3.10 Groundwater Recharge and Macro Water Balance

Water balance of the basin is generally presented as the following formula.

$$\mathrm{Pr} - Qs - R - Er = \Delta Sgr + \Delta Ssr$$

Pr: Precipitation in recharge area, Qs: Discharge of Surface flow,

R: Recharge, Er: Evapo-transpiration, △Sgr: Groundwater storage change

△ Ssr: Surface water storage change

3.10.1 Precipitation

The study area is situated in the downstream of both catchment areas, the Auob and the Nossob River. The areas of them are listed in the Table 3.10-1. The study area occupies approximately 70% of the whole catchment area.

Table 3.10-1 Catchment Areas

Unit: km^2

Catchment	Study	Upstream	Total
Auob	40,002	15,414	55,416
Nossob	29,576	17,410	46,986
Total	69,578	32,824	102,402

The precipitation in an ordinary year was estimated from annual average rainfall of past ten years at nine observation stations before 99-00 rainy season as shown in the Supporting Report Chapter 2. Fig.3.10-1 and Table 3.10-2 show the distribution of annual precipitation of the basin in an ordinary year. On the other hand, the precipitation volume in 99-00 rainy season, which was an extraordinary year in terms of rainfall volume and intensity in short period, is also calculated.

Table 3.10-2 Precipitation Volume in Ordinary Year and 99-00 Rainy Season

Unit: $10^9 m^3$/year

Catchment Area	Ordinary Year		99-'00 Rainy Season	
Upstream Area	7.8	(100%)	17.5	(224%)
Study Area	14.3	(100%)	33.8	(236%)
Total	22.1	(100%)	51.3	(232%)

The precipitation of the study area in an ordinary year is shown in Fig.3.10-2, whereas Fig.3.10-3 shows the heavy rain during Feb. and Mar. in 99-00 rainy season. Table3.10-2 summarize the two cases of precipitation volume in the study area and the upstream area. The table indicates that the precipitation volume in 99-00 rainy season was more than two times of an ordinary year.

3.10.2 Groundwater Recharge

1) Water Level Analysis

(1) Kalahari Aquifer

The average upturn of water level in 99-00 rainy season is recorded at 51cm in Olifantswater West and 254cm in Tugela. It is remarkable that the upturn of water table in Tugela is five times as large as Olifantswater. It can be assumed that J-3K and J-7K are regarded as the representation of the Kalahari Aquifer in Olifantswater West and Tugela respectively. The aquifer contents in Tugela are much better than Olifantswater West as shown in Table 8.6-2.

Table 3.10-3 Aquifer Constants of Kalahari Aquifer

Aquifer	Borehole No.	Specific Capacity (m^3/h/m)	Transmissibility (m^3/day/m)	Permeability (cm/sec)	Storage Coefficient
Kalahari	J3K (Olifantswater)	0.143	6.42	1.50E-04	1.00E-06
	J4K	0.018	0.135	7.74E-06	-
	J6K	0.145	6.23	1.40E-04	1.00E-05
	J7K (Tugela)	0.763	30	1.20E-03	2.00E-04
	J8K	0.016	0.132	5.10E-06	5.00E-03

This may be the main reason for the big difference between their upturns of the water table. It is also reflected the vegetation and geomorphology of the study area as shown in Fig. 3.10-3 and Fig. 2.1-1. These two figures are well related to one another. Tugela is located in "Dwarf Shrub Savanna" area that has scanty vegetation and outcropped bedrocks. The bedrocks have high potential of infiltration but poor ability of containing water within the unsaturated zone because of many cracks and sinkholes in it.

However, recharge in the sand dune area that has a vegetation comprising of Mixed Trees and Shrub Savanna or Camelthorn Savanna, is considerably low because water in the sand dune is easily released by transpiration before reaching the groundwater level.

The average drawdown rate of 5cm/year in the basin means that recharge in an ordinary year cannot even cover the water demand and hence reduce groundwater storage. Groundwater storage change volume (△Sgr) can be estimated as follows.

$\triangle$Sgr = Distribution Area of Kalahari Aquifer×Effective Porosity (5%)×Drawdown (5cm)

$= 5.26\times10^{10}\ m^2\times0.05\times0.05m=0.13\times10^9\ m^3$/year =$\underline{360{,}000m^3/day}$

On the contrary, recharge (R) might be more than the recovery of water level in an extraordinary year in terms of rainfall for example '99-'00 rainy season whose probability is one in 50 years. Suppose an average recovery of water level in whole study area is 50cm, water volume that is equivalent to the recovery can be calculated by the above-mentioned equation.

Recharge > Distribution Area of Kalahari Aquifer × Effective Porosity (5%)×Recovery (50cm)

$= 5.26\times10^{10}\ m^2\times0.05\times0.5m=1.3\times10^9\ m^3$/year =$\underline{3{,}600{,}000m^3/day}$

(2) Auob Aquifer

According to the hydrogeological structure of the Auob Aquifer as shown in Fig. 3.6-9, recharge is not possible by rainfall directly. However, recharge to the Auob Aquifer seems to be indirectly through the Kalahari Aquifer in the central area of the basin where the Kalahari Aquifer covers the Auob Aquifer directly without the Rietmond Member as impermeable layer. (Refer to Fig. 3.6-3, Fig. 3.6-9 to Fig. 3.6-12)

The quantitative analysis of the recharge for the Auob Aquifer based on water level observation is not clear and it is compelled to entrust the further study including analysis of monitoring data from JICA test boreholes. Regarding the recharge of the Auob Aquifer, it is considered as follows in this study.

- No direct recharge to the Auob Aquifer from precipitation. Recharge from the boundary of the basin is negligible.
- The central part of the Auob Aquifer, which is covered directly by the Kalahari Aquifer, is recharged through it indirectly. Response of water level by precipitation is considerably sensitive similar to the Kalahari Aquifer.
- In the place where the Rietmond Member separates the Kalahari and Auob Aquifer from each other, the response is slow and recharge is very low into the Auob Aquifer.

(3) Nossob Aquifer

According to the hydrogeological condition of the Nossob Aquifer as illustrated in Fig.3.6-9, there is no direct recharge from precipitation, thus the water can be regarded as fossil water.

2) Chloride Mass Balance Method

The basin can be recharged by precipitation. At first, the Kalahari Aquifer receives rainwater and it contributes to the Auob Aquifer indirectly. Then, "Chloride Mass Balance Method" (hereinafter referred as CMBM) was applied to estimate recharge volume.

The general equation of this method is as follows

$$R = \frac{(PCl_p + D)}{Cl_{gw}}$$

R: Recharge (mm/year)

P: Mean Annual Precipitation (mm/year)
Cl_p: Chloride concentration (mg/L) in rain
D: Dry chloride deposition (mg/m^2/year)
Cl_{gw}: Chloride concentration (mg/L) in groundwater.

The theoretical background of CMBM is that the total input of chloride by wet and dry atmospheric deposition would equal to the chloride output by transport through the unsaturated zone for a chloride mass balance under steady state conditions if the Kalahari Beds themselves do not produce any chloride.

Formulas, which are used for the inland of the Republic of South Africa; $Cl_p= 0.000002P^2+0.0003P+ 0.2207$, $D=0.1Cl_p$, are adopted in this study. Where, P is the mean annual precipitation (mm/year).

As to Cl_{gw}, the data of water quality, which approximately 300 samples were analysed during the study, are applied for this calculation. The calculations were taken place at every three-kilometre grids and the distribution of recharge intensity is drawn as Fig.3.10-4 and Fig.3.10-5.

(1) Recharge in Ordinary Year

The distribution of recharge in the ordinary year is subdivided northwestern half and southeastern half of the basin by 1 mm/year contour line of recharge. There are some spots that is more than 5mm/year in the former. Total recharge volume is 0.105 billion m^3 /year (288,000m^3/day) calculated by summing up recharge volume at every each grid. It is also equivalent to approximately 1.5 mm/year on average in the whole basin and 0.4% to the total rainfall in catchment area or 0.7% in the basin.

(2) Recharge in 99-00 Rainy Season

It is noticeable thing that recharge in the salt block area where is located southeastern area of the basin was less than 1 mm/year even if it was record-breaking heavy rainfall. In contradiction to this, the northwestern part of the basin received much water as the area recharged more than 5 or 10mm/year extended widely. The total recharge volume is calculated in this rainy season as 0.341 billion m^3/year (934,000m^3/day) which is more than three times as much as ordinary year. It is equivalent to 4.8mm/year or one percentage of the total rainfall.

3) Isotope Method

In this section, the rates of recharge per year in Kalahari Aquifer are estimated by characteristic of displacement of groundwater from metric water line.

According to Harmon Craig's founding (Craig H., 1961 Isotopic variation in meteoric waters,. *Science*,133:1720-1703), the relationship with $\delta^{18}O$ and $\delta^{2}H$ in fresh water correlates on a global scale, which is indicated by a profile in Fig.3.10-1. The Local Metric Water Line (LMWL) is based on the evaporation of local surface water in a certain local place. The groundwater samples in Kalahari show the correlation between the ^{18}O and ^{2}H composition, which plot in Fig. 3.10-1 and not parallel to the LMWL. The lower slope of the $\delta^{18}O$ and $\delta^{2}H$ relationship implies degree of the dry. This indicates groundwater in Kalahari exists in dry condition than LMWL do. Consequently, the groundwater in Kalahari is displaced further from the local meteoric water line. It is considered that during extensive evaporation from the unsaturated zone, kinetic effects by vapour diffusion are greater than those associated with evaporation from open surface. Evaporation from an open surface in a local place causes a non equilibrium enrichment in the residual water. This is due to the difference in gaseous diffusion rates for ^{18}O and ^{2}H through the thin boundary layer of 100% humidity above the water surface. Comparing to LMWL, the layer in Kalahari would be as much thicker and can dramatically increase kinetic evaporation effects. Therefore, the slope of the $\delta^{18}O$ and $\delta^{2}H$ relationship is lower than the range for evaporation from open water surface.

This characteristic can be explained by the concept of displace of groundwater from

LMWL which Allison et al. (1984) developed.

It showed that groundwater recharged under conditions of direct infiltration often possibly indicate the result like the samples in Kalahari. This is due to the mixing that occurred between the evaporated soil moisture and a subsequent rain that infiltrates and displaces the residual soil water downward. Ultimately, this mixed parcel of water will reach the water table. If the recharge conditions remain relatively uniform over time, groundwater should follow a line parcel to but displaced from local meteoric water line. Therefore, the displacement of groundwater from the meteoric water line offers a crude estimate of recharge. In other words, for high rates of recharge, evaporate enrichment is minimal, whereas for low recharge rates, a large displacement for groundwater will be seen.

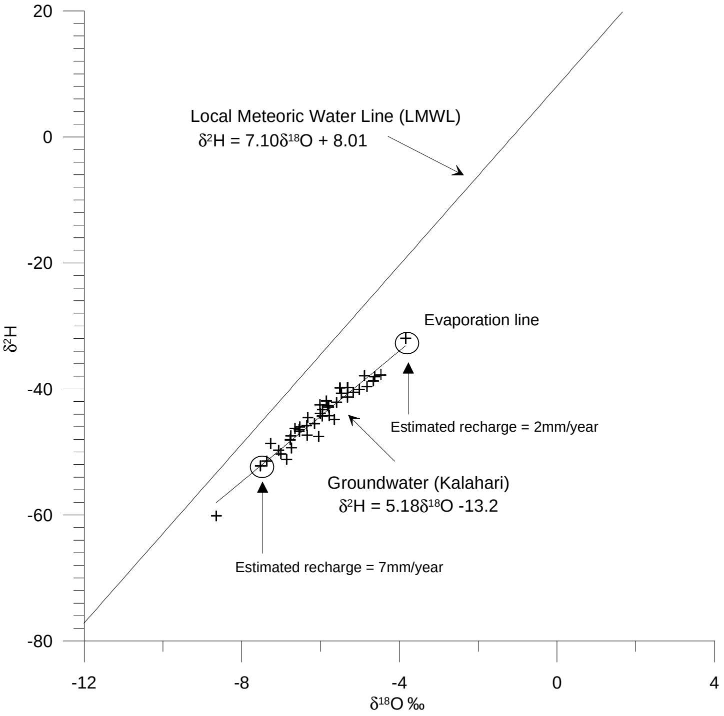


Fig.3.10-1 Evaporation Line of Groundwater in Kalahari Aquifer

Allison et al. (1983) give the empirical relationships:

$$\delta\ 2Hshif = 22/\sqrt{recharge(mm/yr)}$$

By using the above equation, the rates of recharge in Kalahari Aquifer tried to be calculated (see Fig 3.10-1). Accordingly, the result shows the recharge rates in Kalahari range approximately between 2 and 7 mm/year. These values support the estimation of recharge by CMBM in the ordinary year.

3.10. 3 Withdrawal of Groundwater

Intensity of withdrawal from each aquifer in 1999 is presented in Fig.3.10-7. According to the total withdrawal intensity form all aquifers, it concentrates in and around Stampriet where goes in to approximately 60km squared area.

3.10.4 River Discharge

River discharge out of the basin or catchment area is also difficult to estimate because of lacking actual observation data. Since it is inevitable item for the water balance, the data in page 14 in Chapter 2 was applied to estimate it. Based on the data, specific discharge of the Auob River and the Nossob River is estimated to be $328m^3/km^2$ and $472m^3/km^2$ respectively. Therefore, the river discharge in the ordinary year is estimated as follows.

$$Qs=55,416km^2 \times 472m^3/km^2 + 46,986km^2 \times 328m3/km^2 = 4.16 \times 107m^3$$

As to ‘99 -’00 rainy season, the river discharge at Gochas station was recorded 43 million m3 as following table that is approximately 4.6 times compared with the ordinary year. On the assumption that this value is applicable to other catchment area, the river discharge in this season is regarded as $19.14 \times 107m^3$.

Table 3.10-4 Observation Results of Auob River Discharge in 99-00 Rainy Season

Unit: million m^3

Station	Dec. '99	Jan.'00	Feb.'00	Mar.'00	Apr.'00	Total
Gochas	0.12	1.35	8.13	26.49	6.72	42.81
Stampriet	0.43	7.9	10.88	-	-	19.21

Source: DWA

3.10.5 Groundwater Discharge

Directions of groundwater flow in three aquifers are generally northeast to southeast. Outflow volume of groundwater toward outside of the basin is calculated as follows.

$Qd = KiA$ Qd : Groundwater discharge (m^3/day)

K : Permeability (cm/sec)

i : Gradient of piezometric head

A: Cross section area (km^2)

The total outflow of groundwater is estimated as approximately $7,000m^3$/day as shown Table 3.10-5.

Table 3.10-5 Outflow of Groundwater

Aquifer Type	Permeability K (cm/sec)	Gradient of Piezometric Head I	Area of Aquifer Cross Section S (km^2)	Outflow of Groundwater Q (m^3/day)
Kalahari Aq.	1.00E-07	1.31E-03	17.07	**193**
Auob Aq.	3.30E-06	1.42E-03	16.77	**6,790**
Nossob Aq.	8.80E-09	8.50E-04	2.74	**2**
Total	-	-	-	**6,985**

3.10.6 Evapo-transpiration

Since the potential of evaporation in the study area is more than 3,000mm/year as illustrated in Fig.2.3-2, it seems that almost of annual precipitation, which is 200mm/year to 300mm/year, is consumed by evaporation. According to the potential of evaporation, it is no wonder that an entire precipitation in the basin is disappeared under the most appropriate conditions for evaporation.

Though actual pouring rain generally occurs within a few days and some amount of rainfall reaches to the groundwater table under the cool and humid conditions, almost all of recharged water is lost again to the air by transpiration. Then the real chance of recharge seems to be so much limited. As evaporation and transpiration are almost impossible to calculate, the remains in water balance analysis are regarded as them in this study.

3.10.7 Macro Water Balance in the Basin

On the basis of above-mentioned analysis, macro water balance in the study area is illustrated in Fig. 3.10-8 to Fig. 3.10-10. The whole river catchment area, which consists of the Auob river catchment and the Nossob river catchment, is dealt with this macro water balance because it is necessary to consider the river discharge in the balance.

The macro water balance is analysed on two cases, namely, ordinary year and ’99 – ’00 rainy season, moreover each case is subdivided into underground and ground for the sake of convenience.

1) Ordinary Year

(1) Underground

Recharge is only 0.4% (0.105 billion m^3/year) of the total precipitation (22.1 billion m^3/year) or 0.7% of the precipitation in the study area. Withdrawal is only 0.1% (0.015 billion m^3/y) of the precipitation in the study area or 14.3% of the total recharge.

On the other hand, transpiration is almost two times of recharge and a shortage of water balance, which equals to recharge (0.13 billion m^3/year) is covered by the reduction of groundwater storage. Therefore, water level draws down year by year.

(2) Ground

On the ground, river discharge is 114,000m^3/day (0.042 billion m^3/year) or 0.2% of rainfall and 0.4% of rainfall percolates into underground. Yet more than 99% of it disappears by evaporation. According to the evaporation of Namibia as shown in Fig.2.1-2, the potential of evaporation 3,000mm/year suggests that it sounds quite possible.

2) 1/50 Heavy Rain Year ('99-'00 rainy season)

The possibility of the heavy rain which happened during '99-'00 rainy season is one in fifty years. The heavy rain changed the groundwater balance of the basin dramatically. The recharge by the rain stopped not only drawdown of groundwater table but also raised it.

Two cases of the macro balance for the year is studied as follows.

i) Case-1

Recharge in '99-'00 rainy season, which is estimated by CMBM, is adopted in this case.

(i) Underground

The recharge, 0.341 billion m^3/year into the basin is equivalent to 0.7% of the total precipitation, 51.3 billon m^3/year in the whole catchment area or 1.0% of the precipitation, 33.8 billion m^3/year in the basin. The recharge became approximately 3.2 times as much as the ordinary year caused by 2.3 times of precipitation volume.

Assuming that transpiration and groundwater outflow are same as the ordinary year, approximately 31% of recharge contributes to the groundwater storage in the basin.

As a result of the recharge, the water table of the Kalahari Aquifer comes up 4cm in average as shown in Fig. 3.10-9.

(ii) Ground

The heavy rain in ’99-’00 rainy season brought about river discharge at Gochas 4.7 times as much as the ordinary year and recharged into underground 3.2 times as much as the year. Then, the remains 99.2% of precipitation came back to the air by evaporation.

ii) Case-2

The water table of the Kalahari Aquifer rose up approximately 50cm on average in the basin based on the results of DWA’s observation boreholes.

Supposing the transpiration, withdrawal and groundwater flow are likewise the ordinary year, the recharge is equivalent to 4.5 times of Case-1 and approximately 15 times of the ordinary year.

Though the recharge of Case-1 is harmonized with the result by the isotope method, 4cm water table rise is too small than observation results. On the other hand, the recharge in Case-2 supports groundwater simulation model. It seems that the result of isotope method don’t cover extraordinary year as ’99-’00 rainy season but mainly ordinary or average year’s condition. After all, it can be concluded that Case-2 is better for water balance in ’99-’00 rainy season so far.

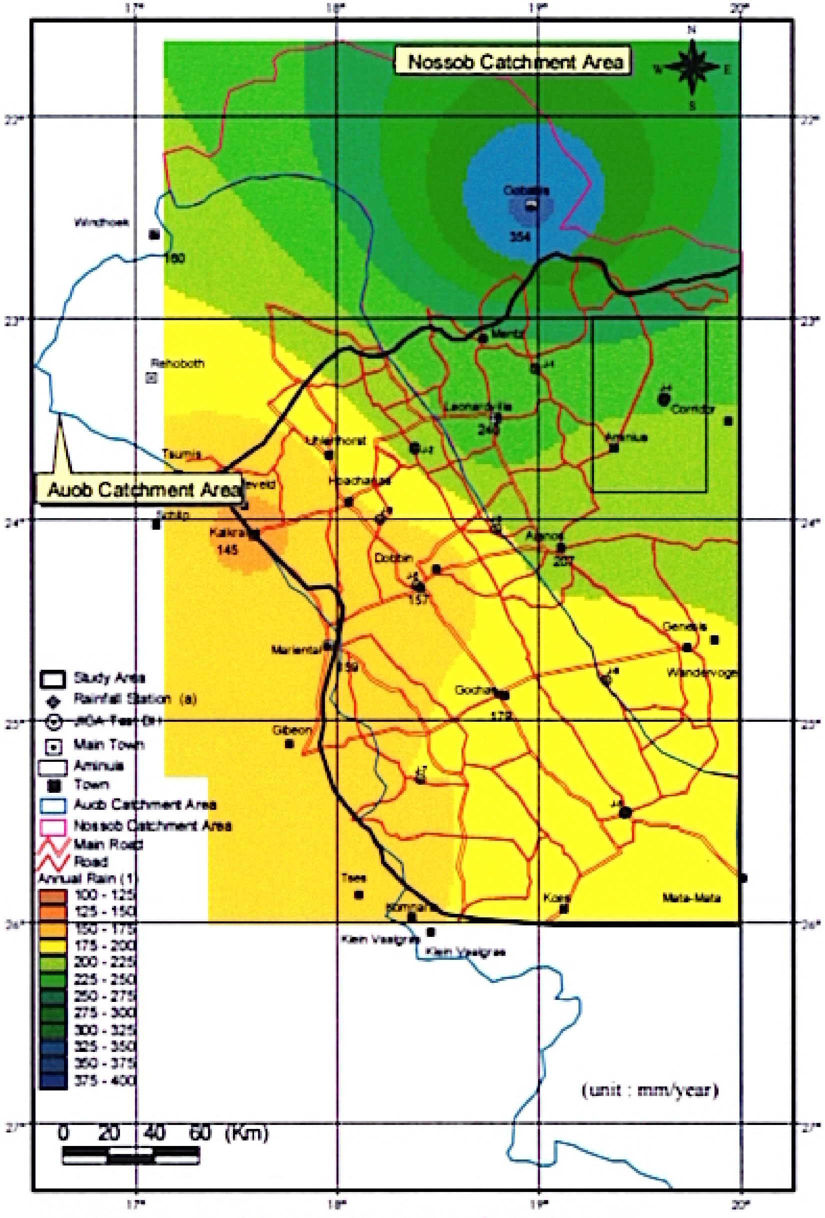


Fig. 3. 10-2 Precipitation of Study Area in Ordinary Year

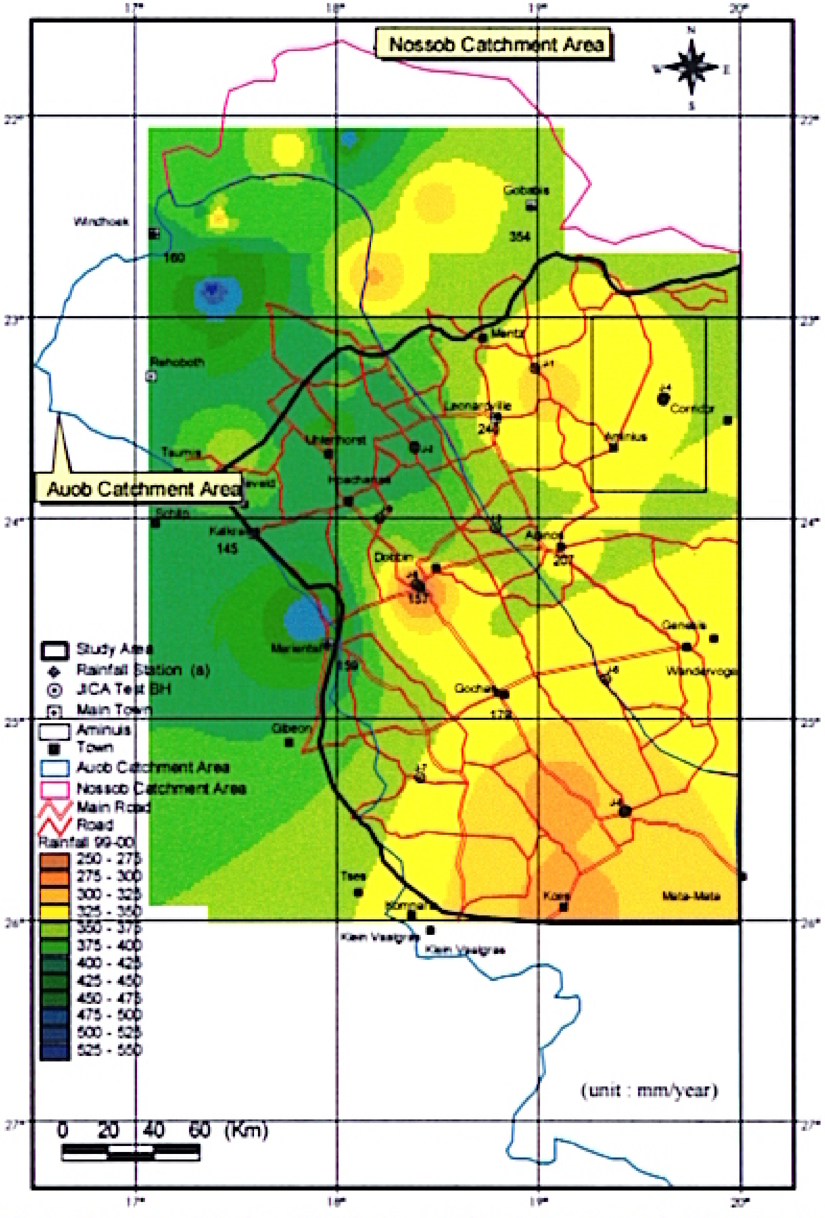
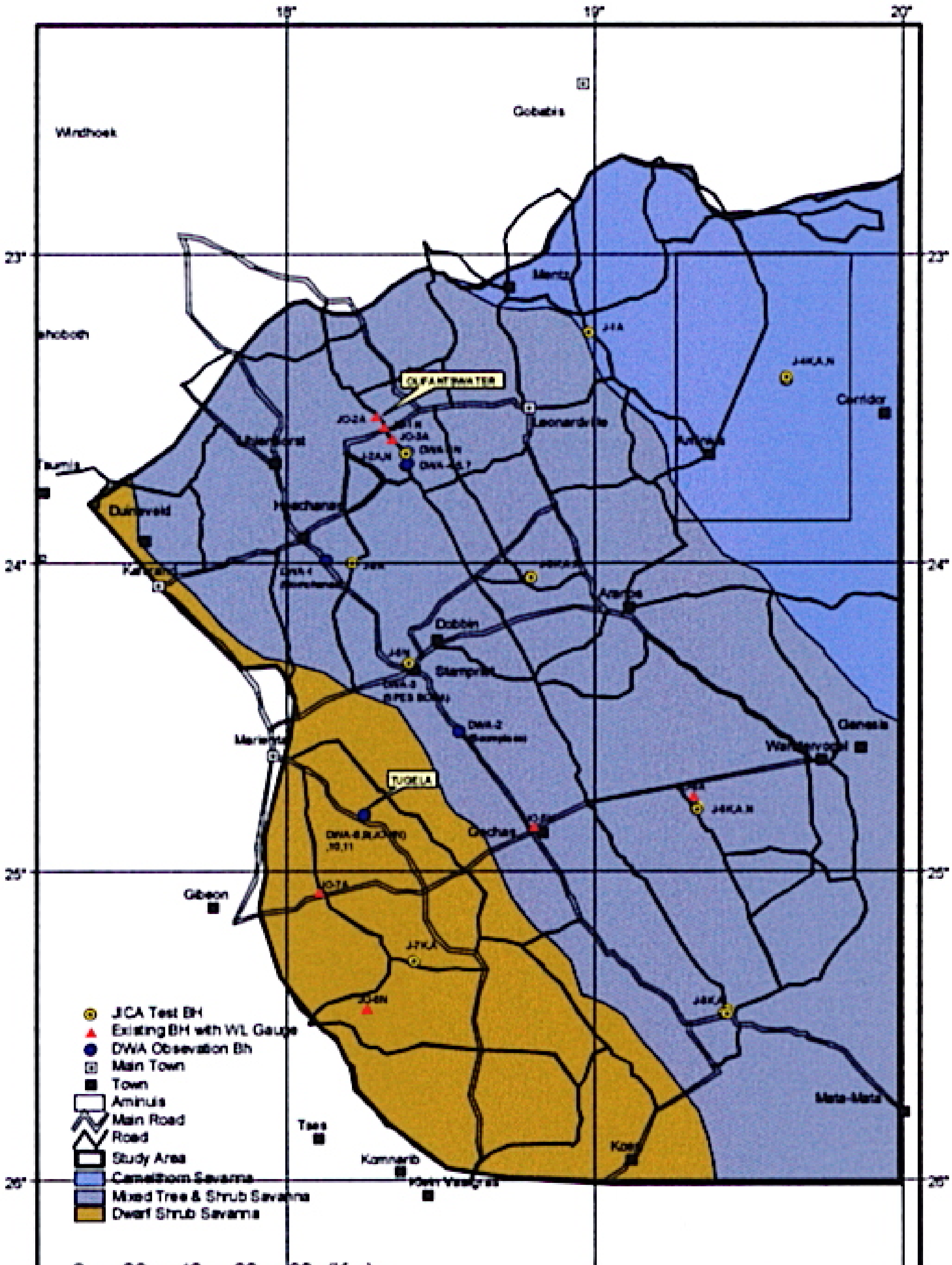


Fig. 3. 10-3 Precipitation of Study Area during Feb. and Mar. in '99-00' Rainy Season



Source; W.Giess, 1970 "Vegetation Map of South West Africa" (1/3,000,000)

Fig.3.10-4 Vegetation Map of Study Area in 1999

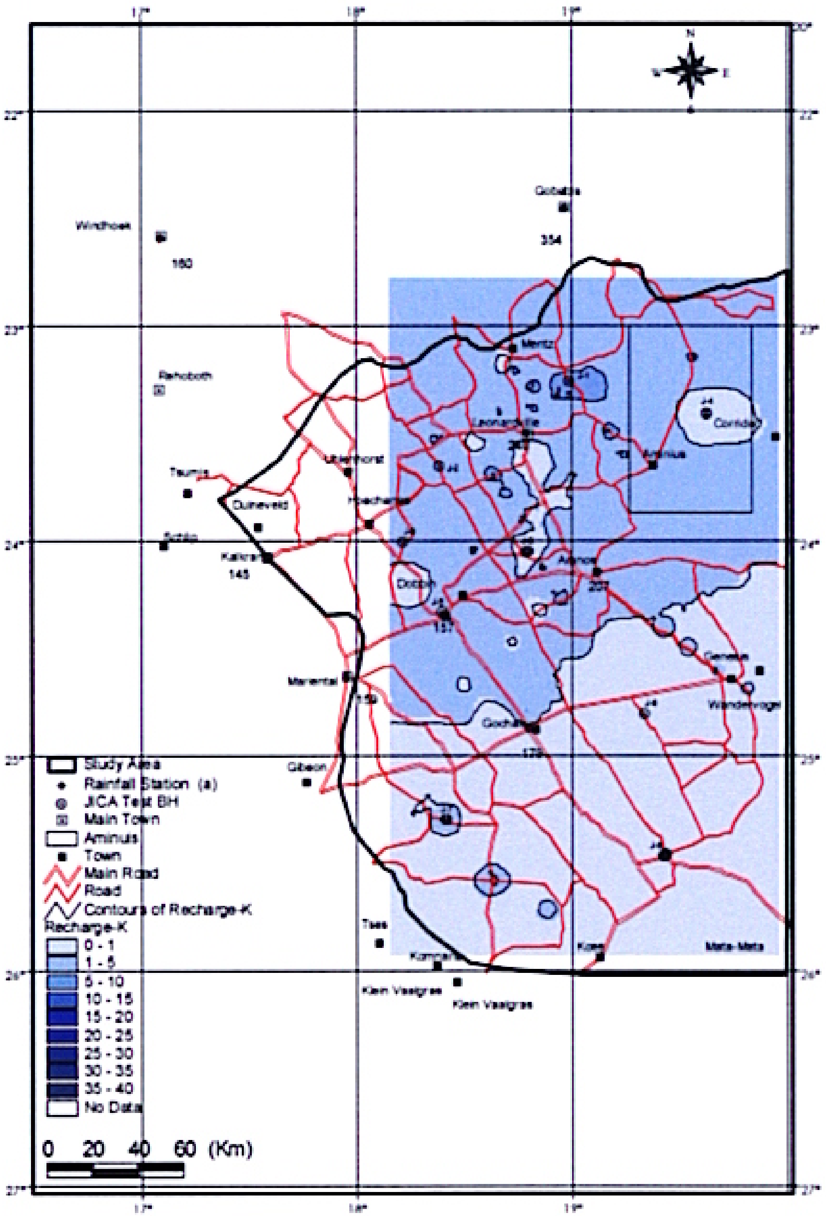


Fig. 3.10-5 Recharge of Kalahari Aquifer in Ordinary Year by CDBM

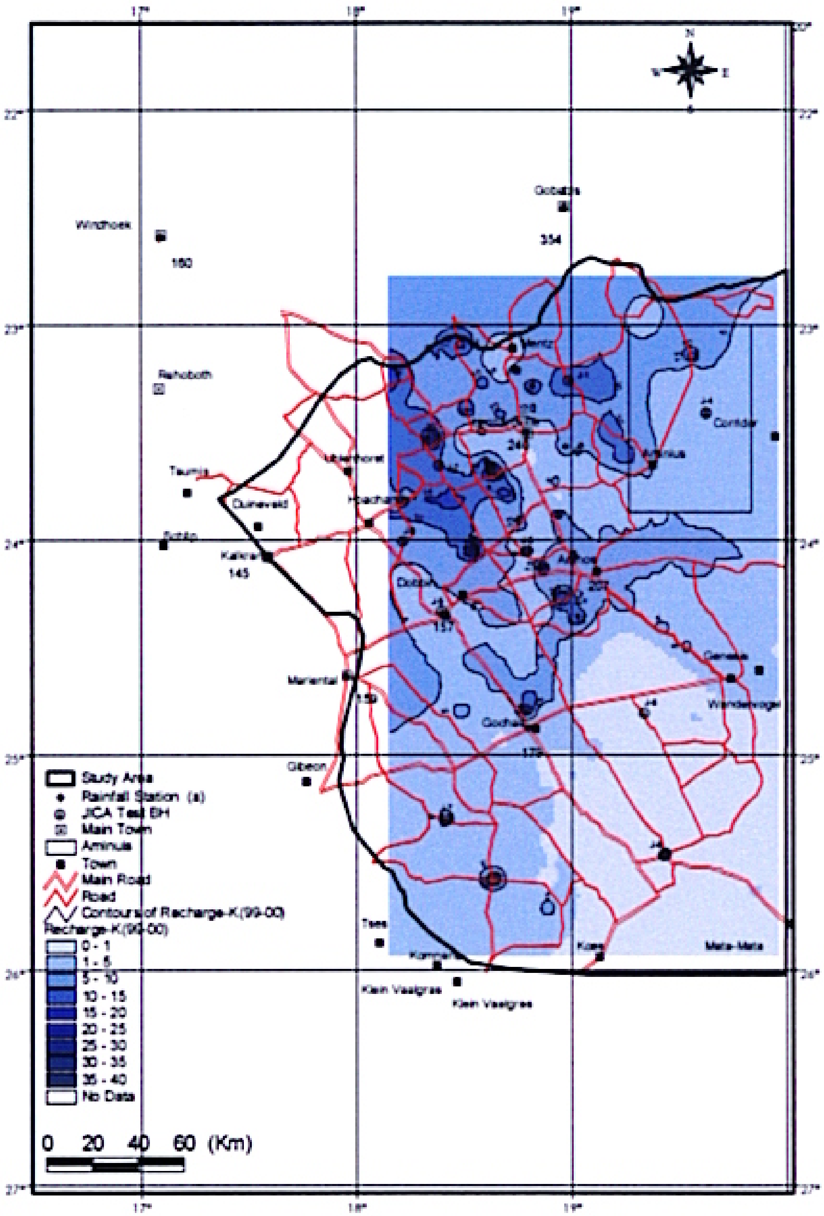


Fig. 3.10-6 Recharge of Kalahari Aquifer in '99-00 Rainy Season Year by CDBM