later years of the cycle is a option that could assist in negating the impacts of overabstraction and should be incorporated into a management plan.

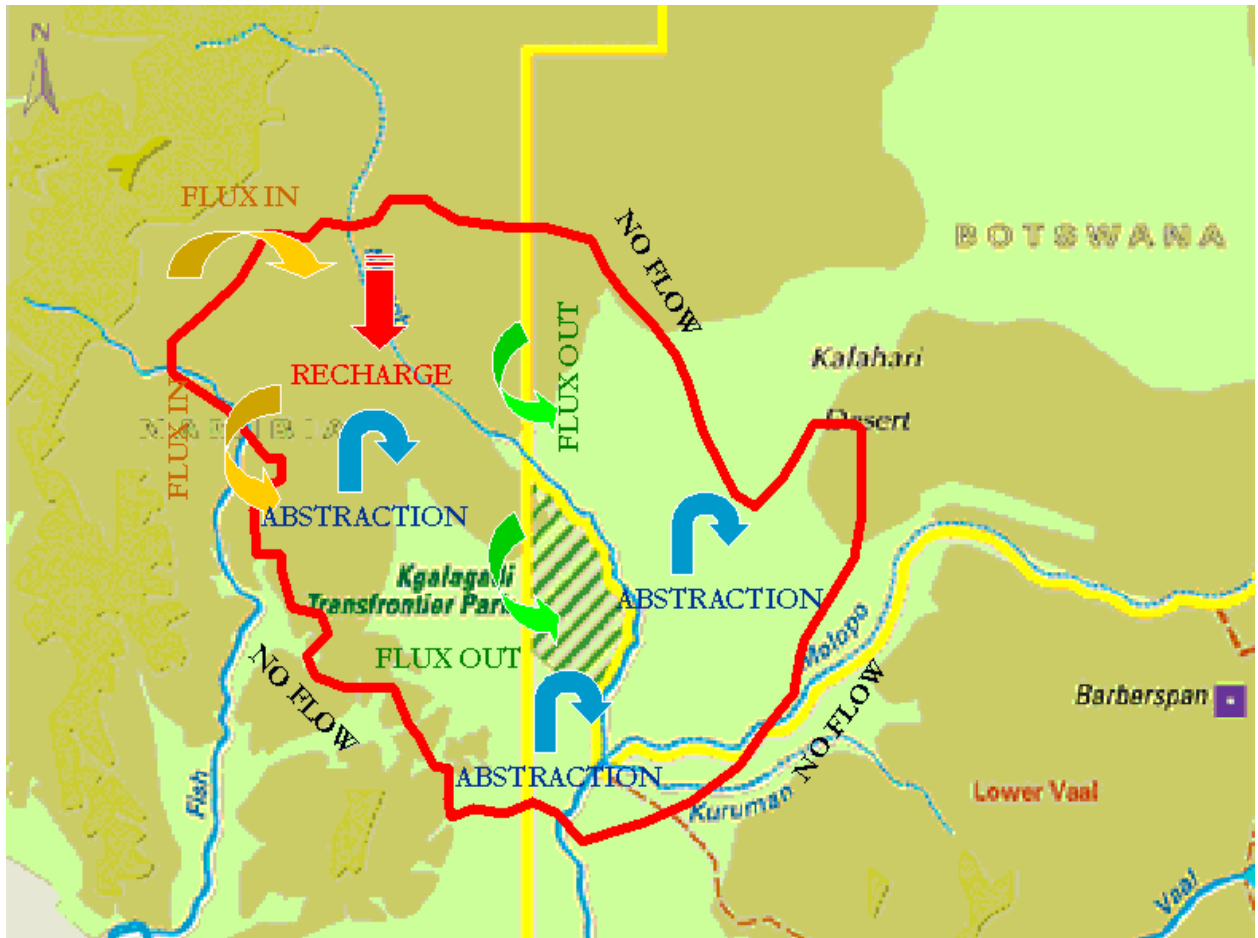


Figure 34: Overall conceptual model of the Auob aquifer system within the three member states.

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