Investigation of the impacts of the proposed Noordoewer/Vioolsdrift dam on the Orange river estuary in Namibia and South Africa - AFRICA 2019, Water Storage and Hydropower Developm...

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Investigation of the impacts of the proposed Noordoewer/Vioolsdrift dam on the Orange river estuary in Namibia and South Africa

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This paper discusses the possible impacts on the Orange River Estuary, of the proposed Noordoewer / Vioolsdrift Dam (NVD) project on the lower Orange River located 300 km upstream of the estuary. The flow patterns and sediment dynamics at the estuary were evaluated as supporting information to the feasibility study of the proposed NVD site. A statistical analysis of the entire flow regimes and monthly sediment concentrations for the Orange River estuary was performed. Six different dam scenarios ranging in height between 35 m and 80 m are compared to the present and the natural states for the 52-year period from October 1931 to September 1983. Another two scenarios were considered for 35 m and 70 m high dams with freshet environmental releases in the range of 20 to 40 m^3/s (monthly average data).

Under "natural" conditions (1920), the sediment load at the Orange River mouth was 51.4 million t/a, but was decreased due to dam development (mainly until 1975) to 19.6 million t/a for the present state, but the proposed NVD scenarios will further decrease the sediment loads at the mouth, to as low as 0.5 million t/a for the 80 m high dam.

All the proposed dam scenarios cause a 39% to 92% reduction in the 1-year to 5-year annual recurrence interval flood peaks compared to the present state. 1D hydrodynamic modelling showed significantly lower water levels and flow velocities in the estuary for the post-dam scenarios than under the natural and present scenarios for these floods. If it is assumed that that the estuary mouth closes when flow rates $< 5\ m^3/s$ occur for 3 months or longer, the mouth closure events would become longer and more frequent with the construction of the NVD project and the estuary channels would become shallower and sediment-laden. Larger post-dam 1 to 5-year ARI floods are required to improve the sediment transport capacity at the estuary and to increase floodplain flooding. If the proposed dam is flushed during the flood season to manage the sedimentation in the reservoir, the number of floods and flood peaks of the small floods will increase at the estuary.

1. Background

The feasibility study for the proposed Noordoewer / Vioolsdrift Dam (300 km upstream of the estuary) required further investigation to address the reservoir sedimentation and its impact on the Orange River estuary. The estuary is located on the South Atlantic Ocean on the border between South Africa and Namibia and is regarded internationally as one of the most significant coastal wetlands. Natural flow along the course of the Orange-Senqu River has been affected by the construction of large dams between 1970 and 1975, that trap sediment and control the runoff that reaches the estuary, which are essential for channel form and riparian ecosystems. It could be beneficial to design the NVD project with flushing, not only to ensure a long-term storage capacity of the reservoir, but to ensure small flood releases with increased sediment loads reach the estuary.

2. Changes in the Estuary's flow regime

2.1 Mean monthly flow rates

A statistical analysis of the entire flow regime for the Orange River estuary was performed and are presented in Fig. 1 in the form of a percentile plot and the percentage difference from the Present and Natural state flow regimes.

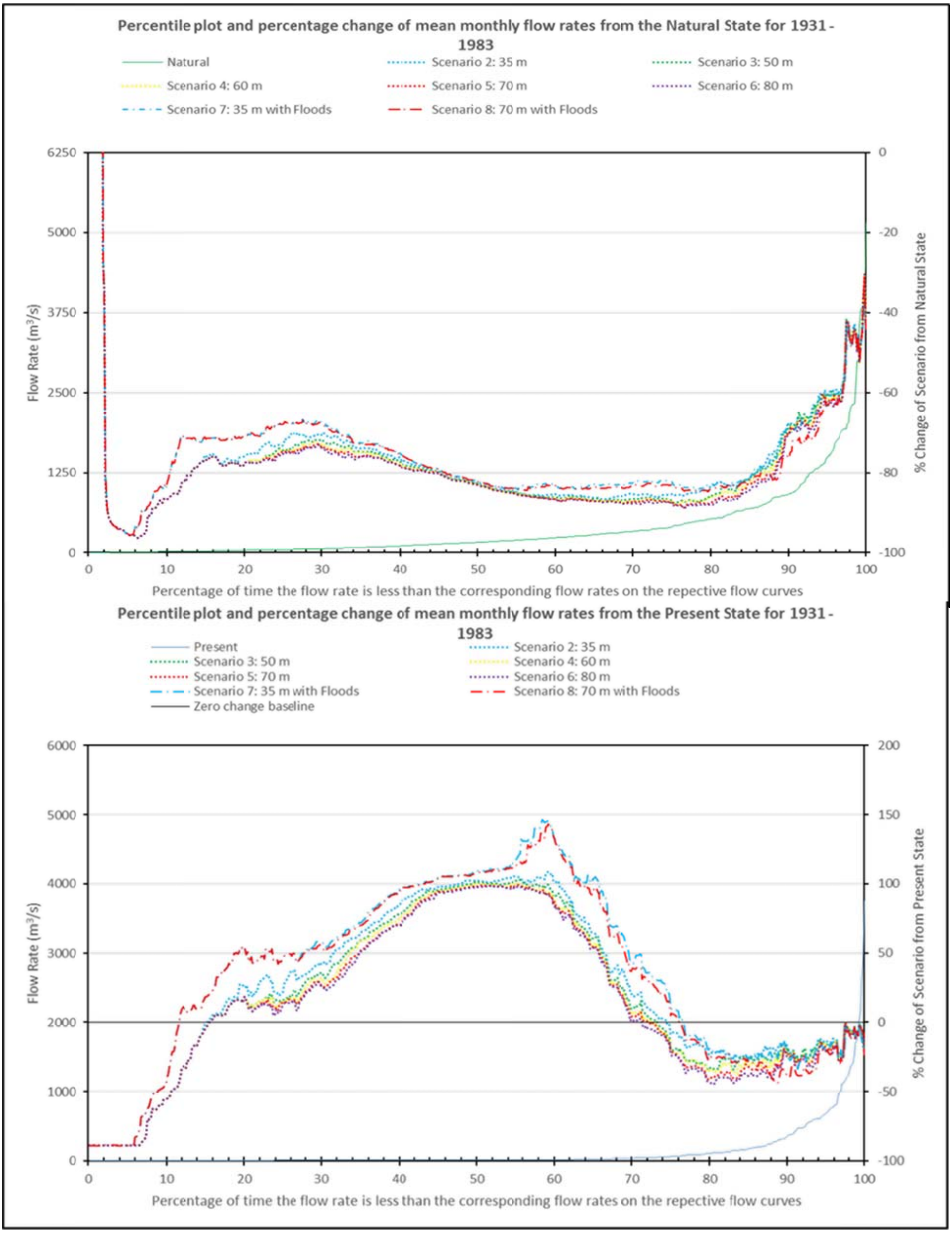

Fig. 1. Percentile plot of mean monthly flows and % difference from Present and Natural states

Evidently, flow rates for all dam scenarios are significantly smaller than that of the natural state over the entire percentile flow range. The reduction in flow rates for Scenarios 2 to 6 are very similar with a small variation between them especially in percentile ranges smaller than the 16 level and in the range between the 96 and 100 percentile levels. Outside these percentile ranges there is a correlation between dam height and impact on flow rate i.e. the higher the dam the larger the reduction in flow. The reduction in flow rates for Scenarios 7 and 8 (both with freshets released from the dam) are also similar but slightly smaller than that for the other scenarios. It is clear that the base flow releases from the proposed dam should be increased to ensure low flows at the estuary of more than 5 m^3/s to prevent mouth closure.

For the present state comparison, all the dam scenarios cause a reduction in flow rates in the percentiles ranges smaller than 12 and larger than 72. Outside these percentile ranges all the dam scenarios cause an increase in flow rates. The reduction in flow rates for Scenarios 2 to 6 are very similar with a small variation between them especially in percentile ranges smaller than the 16 level and between the 95 and 100 percentile levels. In general, there is a correlation between dam height and impact on flow rate i.e. the higher the dam the larger the reduction in referred two extreme percentile ranges and in the mid-percentile range the higher the dam the smaller the increase in flow rate. The changes in flow rates for Scenarios 7 and 8 are also similar and follow the same pattern as Scenarios 2 to 6 but with a slightly larger increase in the mid-percentile range and a smaller decrease in the extreme percentile ranges.

2.2 Durations and frequencies of monthly flow rates

The statistical analysis of the Orange River flow regimes was supplemented with an analysis of the durations and frequencies of monthly flow rates < 5m^3/s over the 52-year data period, presented in Fig. 2 for the different scenarios. If it is assumed that when flow rates < 5m^3/s occur for 3 months or longer the mouth will close, the impact of the dam scenarios is that mouth closure events become longer and more frequent. The impact of Scenarios 2 to 6 are the same with a mean interval between mouth closures of 5 months. Scenarios 7 and 8 have a mean interval between mouth closure of 7 months compared to 52 months for the Natural state and 17 months for the Present state.

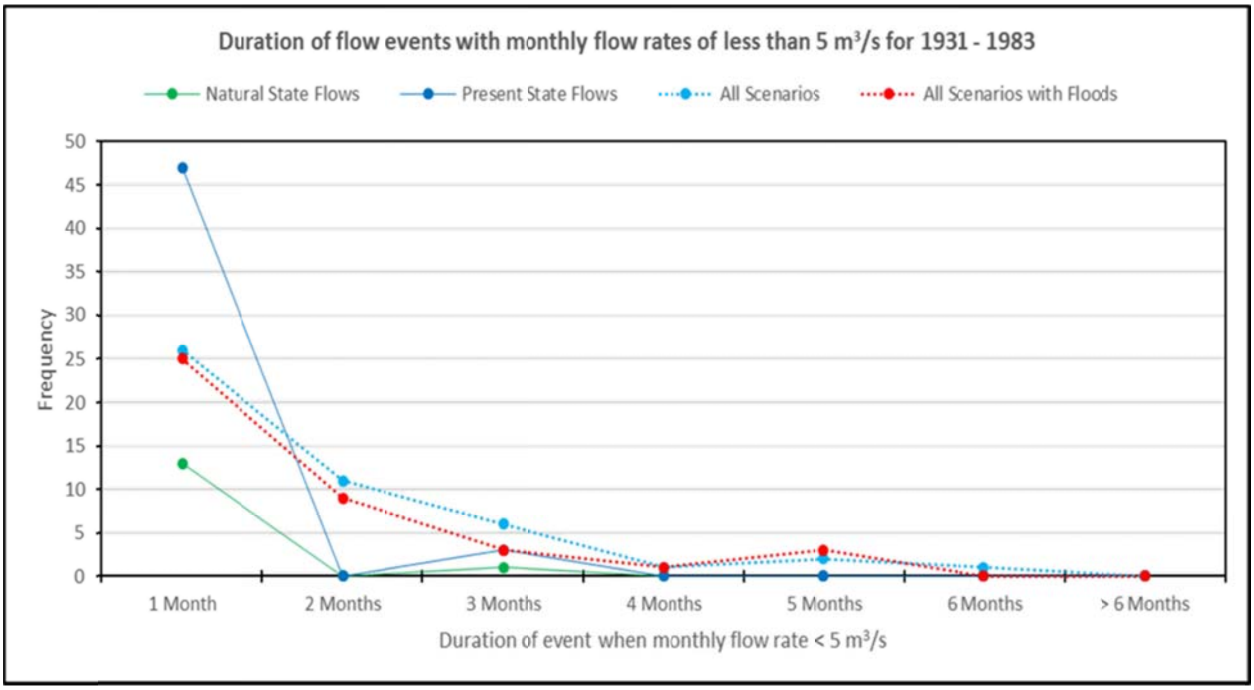

Fig. 2. Duration and frequency plot of monthly flows < 5 m^3/s compared to Present and Natural states

2.3 Annual recurrence interval flood peaks

The instantaneous annual recurrence interval (ARI) flood peaks at the Orange River mouth are indicated in Table 1. There are significant reductions in the 1 to 10-year floods for all the scenarios compared to the natural state (-97% to -63% respectively). The 1 year, 2 year and 5-year flood peak reductions compared to the present state will also be significant (-92% to -39% respectively). These smaller floods are very important for the functioning of the estuary to flood the higher zones and the re-entrain deposited sediment. The 10 year flood and larger floods are less affected by the proposed dam scenarios.

Table 1. Instantaneous flood peaks (m^3/s) for different recurrence intervals at the Orange River mouth

ARI (years)	Natural state	Present state	Scenario 2: 35 m	Scenario 3: 50 m	Scenario 4: 60 m	Scenario 5: 70 m	Scenario 6: 80 m	Scenario 7: 35 m with freshets	Scenario 8: 70 m with freshets
1	1609	699	53	53	53	53	53	53	53
2	4376	1901	366	274	184	159	159	249	171
5	8727	3792	2301	2282	2282	2279	2277	2295	2279
10	11845	5146	4420	4417	4410	4405	4398	4420	4405

2.4 Hydrodynamic modelling of the Estuary

Fig. 3 shows the simulated average water levels obtained from a 1D hydrodynamic model of the estuary.

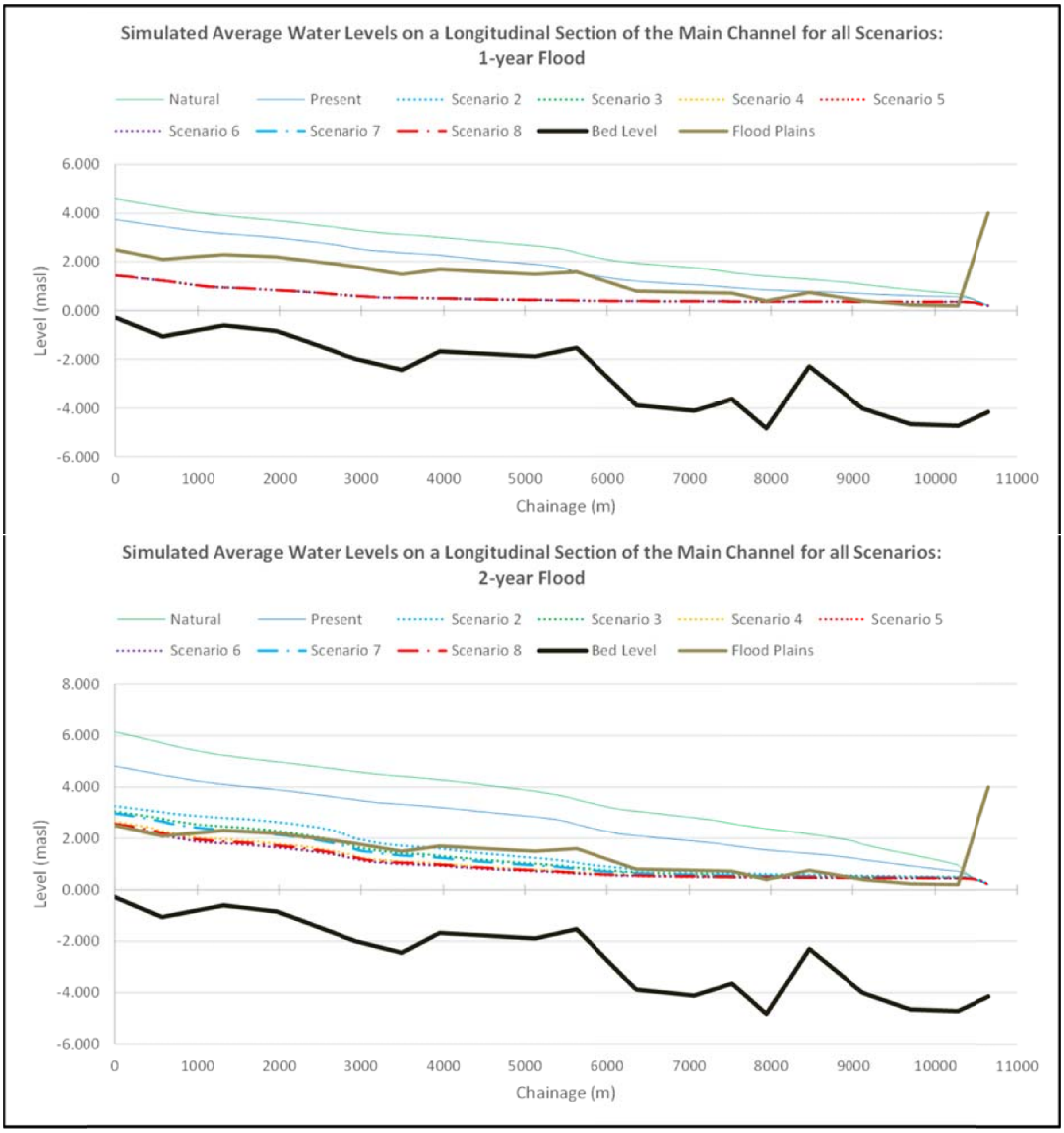

Fig. 3. Simulated average water levels along the estuary for (a) 1 year flood and (b) 2 year flood

The 1D hydrodynamic model was set up based on berm and some underwater survey data obtained from the CSIR. Higher zones in the estuary to 5 masl were built into the model by using elevation data from Google Earth. The berm height was selected as 4 masl. The 1 and 2-year flood peaks were simulated as steady inflow, with the typical sea levels and tidal variation over a period of one month. The small floods were selected because they are the most affected (reduced) by the proposed dam. The mouth opening area, depth and width was determined for each scenario based on the simplified relationships (Equations. 4 & 5) of Stive & Rakhorst (2008) and (Figure II-6-7) of the Coastal Engineering Manual (2006). Fig. 3 indicates the longitudinal section of bed levels and floodplain elevations through the 11 km long estuary with river flow from left to right. From chainage 6.2 km to chainage 10.6 km (the mouth), the floodplains are wide at < 1 masl, but further upstream the floodplain elevations are higher at 2 masl.

The simulated post dam scenario water levels indicate similar water levels for the dam scenario, and these levels are significantly lower than under the natural and present state. The floodplains are partly inundated along the full estuary during the present scenario for the 1 and 2-year floods, but the floodplain flooding for all the dam scenarios generally no longer occurs.

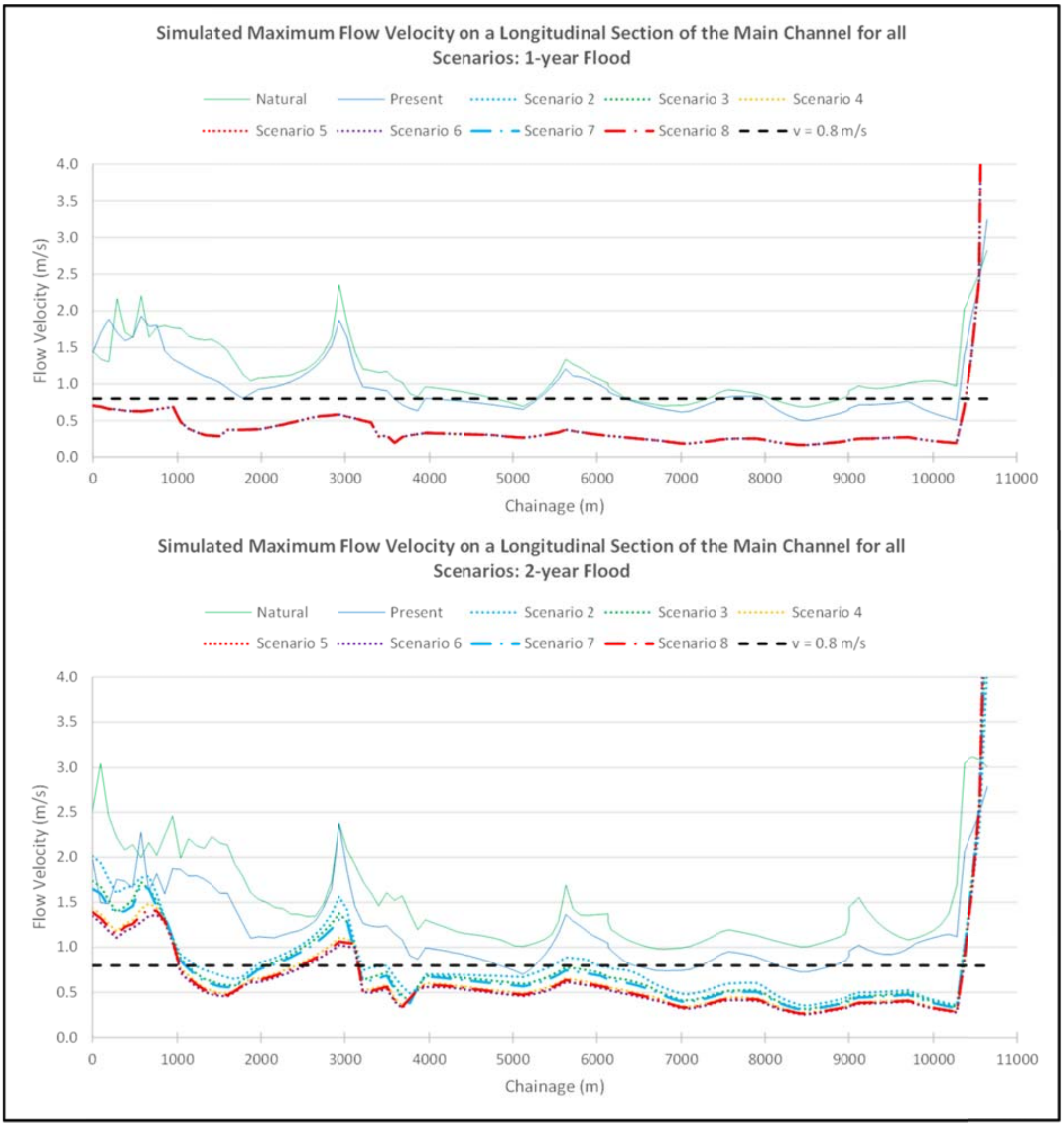

Fig. 4. Simulated maximum flow velocities along the estuary for (a) 1 year flood and (b) 2 year flood

Probably the most important simulation outputs to evaluate the possible impact of the proposed dam scenario, are the simulated flow velocities along the estuary shown in Fig 4. The dotted black line indicates the critical velocity of 0.8 m/s for re-entrainment of non-cohesive sediment from the bed.

Downstream of chainage 3.8 km the present scenario flow velocities generally drop to below the critical velocity, but during the 2-year flood the present scenario velocities are higher than the critical velocity for re-entrainment over the same reach, and therefore the present equilibrium morphology of the estuary is maintained. All the velocities of the future dam scenarios have flow velocities significantly lower than the present scenario flow velocities for the 1 and 2-year floods.

For the future scenarios it is expected that the estuary channels will become shallower due to sediment deposition due to the smaller frequent floods. From chainage 1 to 3.8 km (upper estuary) the main channel could become 40% shallower on average, from chainage 3.8 to 7 km the channel could become 50% shallower, and from chainage 7 km to the mouth the channel could become 60 % shallower. The main channel width will also decrease in the upper river dominated reach by about 10 to 20 % for the dam scenarios from the present scenario.

3. Changes in the Estuary's sediment concentration

A statistical analysis of the calculated monthly sediment concentrations for the Orange River estuary was performed and are presented in Fig. 5 in the form of a percentile plot and the percentage difference from the Present and Natural states. Table 2 gives a summary of the sediment loads at the mouth. The sediment load was 51.4 million t/a under natural conditions (1920), but was decreased due to dam development (mainly until 1975) to 19.6 million t/a, and the proposed NVD dam scenarios will decrease the sediment loads at the mouth significantly, to as low as 0.5 million t/a for the 80 m high dam.

Table 2. Sediment load summary

Description	Natural state	Present state	Scenario 2: 35 m	Scenario 3: 50 m	Scenario 4: 60 m	Scenario 5: 70 m	Scenario 6: 80 m	Scenario 7: 35 m with freshets	Scenario 8: 70 m with freshets
Sediment Load at Mouth (million t/a)	**51.40**	**19.60**	**4.12**	**1.86**	**1.07**	**0.68**	**0.52**	**4.03**	**0.66**
Sediment Trapped in Dam (million t/a)	-	-	11.15	13.62	14.25	14.47	14.40	10.91	14.08
% Sediment Trapped in proposed Dam	-	-	73%	88%	93%	95.5%	97%	73%	95.5%

**based on Brune trap efficiency curve*

The total suspended sediment concentrations (TSS)/turbidity at the estuary for all dam scenarios are significantly smaller than that of the natural state over the entire percentile flow range. In general, the natural TSS concentrations are reduced by all the dam scenarios over the entire percentile range. The reduction in TSS concentrations for Scenarios 2 to 6 are very similar. The reduction in TSS concentrations for Scenarios 7 and 8 (both with floods) are also similar but slightly smaller than that for the other scenarios.

Compared to the present state, all the NVD scenarios cause a reduction in TSS concentrations in the percentile ranges smaller than 12 and larger than 72. Outside of these percentile ranges all the dam scenarios cause increased concentrations compared to the present scenario. The reduction in TSS concentrations for Scenarios 2 to 6 are very similar with a small variation between them especially in percentile ranges smaller than the 16 level and between the 90 and 99 percentile levels. In general, there is a correlation between dam height and impact on TSS concentrations i.e. the higher the wall the larger the reduction in referred two extreme percentile ranges and in the mid-percentile range the higher the wall the smaller the increase in TSS concentrations. The changes in TSS for Scenarios 7 and 8 are also similar and follow the same pattern as Scenarios 2 to 6, but with a slightly larger increase in the mid-percentile range and a smaller decrease in the extreme percentile ranges.

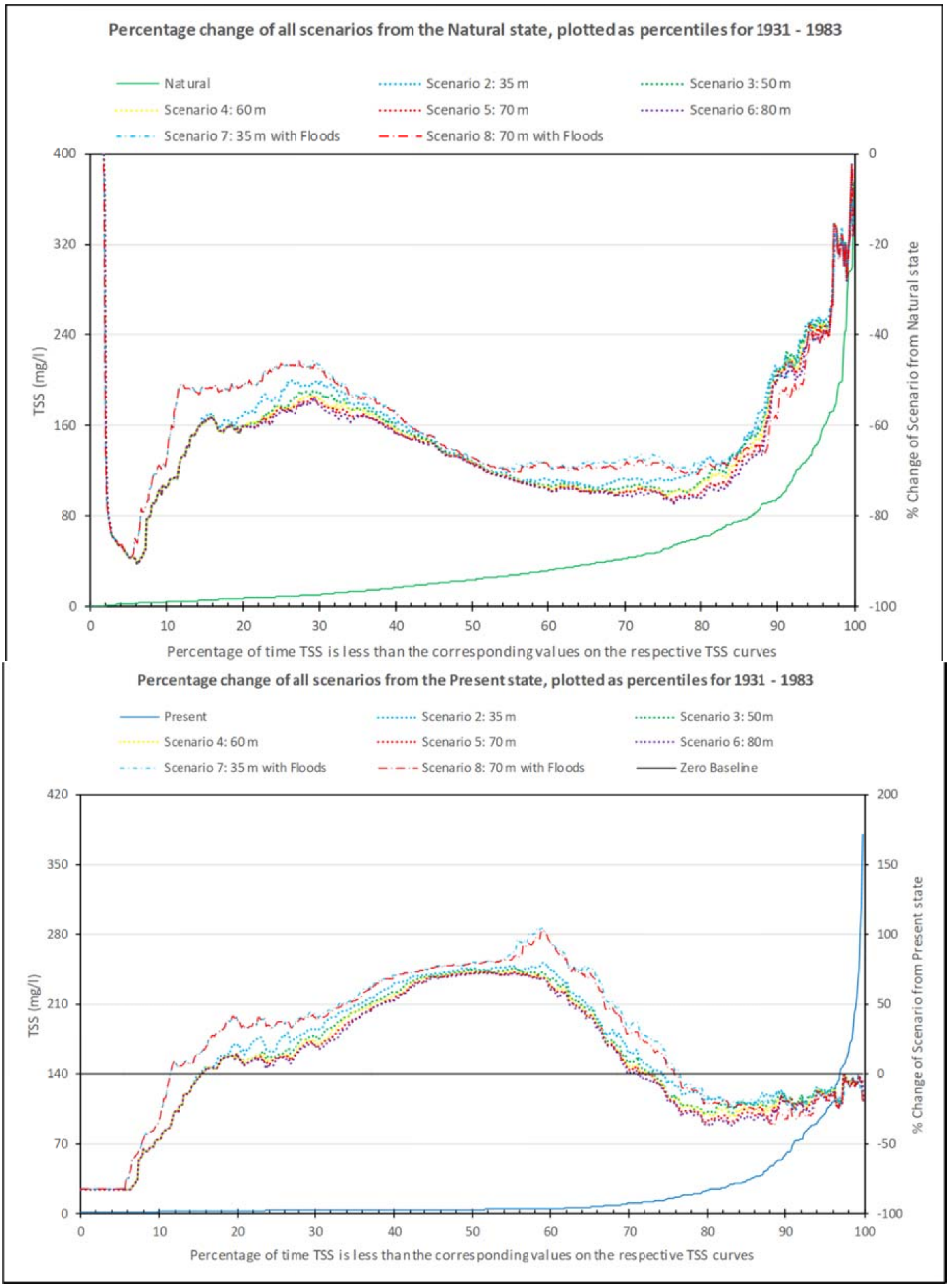

Fig. 5. Percentile plot of mean monthly TSS and % difference from Present and Natural states

4. Conclusions

A statistical analysis of flow regimes and monthly sediment concentrations was done to determine the impact of the proposed NVD project on the Orange River estuary. The durations and frequencies of monthly flow rates at the estuary < 5 m^3/s were compared with that of the natural and present states.

It was assumed that when flow rates < 5m³/s occur for 3 months or longer the estuary mouth will close. All the dam scenarios cause a reduction in flow rates (about 20% to 50%), in the percentiles ranges smaller than about the 12 percentile and larger than about the 72 percentiles, when compared to the present state. The impact of the dam scenarios is that mouth closure events become longer and more frequent. The current scenario mean interval between mouth closures is 17 months, while in future this will decrease to 5 to 7 months for the dam scenarios. The 1-year, 2-year and 5-year flood peak reductions caused by a new dam compared to the present scenario will be significant, with reductions varying between 39 to 92%. These smaller floods are very important for the functioning of the estuary to flood the higher zones and to re-entrain deposited sediment.

A 1D hydrodynamic model of the estuary was set up based on berm and underwater survey data and simulations were done for the present and future dam scenarios. The simulated post dam scenario water levels indicate similar water levels for the dam scenarios, and these levels are significantly lower than under natural and present scenarios. The floodplains are typically partly inundated along the full estuary during the present scenario for the 1-year and 2-year floods, but the floodplain flooding for all the dam scenarios generally no longer occurs. All the flow velocities of the future dam scenarios have flow velocities significantly lower than the present scenario flow velocities for the 1 and 2-year floods. For the future scenarios it is expected that the estuary channels will become shallower due to sediment deposition due to the smaller frequent floods.

Under "natural" conditions (1920), the sediment load at the Orange River mouth was 51.4 million t/a, but was decreased due to dam development (mainly until 1975) to 19.6 million t/a, but the proposed NVD scenarios will decrease the sediment loads at the mouth even more, to as low as 0.5 million t/a for the 80 m high dam.

Based on the above, larger post-dam 1-year, 2-year and 5-year ARI floods are required at the estuary to improve the sediment transport capacity at the estuary and to increase floodplain flooding. With smaller frequent floods for the dam scenarios, the marine sediment will dominate the lower estuary further upstream than under present conditions. It will only be floods larger than the 10-year flood that could reset the estuary bed sediment grading. If the proposed dam is flushed during the flood season to manage the sedimentation in the reservoir, the number of floods and flood peaks of the small floods (<10-year flood) will increase at the estuary.

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