The Impact Of The 1997 Flood Events In The Lower Kuiseb River On The Recharge To The Lower Kuiseb Aquifers.

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1. INTRODUCTION

The Lower Kuiseb Aquifers, comprising Swartbank, Rooibank A and B and Dorop South are currently being over-utilised to supply in the demand of consumers in the Central Namib Area, particularly Walvis Bay and Swakopmund.

Rainfall distribution and intensity during the 1996/97 rainy season resulted in substantial flooding in the Kuiseb River. The localities of the Kuiseb Aquifers are illustrated in Figure 3 in Annexe 1.

The aquifers are exclusively dependent on surface runoff for any level of recharge and it was considered important to assess the recharge of the Lower Kuiseb Aquifers as results of the floods that occurred during the 1996/97 rainy season. Furthermore, until such time that the proposed desalination plant is completed and operational, groundwater resources will remain the sole source of water supply to the major coastal clients. It is thus for management purposes equally important to assess the recharge event in terms of change in abstractable reserves and borehole supply capabilities.

A water balance study on the Kuiseb Delta Aquifer was conducted to determine the recharge that took place during the recent floods in 1997. The inverse modelling technique was used to calculate aquifer parameters and recharge to the Kuiseb Delta Aquifer. An estimate of the net recharge to the aquifer following the 1997 flood event was calculated. Recharge to the upstream Swartbank/Rooibank A Aquifer was calculated from the GEOSEC alluvial reserve program.

This report summarises the effect of the 1997 floods on the water levels and abstractable reserves in the lower Kuiseb Aquifers and the methods used to calculate the recharge that took place in these aquifers. Estimates on recharge from runoff in 1997 are discussed in this report.

2. GROUNDWATER RECHARGE FOR THE SWARTBANK/ROOIBANK A AQUIFER

2.1 Hydrological and Geohydrological Regimes

Rainfall in the Walvis Bay area is on average 12 mm per annum which means that the only mechanism of recharge to the Kuiseb River Aquifers is through surface flow and subsurface base flow in the Kuiseb River.

Water is abstracted from the Dorop South, Rooibank B, Rooibank A and Swartbank well fields. Dorop South and Rooibank B together form part of the Kuiseb Delta Aquifer whilst the Swartbank/Rooibank A Aquifer is situated just upstream from the Delta Aquifer.
Between 1995 and 1997, an average of 3.62 Mm$^3$/annum was abstracted from the Kuiseb Delta Aquifer and about 4.72 Mm$^3$/annum from the Rooibank A and Swartbank well fields. Water levels have progressively been drawn down at Dorop South, Rooibank B, Rooibank A and Swartbank because of abstraction exceeding recharge from runoff.

Recharge to the Kuiseb aquifers is predominantly from runoff events and some subsurface through flow. A good indication of recharge to the aquifers is based on the estimated runoff losses that occur over the whole aquifer domain. Currently surface runoff events in the Lower Kuiseb River are monitored at Gobabeb and Rooibank gauging stations only. The Swartbank gauging station is not suitably equipped and calibrated with the result that only extrapolated runoff figures could be applied here. Hydrological statistics on the return period of the 1996/97 flood is summarised in Annexe 4.

2.2 Comparison between abstraction and abstractable reserves for the Swartbank/Rooibank A aquifer

The average drop in the regional water table over the Swartbank/Rooibank A aquifer for the period between June 1986 to December 1996 is approximately 4.7 m. The hydrographs of some monitoring boreholes in the Swartbank/Rooibank Aquifer are illustrated in Figure 6 in Annexe 2. The decrease in abstractable reserves over this period amounts to 17 Mm$^3$. A comparison between change in abstractable reserves and change in average regional water level is illustrated in Figure 1 below.

At the end of December 1996 the combined estimated abstractable reserves for the Swartbank/Rooibank A aquifer was 34.6 Mm$^3$. The GEOSEC computer program was used for the calculations of the volume of abstractable reserves. Of the total stored reserves calculated, non-abstractable reserves and dead storage for the aquifer amounts to an additional 56.89 Mm$^3$ due to the distribution of the production boreholes and current understanding of the aquifer.

The total combined abstraction for the Rooibank A and Swartbank well fields over the period January to December 1997 amounts to 4.47 Mm$^3$.

The effect of the 1997 floods on the average water levels and abstractable reserves are also illustrated in Figure 1 on page 2. The average rise in the water level over the Swartbank/Rooibank A aquifer at the end of 1997, was 2.23 m. According to GEOSEC calculations the abstractable reserves of this aquifer compartment increased by 10.57 Mm$^3$ to 42.16 Mm$^3$ at the end of December 1997.

Delayed recharge to the aquifer was observed after the floods, presumably due to the extensive intercalated silt deposits found in the upper parts of the alluvium. These silt layers were deposited during previous floods. Due to the semi-confined conditions created by these silt layers, a lag time for infiltration of up to 6 months was observed, in accordance with previous runoff/recharge events observed.
2.3 Calculation of recharge at Swartbank and Rooibank A using runoff, changes in abstractable reserves and abstraction

During the flood events in early 1997, runoff was recorded at both the Gobabeb and Rooibank gauging stations. Unfortunately runoff figures at the Swartbank gauging station were lost due to mainly logistic problems experienced in the Department of Water Affairs who are responsible for such monitoring. An extrapolated estimation from the recordings at the Gobabeb and Rooibank gauging stations were made for the Swartbank station.

The runoff and runoff losses recorded and extrapolated between Gobabeb, Swartbank and Rooibank gauging stations are summarised in Table 1 below. Runoff losses calculated between the Gobabeb-Swartbank and Swartbank-Rooibank gauging stations are also summarised in Table 1 below.

Table 1: Runoff and runoff losses between the Gobabeb, Swartbank and Rooibank Gauging Stations

<table>
<thead>
<tr>
<th>Month</th>
<th>Estimated Flows in Mm$^3$</th>
<th>Flood Losses in Mm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gobabeb</td>
<td>Swartbank</td>
</tr>
<tr>
<td>Jan '97</td>
<td>30.38</td>
<td>*23.40</td>
</tr>
<tr>
<td>Feb '97</td>
<td>21.88</td>
<td>*11.59</td>
</tr>
<tr>
<td>Mar '97</td>
<td>15.64</td>
<td>*8.29</td>
</tr>
<tr>
<td>TOTAL</td>
<td>67.9</td>
<td>*43.28</td>
</tr>
</tbody>
</table>

* Extrapolated value

For practical consideration, the Swartbank station constitutes the upstream boundary and the Rooibank gauging station the downstream boundary of the Swartbank/Rooibank Aquifer. Flood losses over the aquifer domain can partly be ascribed to infiltration that occurred over the aquifer during the event.

The calculated flood losses between the Swartbank gauging station and the Rooibank gauging station constituting the Swartbank/Rooibank Aquifer, amounts to an estimated 22.12 Mm$^3$ (51% of the total flood volume extrapolated at the Swartbank gauging station). The average flood loss calculated between the Gobabeb and Swartbank gauging stations amounts to 36% of the flood measured at Gobabeb.

The processes and factors contributing to flood loss in a river system can be formulated as follows:

\[
\text{Flood Loss} = \text{Infiltration Volume} + \text{Evapotranspiration} + \text{Evaporation} + \text{Base Flow losses}
\]

Abstraction from the Swartbank and Rooibank A well fields for 1997 amounts to a total of 4,47 Mm$^3$ where the change in abstractable reserves in the Swartbank/Rooibank A aquifer over the same period (January to December 1997) amounts to an increase of 10.57 Mm$^3$, calculated from water level observations in monitoring boreholes. Taking only abstraction and change in
abstractable reserves into account, an estimation of recharge to the aquifer can be calculated.

**Table 2** below summarises the abstraction, the volume of change in abstractable reserves and the estimated recharge for the Swartbank and Rooibank A aquifer for 1997.

**Table 2: Infiltration in the Swartbank and Rooibank A Aquifer (January 1997 - December 1997)**

<table>
<thead>
<tr>
<th>YEAR</th>
<th>1997 SWARTBANK Production (m³)</th>
<th>1997 ROOIBANK A Production (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
<td>216 612</td>
<td>108 065</td>
</tr>
<tr>
<td>FEB</td>
<td>264 996</td>
<td>150 065</td>
</tr>
<tr>
<td>MAR</td>
<td>214 839</td>
<td>145 630</td>
</tr>
<tr>
<td>APR</td>
<td>280 934</td>
<td>129 869</td>
</tr>
<tr>
<td>MAY</td>
<td>248 792</td>
<td>125 915</td>
</tr>
<tr>
<td>JUN</td>
<td>398 763</td>
<td>133 433</td>
</tr>
<tr>
<td>JUL</td>
<td>364 120</td>
<td>114 636</td>
</tr>
<tr>
<td>AUG</td>
<td>228 983</td>
<td>120 415</td>
</tr>
<tr>
<td>SEP</td>
<td>136 221</td>
<td>127 585</td>
</tr>
<tr>
<td>OCT</td>
<td>251 354</td>
<td>114 981</td>
</tr>
<tr>
<td>NOV</td>
<td>180 731</td>
<td>118 421</td>
</tr>
<tr>
<td>DEC</td>
<td>180 059</td>
<td>117 000</td>
</tr>
<tr>
<td>SUB TOTAL</td>
<td>2 866 404</td>
<td>1 505 950</td>
</tr>
</tbody>
</table>

Total abstraction - Aquifer = 4 472 354 m³ (A)

Combined Change in Abstractable Reserves Jan '97 - Dec '97 = +7 780 000 m³ + 2 780 000 m³

Change in Abstractable Reserves Jan '97 - Dec '97 - Aquifer = +10 570 000 m³ (B)

Total Recarge (A)+(B) Jan '97 - Dec '97 - Aquifer = 15 042 354 m³

From **Table 2** on page 4, the total recharge from runoff (taking only production and change in abstractable reserves into account) amounts to a total estimate of 15 Mm³ from the 1997 flood events.

This implicates that 68 % of the runoff loss between Swartbank and Rooibank gauging stations infiltrated into the aquifer. The difference (32 %) is lost to evaporation, evapotranspiration and water loss from the aquifer to the dune aquifer by means of subsurface base flow.

In his calculations, Blom (1978) calculated an evapotranspiration of 27 % of the total runoff loss in the 1975/76 flood between Gobabeb and Rooibank.

Taking this percentage into account for the total loss over Swartbank and Rooibank A, a total loss of 5.94 Mm³ can be ascribed to evapotranspiration. This means that the remaining 1.02 Mm³ can probably be ascribed to partly evaporation and base flow loss into the dune aquifer to the west.

A total water balance can then be calculated for runoff losses:
Thus: Runoff Loss = Infiltration Volume + ET + (Evaporation + Base flow losses)

= 15.042 Mm$^3$ + 5.94 Mm$^3$ + (1.02 Mm$^3$)

= 22 Mm$^3$

For the alluvial reserve calculation (GEOSEC) exercise, no inflow into or outflow out of the aquifer was taken into account (inflow = outflow = 0).

3. GROUNDWATER RECHARGE CALCULATIONS FOR THE KUISEB DELTA AQUIFER

3.1 Geohydrological Conceptualisation of the Kuiseb Delta Aquifer

Downstream from Rooibank, the Kuiseb Riverbed widens rapidly to form an extensive delta underlain by the so-called Kuiseb Delta Aquifer. Figure 4 in Annexe 1 gives reference to the diagrammatic conceptualisation of the Kuiseb Delta Aquifers.

The Kuiseb Delta Aquifer is divided into the following areas:

1. The Dorop South Area
2. Dorop North Area
3. Rooibank B Abstraction Area
4. Kuiseb Channel Aquifer

To delineate the aquifer domain, the following boundaries have been taken as the contact between the fresh water aquifer and any of the following (Refer to Figure 4 Annexe 1):

- saline water aquifer - to the west
- bedrock and bedrock highs
- underlying clay and/or clay gravel deposits
- fresh water level

The following points should be noted from Figure 4:

⇒ the aquifer is the thickest in the two zones adjacent to the western contact with the saline wedge. These two zones are the most favourable with the highest transmissivity and storativity values and are referred to as Dorop North and Dorop South accordingly. A zone of lower transmissivity
representing an area composed of extensive silts separates these areas from each other.

⇒ bedrock highs protrude through the aquifer south and east of the present B-abstraction Area.

⇒ The narrow strip of aquifer called the Kuiseb Channel Aquifer, which extends from the A-Area to the Delta is located predominantly south of the present main river channel. There is no aquifer linking the northern limb of the Kuiseb River with the main Kuiseb Channel Aquifer. To the west a zone of low transmissivity values and bedrock highs partly separates the Kuiseb Channel Aquifer from the rest of the Delta Aquifer.

The Delta Aquifer composes predominantly of aeolian sand with extensive intercalation of impermeable fluvial silts. Occasional lenses of coarser grained fluvial sands and grits are encountered throughout most of the Delta Area. The aquifer materials and depositional environment constitute semi-confined groundwater flow conditions.

The conceptualised model as described above was used to construct the aquifer domain used in the groundwater model (See Figure 5 in Annexe 1). For modelling purposes the following boundaries were used:

- A no-flow boundary - it was assumed that the aquifer is bordered in the east by bedrock to confine the eastern extent.
- A constant head boundary - constituting the sea/fresh water interface that forms the western extent of the fresh water aquifer.

Groundwater flow in the Delta Aquifer was calculated to be predominantly from east to west.

### 3.2 Geohydrological Regime

The volume of the saturated fresh water Delta aquifer was calculated by Wiegmans (1991) to be 3,611 Mm$^3$. It is important to note that only 8% of the saturated fresh aquifer (44 Mm$^3$) is located above sea level in an aquifer which is in hydraulic continuity with moderately saline water towards the coast. Any lowering of the water level on the saline fresh water interface will induce movement of saline water toward the current Dorop South well field. The hydrographs illustrating water level fluctuations in the Kuiseb Delta Aquifer are illustrated in Figure 6 in Annexe 2.

Figure 2 below illustrates the average change in water levels over the Dorop South and Rooibank B well fields since 1993. An increase in the average water levels is observed during and after the floods. It should be noted that during the floods the pipeline at Dorop South washed away and as a result abstraction was temporarily terminated for a period of 3 months. During this period abstraction from Rooibank B was increased. This scenario is also reflected in the water levels as indicated in Figure 2. Whereas Dorop South showed a full recovery, Rooibank B experienced a relatively minor recovery due to increased abstraction to meet the demand.
A total of 5.26 Mm$^3$ was abstracted from the Dorop South well field since 1993. The water level in the monitoring boreholes of the Dorop South well field dropped by an average of 0.5 m between 1993 and December 1996 (before the floods). The water levels in Rooibank B well fields dropped by an average 1.61 m over the same period and abstraction from this well field over this period of time amounts to 5.18 Mm$^3$.

As a result of the flood events in the beginning of 1997, the water levels at Dorop South increased by an average of 0.41 m and at the Rooibank B well fields, the water level increased by an average 0.51 m (See Figure 2 below).

3.3 Recharge calculations from modelling results

A numerical finite element groundwater model, using the Aquamod computer modelling programme, was constructed for the Kuiseb Delta Aquifer to calculate aquifer parameters and recharge that took place to the aquifer during the 1997 flood events.

Estimation and verification of the aquifer parameters were carried out by making use of the inverse modelling technique. With the inverse modelling technique, dependent variables are used as input to estimate the independent model parameters. In this case the dependent variables, namely groundwater levels are used to estimate the independent variables, namely transmissivity (T) and storativity (S) values.

A finite element grid was constructed for the aquifer domain and was used for the inverse flow model (See Figure 5 in Annexe 1). Water level recordings from 11 monitoring boreholes situated in both the Dorop South and Rooibank B well fields were used for the calibration of the model. Due to the heterogeneous nature of the aquifer, the model domain was subdivided into 9 zones of different transmissivity and storativity. Water level recordings from January 1994 to December 1996 were used for the calibration of the model due to the fact that recharge from runoff events were insignificant during this period.

3.4 Discussion of modelling results

After calibrating the model, the optimum solution for the parameters yielded values for transmissivity (T) ranging between 15 - 410 m$^2$/day (average of 147 m$^2$/day) and values for specific yield (S) ranging between 13 - 25 % (average of 16.5%).

The calculated aquifer parameters compares well with the parameters calculated by Bush (1991) for the Kuiseb Delta Aquifer. Bush (1991) calculated a transmissivity (T) of between 0 and 440 m$^2$/day and an average specific yield (S) of 15%. These calculations were made from limited aquifer
testing and sedimentological information obtained during the drilling of the boreholes.

The comparison between the actual and the simulated water levels with the optimum calculated parameters is illustrated in Figure 7 in Annexe 2. The simulated water level over the aquifer domain at the end of 1996 is illustrated in Figure 8 in Annexe 3.

The average recharge from base flow and to some extent from runoff events from 1994 to 1996 was calculated during calibration as 0.99 Mm$^3$/annum. This means that the safe yield of the aquifer (Dorop South and Rooibank B areas) in a time of minimum or no recharge from surface flow is, 0.99 Mm$^3$/annum as opposed to 2.0 Mm$^3$/annum for the long term sustainable yield which includes periodic recharge events.

After calibrating the aquifer parameters, recharge was incorporated into the model and a water balance was calculated for 1997 after the flooding of the Kuiseb Delta. From the simulated results, the calculated minimum volume of water recharged to the aquifer from runoff is estimated at 5.6 Mm$^3$. The total recorded volume of water passing the Rooibank gauging station into the Kuiseb Delta region is estimated at 21 Mm$^3$ (See Table 1 on page 3). This means that an estimated recharge of 27% from runoff occurred into the Kuiseb Delta aquifer in the vicinity of the Dorop South and Rooibank B well fields. During modelling, recharge was only calculated for the part of the aquifer where an adequate amount of monitoring boreholes are encountered.

Evaporation in the Kuiseb Delta over the period of the flood and after amounts to an estimated 3.5 Mm$^3$ or 16.6% of the total runoff. The implications of these results are that a 56.4% water loss is calculated. This amounts to a loss of 11.8 Mm$^3$ of runoff water.

Only a small percentage of runoff loss can be ascribed to evapotranspiration. Another possible explanation for the runoff loss can be associated with recharge that took place to the Dorop North Aquifer and the Kuiseb Channel Aquifer, which forms part of the total aquifer domain. During the flood, the Kuiseb River changed its course into the Dorop North Area where infiltration also took place. Inadequate monitoring points in the Dorop North and Kuiseb Channel Areas makes it impossible to do a reliable calculation of the recharge from runoff to these two parts of the aquifer. Delayed recharge to the Rooibank B area is still evident due to water retention in the alluvium. Intercalated silt layers deposited during previous flood events also give rise to delayed infiltration.

The simulated water levels at the end of 1997 over the aquifer domain are illustrated in Figure 9 in Annexe 3.

4. CONCLUSIONS

1. Recharge to the Lower Kuiseb Aquifers is dependent on runoff events and subsurface base flow. After the 1997 floods, recharge to all the aquifers were recorded. Water levels in the Swartbank and Rooibank A areas
increased by an average of 2.23 m and in the Dorop South and Rooibank B areas by 0.41 m and 0.5 m respectively.

2. From recharge calculations, approximately 15 Mm$^3$ of water infiltrated into the Swartbank and Rooibank A areas during runoff. **The safe yield of the Swartbank/Rooibank A Aquifer is 3.3 Mm$^3$/annum.**

3. An estimated 5.6 Mm$^3$ recharged into the Dorop South and Rooibank B areas. **The safe yield of the aquifer (Dorop South and Rooibank B areas) in a time of minimum or no recharge from surface flow is, 0.99 Mm$^3$/annum as opposed to 2.0 Mm$^3$/annum for the long term sustainable yield which includes periodic recharge events.**

4. Infiltration over the Swartbank and Rooibank A areas have a definite delayed time of approximately 6 months due to the extensive silt layers found in the aquifers. A delayed time in infiltration is also inferred for the Rooibank B area. Recovery of the water levels in the Dorop South area was rather profound and rapid due to termination of abstraction combined with recharge resulting from infiltration of surface floodwater.

5. An assessment of recharge from runoff to the Lower Kuiseb Aquifers is greatly dependent on the availability of accurately interpreted hydrological data. All efforts should be made to maintain existing gauging stations at Gobabeb and Rooibank (at least) and to record and evaluate runoff data on a regular basis during flood events.

5. **FURTHER WORK**

The need to properly assess the groundwater potential of the so-called Lower Kuiseb Aquifers in terms of recharge and sustainable yield requires that further work be conducted to refine existing concepts and approaches. Of particular reference in this regard would be a collation of existing data from previous investigations to determine more accurately the aquifer boundaries, boundary conditions, dynamics of natural recharge and discharge. Once all the relevant information have been compiled and verified, proper conceptualisation of the aquifer system can be done for further application in numerical groundwater flow models. Such models, if realistically conceptualised and constructed, can usefully be applied for management purposes.

Viewed in the context of water supply and the future construction of a desalination plant to augment water supply to the Central Namib Area, such (further) work would be essential to optimally and sustainably utilise available groundwater resources.

A project aimed at these objectives has been compiled and submitted to the Netherlands Government for external funding to employ foreign experts to assist with the work. The proposal, which was well received, is currently being revised in accordance with the conditions stipulated for technical co-operation by the Netherlands Government. When finally approved, work is expected to commence early 1999.
Compiled by

C. Wessels
6. RECOMMENDATIONS

It is recommended that:

1. The problems concerning the loss of flood monitoring data at the Swartbank and Rooibank gauging stations should be taken up for discussion with the Department of Water Affairs to ensure the accuracy and completion of future flood monitoring data at both gauging stations.

NAMWATER
DEPARTMENT OF WATER AFFAIRS

7. APPROVAL OF RECOMMENDATIONS

The recommendation in this report is supported and submitted to the General Manager, Engineering and Scientific Services for approval.

MANAGER: GEOHYDROLOGY DIVISION
DATE:

The recommendation in this report is approved.

GENERAL MANAGER, ENGINEERING AND SCIENTIFIC SERVICES
DATE:
8. REFERENCES


Compiled by

C Wessels
Geohydrologist
Date:
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