Reservoir sedimentation analysis of the proposed Noordoewer/Vioolsdrift dam on the Orange river and evaluation of sediment control mitigation measures

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3 authors:

Gerrit Basson
Stellenbosch University

Ousmane Sawadogo
Stellenbosch University

Jeanine Vonkeman
Stellenbosch University

Reservoir sedimentation analysis of the proposed Noordoewer/Vioolsdrift dam on the Orange river and evaluation of sediment control mitigation measures

Prof G.R. Basson, Dr O. Sawadogo and J.K. Vonkeman
Department of Civil Engineering
Stellenbosch University
Stellenbosch 7600
South Africa

The Orange River Re-Planning Study (ORRS, 1997) recommended that the proposed Noordoewer/Vioolsdrift Dam (NVD) site be further investigated as possible dam development downstream of Vanderkloof Dam, in the lower reach of the 2200 km long Orange-Senqu River. The Lower Orange River Management Study (LORMS, 2005) recommended that a re-regulating dam be constructed at the NVD site on the border between Namibia and South Africa in order to increase the availability of water to meet both the future human and ecological water requirements for the Lower Orange River and the river estuary. This paper addresses the NVD feasibility study findings based on the joint study by Namibia and South Africa related to sedimentation.

The sedimentation investigation consists of two phases i.e. (1) the determination of the sediment yield at the proposed NVD site and (2) the reservoir sedimentation hydrodynamic modelling, including the flood level simulations due to sedimentation and the feasibility of flushing sediment from the reservoir. From the sediment yield analysis, the proposed long-term sediment load at the NVD site is 16.4 million t/a. Based on the 2D hydrodynamic modelling, the proposed NVD reservoir would have 47% and 77% of the original storage capacity after 100 years of operation, for the 70 m and 90 m high dam scenarios respectively. The reservoir traps 97 % of the sediment load.

Reservoir sedimentation mitigation measures were investigated to extend the life of the dam, based on ICOLD (1999) guidelines. Simulations were carried out to evaluate reservoir drawdown flushing during floods and local pressure flushing at the dam outlet for irrigation. Based on the expected relatively large sustainable equilibrium FSC of 70 % of the original FSC for the NVD project, it is proposed that the 70 m high dam (or a lower dam), with a smaller dead storage for sedimentation, is designed with drawdown flushing during floods.

1. Background

The feasibility study for the proposed Noordoewer/Vioolsdrift Dam required further investigation addressing the reservoir sedimentation because the Orange-Senqu River basin is one of the most significant river basins in southern Africa. It is shared among four countries, namely Lesotho, South Africa, Botswana and Namibia. Fig. 1 shows the schematic representation of the annual sediment loads (in red) for the Orange/Senqu River and its tributaries (in purple) relative to the proposed NVD site. The total average sediment outflows from catchments areas within the Orange-Senqu River basin were computed at different gauging stations and reservoirs along the river, based on the South African Water Research Commission (WRC, 2012) methodology.

The impact of reservoir sedimentation is significant in the Orange-Senqu River basin. Some reservoirs have lost substantial volumes of their original storage capacity due to sedimentation. The loss in storage directly reduces the available yield of the reservoir, resulting in the possible under supply to relevant water users. Sedimentation could result in serious socio-economic losses, environmental and aesthetic problems, considering the dependence on water stored in reservoirs for potable, irrigation, recreation, hydropower production and flood control purposes. Specifically, food production from irrigated agriculture along the Orange River can be affected by reduced water storage volumes in reservoirs.

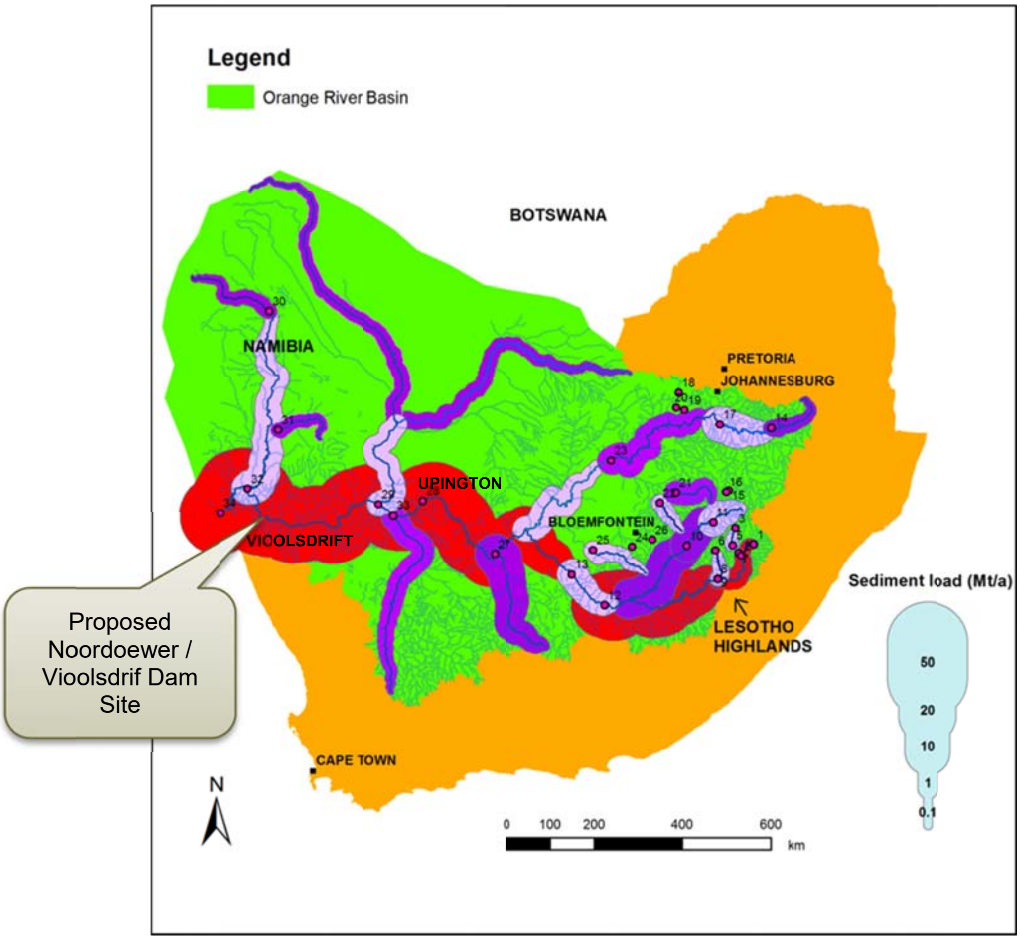

Fig. 1. Schematic representation of tributaries and sediment loads on the Orange-Senqu River catchment area (based on the WRC (2012) methodology)

2. Sediment yield

Table 1 summarizes the long term sediment loads obtained from different data sets and assumptions. It is proposed that the high long term sediment load of 16.4 million t/a is used to evaluate the reservoir sedimentation of the proposed NVD Dam at Vioolsdrift. This is 46 % more than the mean long term load of 11.2 million t/a to compensate for limited large flood TSS data but is similar to the mean annual load of previous studies. There is confidence in this value because it was calibrated against South Africa's Department of Water and Sanitation's (DWS) Total Suspended Solids (TSS) data at Upington, turbidity data of the //Khara Hais Local Municipality at Upington and observed post-1976 reservoir sedimentation in the catchment. The proposed sediment load of this study is conservatively high and should cater for possible but limited future land degradation and climate change.

Table 1. Long term sediment loads at Vioolsdrift

Upington (million t/a)	Vioolsdrift (million t/a)	Comments
1) Reviewing previous studies of the ORRS (1997) and LORMS (2005) by the DWS		
-	Mean: 16.6	These studies were based on pre-dam development sediment concentration data. The indication is that the dams completed between 1970 and 1975 had a significant impact in decreasing the sediment load in the Lower Orange River since 1976.
-	High: 25.0	
2) The regional methodology developed by the WRC (2012) for ungauged catchments		
25.5	29.9	These relatively high loads are attributed to the fact that the WRC method was calibrated with pre-dam historical sediment (1929 to 1969). Subsequent to this period, additional sediment yield data was obtained

		from reservoir sediment deposition data. However, not much data was available in the Lower Orange River in Namibia and Botswana for calibration due to the nature of the ephemeral rivers. The sediment loads for these regions were based on a comparative analysis of erosion hazard classes of the adjacent river catchments located in South Africa.
3) Suspended sediment concentration data sampled by SA's Department of Water & Sanitation		
4.7	9.1	The TSS concentration data collected by the DWS at the flow gauging stations of Upington (D7H005) and Prieska (D7H002) were used to calculate sediment loads, found to be similar and combined to give a larger database for the post-dam period 1976 to 2015. The results were scaled up from 23.5 million t/a to obtain the same 43.8 million t/a sediment load for the 20 year period 1949 to 1969, based on published data for Upington and Prieska (Rooseboom, 1992). The post-dam data was also scaled up at Upington, due to limited data being available for this period, to rather represent an upper envelope for the observed sediment loads at river flows above 1000 m^3/s. If the pre-dam sediment rating was applied to the period from 1976 to 2015, a sediment load of 42.4 million t/a would theoretically have been observed. The difference in the pre- and post-1976 sediment loads is 37.7 million t/a (or 1507 million t over a 40 year period). The reduction in sediment load can be accounted for by the 1547 million t sediment deposition observed in the Orange-Senqu River basin reservoirs (based on reservoir survey data from the DWS dam list of 2015).
6.8	11.2	The flow record from 1976 to 2015 used in the TSS analysis does not have large floods and therefore a 50 and 100 year flood was added to the flow record.
4) Turbidity data recorded by the //Khara Hais Local Municipality at Upington		
High: 12.0	High: 16.4	The recent TSS dataset from DWS is relatively small and underestimates sediment loads for larger flows above 2000 m^3/s so it was supplemented with turbidity data sampled every 2 hours at the raw water intake of a local water treatment works from 2000 to 2015. The corresponding TSS data was used to convert the turbudity data to sediment concentrations and loads. There are uncertainties in the long term sediment yield due to the scatter in the data and the limited data points above 2000 m^3/s. Therefore, it was decided to also consider a high sediment load relationship. It was based on the reliable TSS data for low discharges and on the //Khara Hais Local Municipality data for larger discharges. Note that the suspended sediment concentrations and loads were increased by 25% to allow for bed load and non-uniformity in suspended sediment concentrations across the river.

3. Hydrodynamic modelling

The long-term reservoir sedimentation after 50 and 100 years of the proposed NVD reservoir was simulated by the 2D hydrodynamic model Mike21C. Two different dam height scenarios were evaluated, namely a 70 m high dam with a Full Supply Level (FSL) of 230 masl and a 90 m high dam with a FSL of 250 masl. The reservoir bathymetry over a 125 km reach was obtained from LiDAR survey data. The curvilinear grid was set up with cell sizes of 80 m wide and 240 m long in the flow direction. Typical hydraulic roughness Manning n values were used: 0.025 for the reservoir, 0.035 for the main channel and 0.050 for the river floodplain. The upstream flow boundary was based on the 100 year scaled daily inflow record of the DWS gauging station DH003 while the downstream reservoir levels were based on the mass balance of the dam considering daily rainfall and evaporation, monthly demands abstracted and spillage.

The upstream boundary of the model also included a time series of cohesive sediment concentration, based on the calibrated sediment load-discharge rating at Upington. The cohesive sediment size of 0.033 mm was determined from a grading analysis of sediment samples collected from the field. Non cohesive sediment fractions were also implemented: 30% of 2.751 mm, 30% of 0.531 mm and 40% of 0.182 mm. The long term deposited sediment density was specified as 1.35 t/m^3 which is typical for a storage operated reservoir in South Africa.

3.1 Reservoir sedimentation without flushing

Fig. 2 shows longitudinal sections of the simulated bed level change after 50 and 100 years for the 70 m and 90 m high dams. The 70 m high dam has much lower operating levels than the 90 m dam and this causes the sediment to be deposited much further into the reservoir. The deposited sediment volumes based on the high sediment load of 16.4 million t/a are indicated in Table 2.

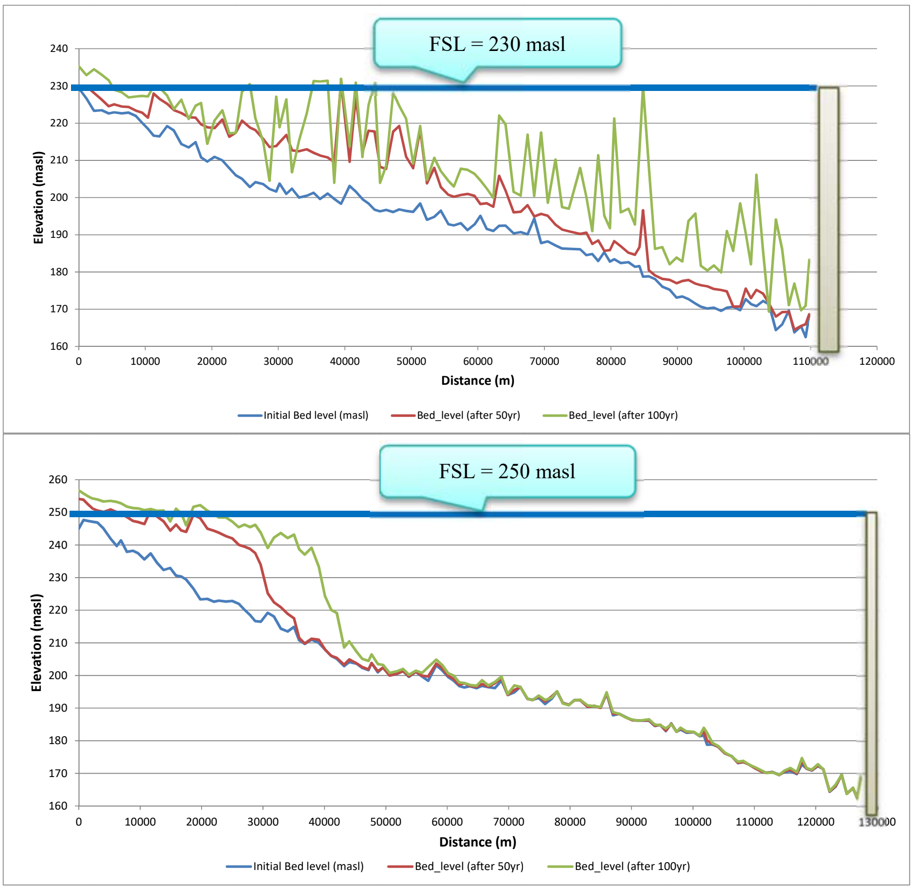

Fig. 2. Sediment deposition after 50 and 100 years for (a) the 70 m high dam and (b) the 90 m high dam

Table 2. Simulated sediment volumes in the reservoir after 50 and 100 years of operation without sediment flushing

Dam FSL (masl)	230		250	
Original FSC (million m^3)	2240		5030	
Time period in years (X)	50	100	50	100
Volume of sediment in the reservoir after X-years (million m^3)	589	1178	589	1178
FSC remaining after X-years (million m^3)	1651	1062	4441	3852
Percentage of the original FSC remaining after X years (%)	74	47	88	77

Design for sedimentation and dead storage was based on ICOLD (2009): "*A storage operated (minimisation of spillage) reservoir is typically sized to accommodate the expected 50-year sediment* *volume allowing for trap efficiency. This volume is considered as dead storage in the water resources yield analysis, which means that only after 50 years of operation will sedimentation start to impact on the water firm yield.*" Both dams trap almost all the incoming sediment load (97% trapping efficiency) and it is only the colloidal fraction (3%) that is spilled downstream. Nonetheless, both dams have relative large storage capacities remaining after 100 years of operation. The worst rate of sedimentation experienced in the 230 masl FSL dam is at 0.53 % of the original FSC per year, which is slightly less than the typical rate in Africa of 0.6 % per annum (ICOLD, 2009). A dead storage for sedimentation for 50 years was allowed for in the reservoir: 16.4x50x0.97/1.35=589 million m^3.

3.2 Reservoir sedimentation with flushing

Sediment can be removed by pressure flushing without water level drawdown or by water level drawdown flushing during floods. Pressure flushing would keep the local intake area clear of sediment but to remove sediment over the length of the reservoir, water level drawdown with free outflow during floods is required. Flushing with water level drawdown during floods can be used to extend the reservoir life and to reduce the initial required dead storage capacity and dam height. The NVD reservoir shape is ideal for flushing since the valley is narrow but in this case, there is little excess water available for flushing.

ICOLD Bulletin 115 (1999) provides guidelines on when flushing operations could be feasible, based on the two ratios K_t = FSC/MAR (yr) and K_w =FSC/MAS (yr), where MAS = mean annual sediment load. Table 3 gives the $K_w > 0.2$ and $K_t > 50$ values for the two dam scenarios which suggests that normal storage operations, and not drawdown flushing operations, are feasible. The feasibility of flushing sediment from the reservoir was further investigated by 3D modelling for local pressure flushing and 2D modelling for general flushing by water level drawdown.

Table 3. NVD project K_t and K_w values

Dam FSL (masl)	230	250
MAR river inflow (million m^3/a)	3008	3008
MAS (million m^3/a) (@1.35t/m^3)	12.1	12.1
K_w (years)	0.74	1.67
K_t (years)	184	414

3.2.1. Local Pressure Flushing Simulation by 3D CFD Model

Pressure flushing for the 70 m high dam was simulated by ANSYS Fluent with user defined functions for sediment transport. A bottom outlet was designed to discharge the 5-year flood of 3500 m^3/s when the dam is full. The outlet dimensions are 11.3 m x 11.3 m with an invert level of 162 masl at the current river bed elevation. The model was set up with 200 000 cells with a 0.4 m cell size, a 34 m sediment depth, 34 m water depth, 0.8 mm particle size and 0.01 s time step. Fig. 3 shows the simulated scour hole with a volume of approximately 50 000 m^3 after 82 minutes. The required duration of pressure flushing would be 3 hours which should be done during periods of flood inflow into the reservoir, typically when the current 2-year flood of 1800 m^3/s is exceeded.

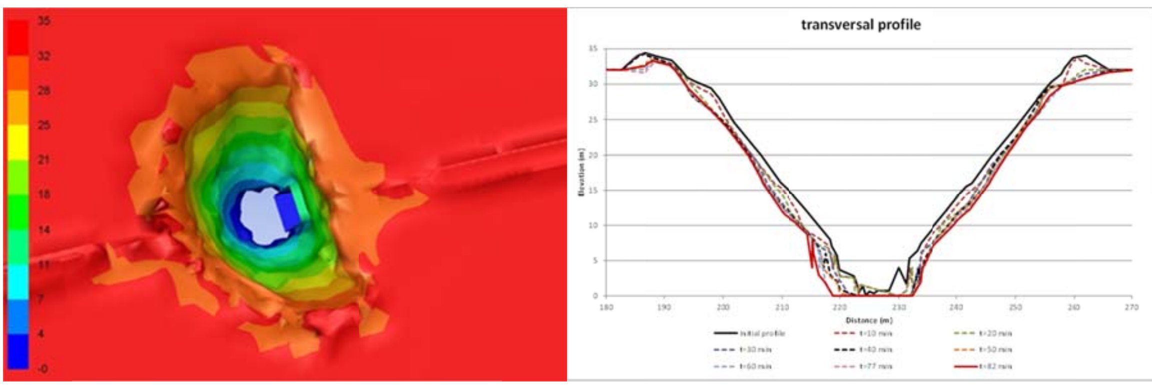

Fig. 3. Bed levels simulated by 3D pressure flushing simulations

3.2.2. Drawdown Flushing During Floods

Emptying the reservoir to flush during floods could result in a reduced firm yield and would have to be done when the dam is spilling under storage operation conditions. The long term daily water levels in the reservoir are plotted in Fig. 4 for the 70 m and 90 m high dams without flushing and with flushing done when the reservoir inflow exceeds 500 m^3/s. Evidently it is not practical to flush the 90 m high dam because there is no excess runoff inflow available to fill the reservoir after drawdown flushing. It is possible to draw down the 70 m high dam though before any floods > 500 m^3/s arrive at the dam. Twelve days are required for drawdown from a full reservoir to limit the free outflow discharge to 2000 m^3/s.

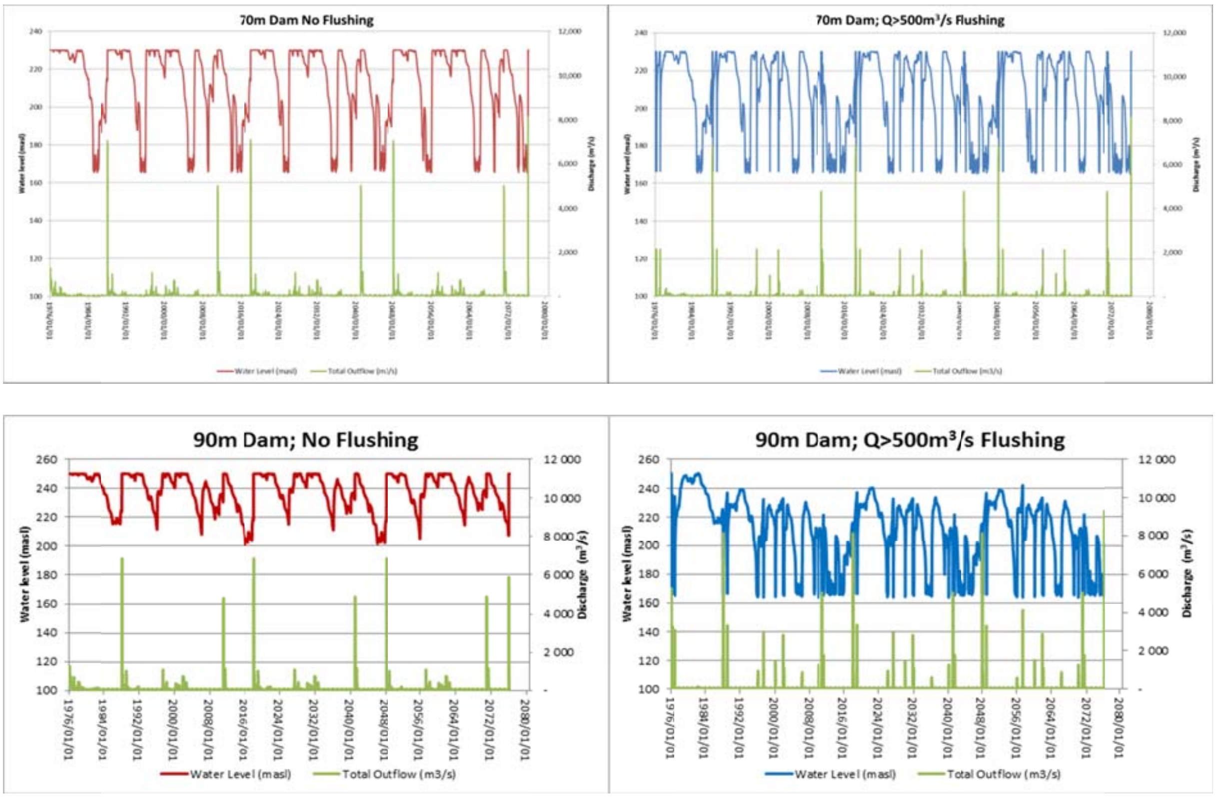

Fig. 4. Daily reservoir water levels and combined reservoir flushing, spillage and abstraction discharges

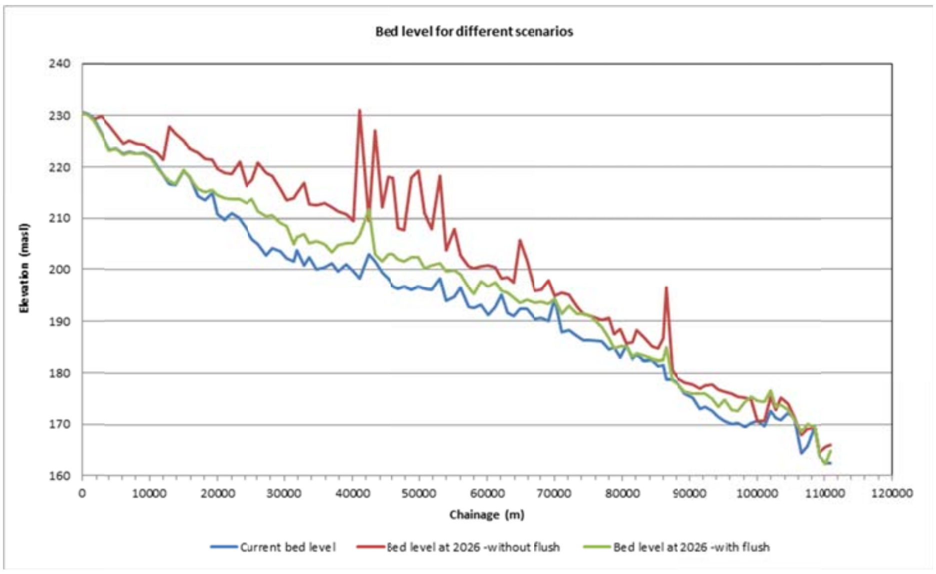

Fig. 5. Sediment deposition after 50 years for the 70 m high dam with and without flushing

2D hydrodynamic model flushing simulations were also done for all the observed floods from 1976 to 2026 with river flows > 500 m^3/s. The same Mike21C model setup was used but with lower water levels at the dam during flushing. Fig. 5 shows the simulated bed levels along the 70 m high dam for storage and flushing operation after 50 years. With flushing, most of the incoming sediment load is sluiced through the reservoir without deposition. Table 4 shows the simulation results for 50 and 100 years.

Under storage operation 589 million m^3 sediment (97% trapping) would be deposited in the dam after 50 years, but if drawdown flushing is done only 107 million m^3 sediment (18% trapping) would be deposited in the dam. The actual operation of the dam could however deposit more sediment in the reservoir if the operating rules are not followed judiciously, if a bottom outlet gate has to undergo maintenance, etc. Other dams in South Africa with flushing operation have long term storage capacity of about 25% to 40% of the original FSC but are poorly operated for flushing and the equilibrium reservoir storage capacities could have been much larger. To be conservative the storage loss with drawdown flushing is estimated at 268 million m^3 after 100 years (23% trap efficiency) for the 70 m high dam (12% FSC lost).

Table 4. Comparison of FSC in the 70 m high dam without flushing and with drawdown flushing for Q > 500 m^3/s

Mode of operation	Without flushing		With flushing	
Time period in years (X)	50	100	50	100
Volume of sediment in the reservoir after X-years (million m^3)	589	1178	107	268
FSC remaining after X-years (million m^3)	1651	1062	2133	1972
Percentage of the original FSC lost after X years (%)	26	53	5	12

Fig. 6 shows the expected change in FSC over time of the proposed 70 m dam. Without drawdown flushing the FSC will decrease to almost zero after 200 years of operation. Drawdown flushing releases only 58 million m^3/a more water than would have spilled with storage operation. This corresponds to a 1.9% reduction in the MAR while pressure flushing would cause a 0.3% reduction. With drawdown flushing, the long term equilibrium storage capacity is estimated at a minimum of 70 % of the original FSC, equal to 1568 million m^3, reached by 190 years after commissioning. These findings indicate that the drawdown flushing of sediment could be feasible for the 70 m high dam and could even be more effective if a lower dam is considered.

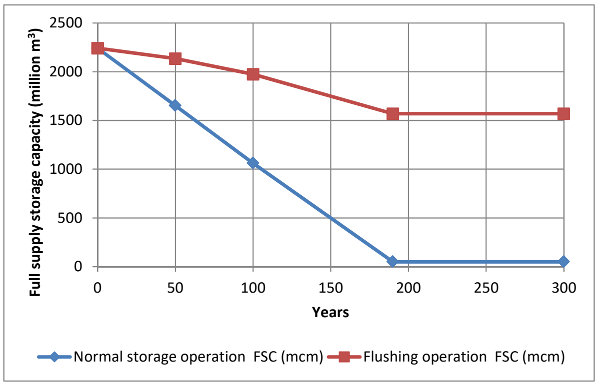

Fig. 6. Expected FSC changes due to sedimentation over a 300 year period for the 70 m high dam

3.3 Other Sedimentation Mitigation Measures

Other possible sedimentation mitigation measures at the reservoir include:

- An upstream check dam is expensive and has a limited life due to large floods
- Bypassing sediment or off-channel storage is not feasible at the NVD as the reservoir is too long
- Passing incoming sediment loads through the reservoir by density current venting is not applicable to the NVD site as it has turbulent suspended sediment transport
- Dredging sediment from the reservoir has a high cost for large volumes, a large disposal area is needed and it is not feasible economically or environmentally

- Compensating for reservoir sedimentation by raising the dam and allowing additional dead storage may be cost-effective in the short-term but it does not provide a long-term solution.

4. Conclusions

From the sediment yield analysis, the proposed long-term sediment load at the NVD site is 16.4 million t/a. Based on the 2D hydrodynamic modelling, the proposed NVD reservoir would have 47% and 77% of the original storage capacity after 100 years of operation, for the 70 m and 90 m high dam scenarios respectively. It would be beneficial to design the NVD project with sediment flushing to maintain a long-term equilibrium storage capacity of the reservoir while ensuring that small floods from the dam can still deposit increased sediment loads at the estuary. Reservoir sedimentation mitigation measures were investigated to extend the life of the dam, based on ICOLD (1999) guidelines.

The ICOLD (1999) general dam flushing requirements indicate that the proposed reservoirs are relatively too large for the runoff to have enough excess water for flushing during the full flood season and water mass balance calculations indicated that the 90 m high dam cannot be flushed. Local pressure flushing and reservoir drawdown flushing during floods > 500 m^3/s were however evaluated for the 70 m high dam by 3D and 2D numerical modelling. It was found that flushing could be feasible and maintain a long-term storage capacity, while without flushing the FSC will be almost zero after 200 years.

Based on the expected relatively large sustainable equilibrium FSC of 70 % of the original FSC for the NVD project, it is proposed that the 70 m high dam (or lower dam), with a smaller dead storage for sedimentation is designed with drawdown flushing during floods. The dam should have large bottom outlets at the current river bed for drawdown flushing during floods exceeding 500 m^3/s. Pre-releasing should commence at least 12 days before the flushing starts and the flushing duration could be anything from a few days to longer than a month based on the inflow flood hydrograph. Pressure flushing may be required for the 70 m high dam with storage operation because the sediment deposition will occur near the dam due to low water levels coinciding with large floods.

References

1. **Le Grange , A. P., Badenhorst, D. B., & Basson, G. R.** (1997). Sedimentation of Reservoirs in the Orange River Basin. Orange River Re-planning Study (ORRS). Report No PD 0010015495. Department of Water Affairs. Pretoria.
2. **DWAF.** (2005). Dam Development Options and Economic Analysis Report: Appendix G: Sedimentation Analysis. Pre-feasibility study into measures to improve the management of the lower orange river and to provide for future developments along the border between Namibia and South Africa (LORMS), Report number PB D000/00/4403.
3. **WRC.** (2012). Sediment yield prediction for South Africa – 2010 Edition. Compiled by Msadala, V., Gibson, L., Le Roux, J., Rooseboom, A. & Basson, G.R. SA Water Research Commission.
4. **Rooseboom, A.** (1992). Sediment transport in rivers and reservoirs – a Southern African perspective. WRC Report No. 297/1/92. Water Research Commission. Pretoria, South Africa.
5. **DWS.** (2015). Dam list - Reservoir survey data base. SA Department of Water and Sanitation.
6. **ICOLD** (1999). Dealing with Reservoir Sedimentation. Guidelines and case studies. Bulletin 115.
7. **ICOLD** (2009). Sedimentation and Sustainable Use of Reservoirs and River Systems. BULLETIN 147

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The Authors

Prof G.R. Basson is the Water and Environmental Engineering Division Head of the Civil Engineering Department of Stellenbosch University. He obtained a PhD from Stellenbosch University in 1996 and has more than 30 years' experience in the fields of river hydraulics, fluvial morphology and the design of large hydraulic structures. He has worked on projects in 21 countries. He is honorary Vice President of ICOLD.

Dr O. Sawadogo graduated with a PhD from Stellenbosch University in 2015. He has more than 9 years' experience in hydrodynamic mathematical modelling applied in river hydraulics and fluvial morphology, flood hydrology and flood line determination. He currently holds a position of Hydraulic Modeller and Researcher at the Department of Civil Engineering, Stellenbosch University.

J.K. Vonkeman is a post-graduate water engineering student and junior research engineer at Stellenbosch University. She completed her BEng (Cum Laude) in Civil Engineering at the University of Pretoria in 2014 and is currently developing a numerical model for her PhD on bridge pier scour.