Modelling of long-term sedimentation at Welbedacht Reservoir, South Africa

J W L de Villiers and G R Basson

This paper describes two-dimensional mathematical modelling of reservoir hydrodynamics and cohesive sediment transport processes, using advection-dispersion theory. Creating such a numerical model involves setting up a suitable curvilinear grid and requires data of the bathymetry, recorded inflows and water levels. It also requires sediment characteristics and transport parameters. These parameters have to be specified by the user based on previous experience and field measurement data.

The Mike21C software from DHI Water and Environment, modified for reservoir sedimentation processes, is used to model the transport of fine cohesive sediment for Welbedacht Reservoir. The reservoir has a relatively narrow basin that constantly experiences extremely large sediment load inputs from the Caledon River. The parameters of flow, sediment characteristics and sediment transport are investigated, calibrated and validated for the Welbedacht Reservoir case study. The calibrated model is then further applied to determine the long-term future equilibrium sedimentation levels as well as future flood levels.

INTRODUCTION

Reservoir sedimentation

Reservoir sedimentation is a worldwide problem, with the annual loss in storage capacity due to sedimentation estimated at 1% of the original storage capacity, or 50 km³ (Batuca & Jordaan 2000). This equates to a replacement cost estimated by the World Bank at USD 13 billion per year needed to maintain the current total storage capacity (Palmieri 2003). Worldwide the average age of reservoirs is now about 35 years. Most of the existing reservoirs will be completely silted up in 200 years’ time, assuming no intervention. Figure 1 shows the growth in the storage capacity and sediment deposition worldwide.

In South African reservoirs, Jordaan (1989) found the average sedimentation rate per year to be 0.5%, equivalent to the loss of 150 million m³ of storage capacity each year. Beck and Basson (2002) calculated this rate as 0.34%, based on more recent data.

Worldwide there are many cases where extreme sedimentation has reduced a reservoir’s lifespan to only a few years. A well-known example of where these problems have occurred in South Africa is Welbedacht Reservoir on the Caledon River in the Free State Province. This dam was constructed in 1973 with the purpose of supplying water to the city of Bloemfontein via the 115 km long Caledon–Bloemfontein pipeline. By 1988, 15 years after construction, it had already lost 73.2% of the original storage capacity at an average annual sedimentation rate of 4.5% (Clark 1990). Flushing operations have been carried out since 1991 but with limited success. The reduction in storage created problems in meeting the Bloemfontein demand at an acceptable level of reliability and, as a result, the 50 m high off-channel...
Knelpoort Dam had to be constructed in 1988. By 2002 the Welbedacht Reservoir had lost 89.9% of its original storage capacity (DWAF 2006). It can be seen in figure 2 that Welbedacht is the worst of the selected reservoirs, but not the only reservoir experiencing heavy sedimentation in South Africa.

The Mike21C model
Mike21C is a two-dimensional (in plan) modelling tool that simulates reservoir hydrodynamics and cohesive sediment transport processes with an advection-dispersion module. The hydrodynamics and sediment transport calculations are fully coupled. Creating such a numerical model involves setting up a suitable curvilinear grid and requires data of the bathymetry, recorded inflows and water levels. It also requires sediment characteristic parameters and transport parameters. These parameters have to be specified by the user based on previous experience and field measurement data.

The version of Mike21C that was used for this study was designed by DHI (2003) to model the transport of only one size of fine cohesive sediment during a simulation. The model also determines the helical flow intensity and dispersion coefficients internally based on the flow curvature and vertical velocity profiles. Mike21C was used to model the transport of fine sediment for Welbedacht Reservoir.

Welbedacht Reservoir
Welbedacht Dam, which was completed on the Caledon River in 1973, is located in a high sediment yield region. During the first three years of operation the reservoir had lost 36 million m³ of its original 114 million m³ storage capacity due to sedimentation. Figure 3 shows the losses in storage capacity over the years. Figure 4 shows the longitudinal profile of the reservoir bed (lowest point on the sections) determined by survey data. Also shown in figure 4 is the projected future equilibrium sedimentation level of the reservoir as calculated by Rooseboom et al (1986).

As a result of this extreme case of sedimentation, the existing Jim Fouché Bridge in the upper reaches of the reservoir experiences regular flooding. This is because the height of the bridge openings has been reduced from 13 m to only 1 m since the dam was built. The bridge is located 42.5 km upstream of the dam.

All the historical data of inflows and reservoir levels that were used in the model were obtained from the Department of Water Affairs and Forestry (DWAF 2004). The model was formulated with upstream inflow data from the flow measuring station at Jammersdrift and downstream reservoir water level data from station D2R004 at Welbedacht Dam. An aerial photo of the reservoir can be seen in figure 5.

Mike21C Hydrodynamic Module
Two hydrodynamic modules are available for use in Mike21C. They are the fully hydrodynamic module and the quasi-steady module.

In this research, the quasi-steady module was used. This solver is a predictor-corrector algorithm that originates from methods for incompressible fluid flow. It is mostly used for reservoir applications with long simulation periods. This is because the quasi-steady solver does not determine the pressure from the continuity equation but from other implicit methods. This simplifies the calculations at each time step, effectively reducing the computational time. The governing equations of momentum and continuity of the quasi-steady module in terms of a Cartesian, rectangular coordinate system are (DHI 2003):
The total time derivative is given by:

\[
\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{\partial}{\partial x} (\alpha_x p) + \frac{\partial}{\partial y} (\alpha_y q)
\]  

(4)

The advection-dispersion model of cohesive sediment transport

The equations of hydrodynamics and sediment transport are solved simultaneously. The transport of fine sediments is calculated in Mike21C by the advection-dispersion module. Mass transport is controlled by the two mechanisms of advection and dispersion. Advection accounts for the movement of the solute, linked to the fluid, with the average water velocity. Diffusion accounts for mixing caused by turbulence or by the random particle movement from a higher concentration to a lower concentration. The combination of advection and diffusion is termed dispersion.

The transport of the suspended sediments is described by an advection-dispersion (AD) equation (Basson et al 2003):

\[
\frac{\partial h_c}{\partial t} + \frac{\partial p'}{\partial x} + \frac{\partial q'}{\partial y} = \frac{\partial}{\partial x} \left( h D_{xx} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( h D_{yy} \frac{\partial q}{\partial y} \right) + E - D \]  

(5)

Where:

\( p', q' \) = modified flux field \((m^2/s)\) according to the equation below. The modified flux field that transports the suspended sediment is derived from the depth integrated flux field in the manner:

\[
\left( \frac{p'}{q'} \right) = \alpha_{01} \left( \frac{p}{q} \right) + \alpha_{02} \frac{h}{R} \left( -\frac{q}{p} \right) \]  

(6)

\( c \) = concentration \( (g/m^3) \)

\( D_{xx} \) = dispersion in the x-direction (includes advection and turbulent diffusion)

\( D_{yy} \) = dispersion in the y-direction (includes advection and turbulent diffusion)

\( E \) = erosion function

\( D \) = deposition function

\( \alpha_{01} \) and \( \alpha_{02} \) are functions of the distribution of momentum and sediment over the water column. \( \alpha_{01} \) is the stream-wise advection constant that is defined by the user. \( \alpha_{02} \) is calculated internally by the model from the helical flow (taken from standard theory) and the distribution of sediment.

The dispersion in the equation originates from the flow profile functions. The dispersion coefficients are therefore determined by the model itself. Additional molecular diffusion can be added although no molecular diffusion was activated in the simulations in this study.

The output from this model comprises the suspended sediment concentrations and deposited layer thicknesses and resulting bathymetry at all computational points at all time steps.

MODEL PARAMETERS

The bathymetrical data is entered into Mike21C as a data file while the hydrological data, such as water level and inflow, is entered in time-series format. The other parameters that need to be specified are those of sediment characteristics and transport parameters.

Sediment particle size and settling velocity

The sediment particle size distribution can be determined with a sieve analysis for coarse material and with the standard ASTM
where:

\[ D = w_s \cdot c \cdot \left(1 - \frac{\tau}{\tau_{cd}}\right) \]  

where: \( D \) is the rate of deposition, \( w_s \) is the settling velocity, \( \tau \) is the bed shear stress and \( \tau_{cd} \) is the critical shear stress for deposition.

**Critical shear stress for erosion**

This is the value of bed shear stress that has to be exceeded for the erosion process to commence at a rate given by the equation (DHI 2003):

\[ E = E_0 \left(1 - \frac{\tau}{\tau_{ce}}\right)^m \]  

where \( E_0 \) is the erosion constant, \( m \) is the exponent of erosion and \( \tau_{ce} \) is the critical shear stress for erosion. The values of \( E_0 \) and \( m \) determine the scale of erosion.

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**Table 1 Calibration model variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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<tr>
<td>Bed roughness – Manning M (m^0.33/s)</td>
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</tr>
<tr>
<td>Critical shear stress for deposition (N/m²)</td>
<td>0.05</td>
</tr>
<tr>
<td>Critical shear stress for erosion (N/m²)</td>
<td>1.04</td>
</tr>
<tr>
<td>Eddy viscosity (m²/s)</td>
<td>0.01</td>
</tr>
<tr>
<td>Sediment porosity</td>
<td>0.5</td>
</tr>
<tr>
<td>Sediment relative density (kg/m³)</td>
<td>2.65</td>
</tr>
<tr>
<td>Erosion constant ( E_0 ) (g/m²/s)</td>
<td>0.1</td>
</tr>
<tr>
<td>Exponent of erosion</td>
<td>2</td>
</tr>
<tr>
<td>Dispersion (as molecular diffusion)</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 7 The 1973 bathymetry (in plan) used in the Welbedacht model**

**Figure 8 Median particle sizes of bed grab samples taken along Welbedacht Reservoir**

**Figure 9 The 1973–1976 time-series for the model’s inflow and downstream water levels based on observed data (FSL = 1 402.9 masl)**
For all simulations in this study, this parameter is kept at a constant value of 0. The molecular diffusion has very little effect on the overall dispersion. The \( x \) and \( y \) horizontal dispersion coefficients are determined by the model itself.

**Eddy viscosity**

The eddy viscosity is chosen as constant throughout the model. If the model is applied to a reservoir system, this value can be taken as 0.01 m\(^2\)/s. For small scale models such as flumes with small grid spacing relative to the depth, the eddy viscosity may be neglected. Eddy viscosity becomes important when the horizontal grid spacing of a model is much larger than the water depth, as in the case of reservoir models (DHI 2003).

**Dispersion**

This parameter specifies the amount of added molecular diffusion required for the simulation. For all simulations in this study, this parameter is kept at a constant value of 0. The molecular diffusion has very little effect on the overall dispersion. The \( x \) and \( y \) horizontal dispersion coefficients are determined by the model itself.

**CALIBRATION: 1973–1976**

As a calibration case the model simulated the three-year period from 1973 to 1976. The Department of Water Affairs and Forestry carried out hydrographic surveys of the basin during 1973 and 1976, and therefore the original and end bathymetries were known (DWAF 2004). The geometry of the reservoir was derived from the 1973 survey data, and mapped with a curvilinear grid, as shown in figure 6. The grid contains 360 cells in the longitudinal direction and 16 cells in the transverse direction, totalling 5760 cells when the model is fully flooded. Figure 7 shows the original 1973 bathymetry of Welbedacht Reservoir, imposed on the grid.

During this study, 28 bed sediment samples were taken along the reservoir from two kilometres upstream of the Jim Fouché Bridge down to the dam. Figure 8 shows the variation in the median particle sizes of the samples taken along the reservoir. Most of the median values lie around a size of 0.1 mm. This means that the bed is sandy. However, all the samples had more than 7 % of silt and clay (particles smaller than 0.065 mm) and therefore the bed will have the characteristics of a cohesive bed, according to Beck and Basson (2002).

Since the model is required to transport the sediment deep into the reservoir, a median value for a sediment sample taken close to the dam will be a better estimation of the representative size, especially for the 1973 to 1976 period. The median sizes found close to the dam varies between 0.008 mm and 0.011 mm in diameter.

Basson and Rooseboom (1997) used a suspended sediment size distribution from observed data for Welbedacht Reservoir inflow, as shown below:

- Fraction 1: \( d_{50} < 0.05 \) mm, 76 % (clay)
- Fraction 2: \( 0.05 \) mm \(< d_{50} < 0.106 \) mm, 19 % (silt)
- Fraction 3: \( 0.106 \) mm \(< d_{50} < 0.25 \) mm, 5 % (fine sand)

Based on mass, these values produce a weighted average particle size of 0.0427 mm, which will have a settling velocity of 0.00164 m/s, as calculated by Stokes’ Law. The settling velocity is taken as 0.001 m/s for the first calibration run. The following dependency rate of concentration to discharge was used in the study by Basson et al (2003):

\[
C = 793.32Q^{0.664} \tag{9}
\]

where: \( C \) is in g/m\(^3\) and \( Q \) in m\(^3\)/s

Basson et al (2003) calibrated the Welbedacht model successfully with this dependency rate and therefore the same dependency rate will be used here. According to this rate, the catchment area yields sediment at 2 950 t/km\(^2\)/a for the 1973 to 1976 period. In order to calibrate the model, the aim was that the simulated 1976 bathymetry matched the 1976 surveyed bathymetry. This was first attempted using the historical time-series and variables as shown in table 1 and figure 9.

The critical shear stress for erosion is kept at 1.04 N/m\(^2\), the value used in the study by Basson et al (2003), where some erosion did occur. The value of \( \alpha_{01} \) is at its maximum value of 1.0 to ensure that the sediment concentration is evenly distributed throughout
the depth of flow and that it carries as far as possible into the reservoir. The only remaining parameters are those of critical stress for deposition and settling velocity. Both will have an influence on how even the sediment will deposit throughout the reservoir. Firstly the settling velocity will be calibrated and then the critical stress for deposition.

Settling velocity sensitivity study
With all other parameters kept constant as in table 1, the sectional variations for different values of the settling velocity $w$ are shown in figures 10, 11 and 12. These are the DWAF survey sections 41, 26 and 9. Section 41 is 40 km upstream of the dam, section 26 is 20 km upstream of the dam, and section 9 is three km from the dam. The locations of these sections are shown in figure 5.

It is expected that the smaller the settling velocity, the further the sediment will be carried into the reservoir towards the dam. When the settling velocity is large, the sediment will deposit close to the upstream boundary.

The upstream section 41 does not show large variation in deposited layer thickness for the various settling velocities. All the simulations did however deposit a relatively accurate amount within the main channel, of which simulation with the highest settling velocity, 0.005 m/s, seemed to be most accurate.

At section 26, the simulation with $w = 0.005$ m/s delivered the sediment accurately within the main channel. The simulation with $w = 0.005$ m/s has an evenly distributed layer over the whole section and also deposits the largest volume of all the simulations.

The downstream section 9 is the longest section throughout the reservoir and it lies only three kilometres from the dam wall in the area where the heaviest sediment deposits have occurred. This makes the section the most important section for evaluating the parameter of settling velocity. The simulation with $w = 0.0001$ m/s produced the best results at this section.

The figures above each produced three different answers to the question of settling velocity, and none of them is the estimated settling velocity of 0.00164 m/s. It was however decided to use a settling velocity of 0.0001 m/s since it performed well in all three sections and especially in section 9 where the largest deposits are expected. This settling velocity corresponds to a particle diameter of 0.011 mm, which relates very well with the median particle sizes of the samples taken close to the dam.

Sensitivity study for the critical shear stress for deposition, $\tau_{cd}$
A new set of calibration simulations were run, with a fixed value for $w$ of 0.0001 m/s and varying values of critical shear stress.

![Figure 13 Deposited sediment layers at section 41 for different shear stresses for deposition](image1)

![Figure 14 Deposited sediment layers at section 26 for different shear stresses for deposition](image2)

![Figure 15 Deposited sediment layers at section 9 for different shear stresses for deposition](image3)

![Figure 16 Deposited sediment layers at section 41 for different stream-wise constants](image4)
As before, the results are again plotted and evaluated on the three sections in figures 13, 14 and 15.

In all of the above sections, the deposited sediment layer produced by the simulation with \( \tau_{cd} = 0.05 \) N/m\(^2\) is the closest to the surveyed bathymetry. Both the other simulations, with a larger \( \tau_{cd} \) of 0.1 N/m\(^2\) and a smaller \( \tau_{cd} \) of 0.01 N/m\(^2\), resulted in less deposition at these sections than with \( \tau_{cd} = 0.05 \) N/m\(^2\). This is probably because a large value of \( \tau_{cd} \) like 0.1 N/m\(^2\) would deposit all the sediment already at the upstream boundary, while a smaller \( \tau_{cd} \) like 0.01 N/m\(^2\) would not cause large amounts of sediment to be deposited, and the sediment would remain in suspension and be flushed out at the downstream boundary. The best value adopted for \( \tau_{cd} \) is thus 0.05 N/m\(^2\).

Sensitivity study for the stream-wise advection constant,

The best values for \( \tau_{cd} \) and \( w \) were determined as 0.05 N/m\(^2\) and 0.0001 m/s respectively. It was decided to investigate more values of \( \alpha_{01} \) since the deposition was still slightly less than what was expected, but this could be due to the assumed sediment concentration-discharge relationship. Simulations were run with \( \tau_{cd} \) and \( w \) at the values mentioned above, and \( \alpha_{01} \) values of 0.1, 0.5 and 1.0. The results are shown in figures 16, 17 and 18.

It seems that a value for \( \alpha_{01} \) of 1.0 still produced the most deposition, as would be expected. The values for \( \alpha_{01} \) of 0.5 and 0.1 produced less deposition because the velocity distribution was then at a maximum near the bed, which is not suitable for the process of deposition. It would have created higher bed shear stresses which could even have exceeded the critical shear stress for erosion. A value for \( \alpha_{01} \) of 1.0 was therefore used in the validation simulation.

VALIDATION: 2000–2002

The values of \( \tau_{cd} \), \( w \) and \( \alpha_{01} \) were calibrated at 0.05 N/m\(^2\), 0.0001 m/s and 1.0 respectively. The result from the validation, using these values, would ultimately determine the validity and accuracy of the values.

This validation basically followed the same procedure as the 1973–1976 calibration, but used observed data for the two-year period from July 2000 to July 2002. Once again, basin surveys were carried out during both 2000 and 2002 (DWAF 2004) and therefore the original and end bathymetries were known. The 2000 bathymetry can be seen in figure 19. The same grid from the previous calibration was used for this simulation. Once again, the observed dam water levels were used at the downstream boundary. For the upstream boundary, the observed releases from the dam were used, since the upstream

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**Table 2 Validation model variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed roughness – Manning M (m(^{0.33})/s)</td>
<td>50</td>
</tr>
<tr>
<td>Critical shear stress for deposition (N/m(^2))</td>
<td>0.05</td>
</tr>
<tr>
<td>Critical shear stress for erosion (N/m(^2))</td>
<td>1.04</td>
</tr>
<tr>
<td>Eddy viscosity (m(^2)/s)</td>
<td>0.01</td>
</tr>
<tr>
<td>Settling velocity, w</td>
<td>0.0001</td>
</tr>
<tr>
<td>Stream wise constant ( \alpha_{01} )</td>
<td>1.0</td>
</tr>
<tr>
<td>Sediment porosity</td>
<td>0.5</td>
</tr>
<tr>
<td>Sediment relative density (kg/m(^3))</td>
<td>2.65</td>
</tr>
<tr>
<td>Erosion constant ( E_{0} ) (g/m(^2)/s)</td>
<td>0.1</td>
</tr>
<tr>
<td>Exponent of the erosion</td>
<td>2</td>
</tr>
</tbody>
</table>

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**Figure 17 Deposited sediment layers at section 26 for different stream-wise constants**

**Figure 18 Deposited sediment layers at section 9 for different stream-wise constants**

**Figure 19 The 2000 survey bathymetry (in plan) used for the validation**
Jammersdrift gauging station was no longer operational during this period.

Due to the high silt content, the cohesive modelling approach adopted for the 1973–1976 simulation was again used for the 2000–2002 period. No upstream sediment concentrations have been monitored since 1976, and the original concentration-discharge relationship for 1973 to 1976 was again used for the sediment yield. The variables and historical time series that were used are shown in table 2 and figure 20.

The validation simulation produced the results at the same three sections used previously, as shown in figures 21, 22 and 23.

In general, there are no large differences between the 2000 and 2002 surveyed sections, although the main channel at section 9 has shifted to the right during this period. The simulated 2002 bathymetry is not an exact match against the 2002 surveyed bathymetry. The simulation produced deposition at all three sections and section 41 seems especially well calibrated. At section 26 the simulation produced some deposition where there should have been slight erosion. Section 9 is difficult to evaluate because it seems to have shifted to the right, probably due to the flushing operation. In general, the validation can be considered successful since there was even deposition on all three sections, as was the case with the successful calibration run.

It should be noted that the original rate of dependency of the concentration to discharge is a slight underestimation of the real sediment yield. This can be seen in the results from the calibrated and validation simulations. The resulting deposition at the sections is always slightly less than the surveyed profile.

The calibrated parameters relate well with those in the Mike21C model study by Basson et al (2003). The only difference was the change in settling velocity from 0.001 m/s to 0.0001 m/s. It should be noted that the model used in this research had a domain that was 50% longer than the model used by Basson et al (2003). The change in settling velocity was necessary to carry the suspended sediment through the 48 km length of the model.

**LONG-TERM SEDIMENTATION SIMULATIONS**

Further simulations were run with predicted future inflow and water levels from 2002 to 2011 and from 2002 to 2029. These inflows were basically the 1973–1976 inflow time-series run continuously over the 9- and 27-year periods. The downstream water level was kept constant at the full supply level of 1 402.9 masl. The results on the longitudinal profile of these simulations are shown in figure 24.

It can be seen from figure 24 that the simulations showed no large changes in the bathymetry after 2011. The 2011 and 2029 levels are very similar and it can be said that
they represent the equilibrium sedimentation levels. The future equilibrium levels predicted by Rooseboom et al. (1986) are still higher than even the 2029 levels simulated in this study closer to the dam (30 km), but in the upper reaches the simulated future bed levels are higher. The simulated 2029 bathymetry is shown in figure 25. The Rooseboom et al. (1986) method assumed that Boogoeberg Reservoir, further down in the same river system, had reached equilibrium at 367 m above mean sea level (masl). The sediment problem in South African reservoirs has reached equilibrium between the discharge dependency, Welbedacht Reservoir. Calibration of such a model involves data collection and sensitivity studies on a trial and error basis. When simulations are performed into the future (2029), with the assumed sediment concentration-discharge dependency, Welbedacht Reservoir reaches a dynamic equilibrium between the sediment transport processes of deposition and erosion.

CONCLUSIONS

This research showed that Mike21C, run in quasi-steady mode with an advection-dispersion module, is adequate for creating and calibrating a sedimentation model for extreme cases of reservoir sedimentation such as Welbedacht Reservoir. Calibration of such a model involves data collection and sensitivity studies on a trial and error basis. When simulations are performed into the future (2029), with the assumed sediment concentration-discharge dependency, Welbedacht Reservoir reaches a dynamic equilibrium between the sediment transport processes of deposition and erosion.

REFERENCES


DHI (Department of Water Affairs and Forestry) 2004 Data of hydrographic surveys, inflows and water levels of Welbedacht Reservoir, Pretoria: The Department.

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DHI (Department of Water Affairs and Forestry) 2004 Data of hydrographic surveys, inflows and water levels of Welbedacht Reservoir, Pretoria: The Department.

DWA (Department of Water Affairs and Forestry) 2004 Data of hydrographic surveys, inflows and water levels of Welbedacht Reservoir, Pretoria: The Department.

DHI (Department of Water Affairs and Forestry) 2004 Data of hydrographic surveys, inflows and water levels of Welbedacht Reservoir, Pretoria: The Department.

DWA (Department of Water Affairs and Forestry) 2004 Data of hydrographic surveys, inflows and water levels of Welbedacht Reservoir, Pretoria: The Department.

DHI (Department of Water Affairs and Forestry) 2004 Data of hydrographic surveys, inflows and water levels of Welbedacht Reservoir, Pretoria: The Department.

DWA (Department of Water Affairs and Forestry) 2004 Data of hydrographic surveys, inflows and water levels of Welbedacht Reservoir, Pretoria: The Department.