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Sharing Water: Multi-Purpose of Reservoirs and Innovations

Reservoir sedimentation mitigation measures to deal with a severe drought at Graaff-Reinet, South Africa

Mesures d'atténuation de l'alluvionnement du réservoir pour faire face à une grave sécheresse à Graaff-Reinet, Afrique du Sud

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Abstract. The Nqweba Dam is one of the oldest dams in South Africa and was commissioned in 1925 for irrigation. The original reservoir depth at the dam wall was 31 m, but over the years sedimentation has reduced the water depth to 9.8 m. The original storage capacity of 79 million m^3 has decreased to 46 million m^3 by 2020. The dam supplies the town of Graaff-Reinet and due to the growing population at 1.9% pa it was realised in 1995 that the water use should change from irrigation to 100% potable use. For the past 25 years the town has been supplied from the dam when it has water and from ground water when the dam runs empty during droughts. The current water requirement of the town is 3.3 million m^3/a and during 2019 the dam ran dry, while the ground water resource only supplied less than 50% of the demand. Urgent short and medium term measures were sought to solve the water crisis. Dam raising was found not to be beneficial, but options to increase storage capacity such as dredging or a new off-channel dam, and reduce evaporation such as floating balls/solar panels on part of the reservoir will restore the dam's firm yield.

Résumé. Le barrage de Nqweba, l'un des plus anciens barrages d'Afrique du Sud, a été mis en service en 1925 pour l'irrigation. La profondeur initiale de la retenue était de 31m, mais au fil des ans, l'alluvionnement a réduit la profondeur de l'eau à 9,8m. La réserve totale initiale de 79 millions de m^3 a été réduite à 46 millions de m^3 en 2020. Le barrage alimente la ville de Graaff-Reinet et en raison de l'augmentation de la population (1,9 % par an), il a été établi en 1995 que l'utilisation de l'eau devait passer de l'irrigation à une utilisation 100 % potable. Depuis 25 ans, la ville est alimentée par le barrage lorsqu'elle a de l'eau et par les eaux souterraines lorsque le barrage se vide durant les sécheresses. Les besoins actuels en eau de la ville s'élèvent

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à 3,3 millions de m^3 par an. En 2019, le barrage s'est asséché tandis que la ressource en eau souterraine a fourni moins de 50% de la demande. Des mesures urgentes à court et moyen terme ont été recherchées pour résoudre la crise de l'eau. L'élévation du barrage n'a pas été bénéfique, mais des options pour augmenter la capacité de stockage sont étudiées, tel que le dragage ou un nouveau barrage hors chenal, ainsi que l'utilisation de ballons flottants / panneaux solaires sur la retenue pour rétablir le rendement ferme.

1 Background

The Nqweba Dam was constructed in 1925 to supply Graaff-Reinet in the Eastern Cape of South Africa, initially to support irrigation and later in 1995 solely to satisfy the potable water demand of the town due to the growing population. However, the reservoir is characterized by a large surface area with high evaporation rates and a low assurance of supply, having only overflowed 8 times and dried up 9 times to date. Furthermore, 42% or 33 million m^3 of its original capacity of 78.8 million m^3 has been lost due to sedimentation (Fig 1.). Based on the historic firm yield of 1.9 million m^3/a, the Nqweba Dam cannot supply Graaff-Reinet's 3.3 million m^3/a demand, which is projected to increase to 5.6 million m^3/a by 2050 due to the population growth. During 2019 the dam ran dry once again while the ground water resource supplied less than 50% of the demand (Fig 2.). Urgent short and medium term measures were sought to solve the water crisis. Different scenarios are presented to increase the Nqweba Dam's firm yield in a sustainable and economic manner.

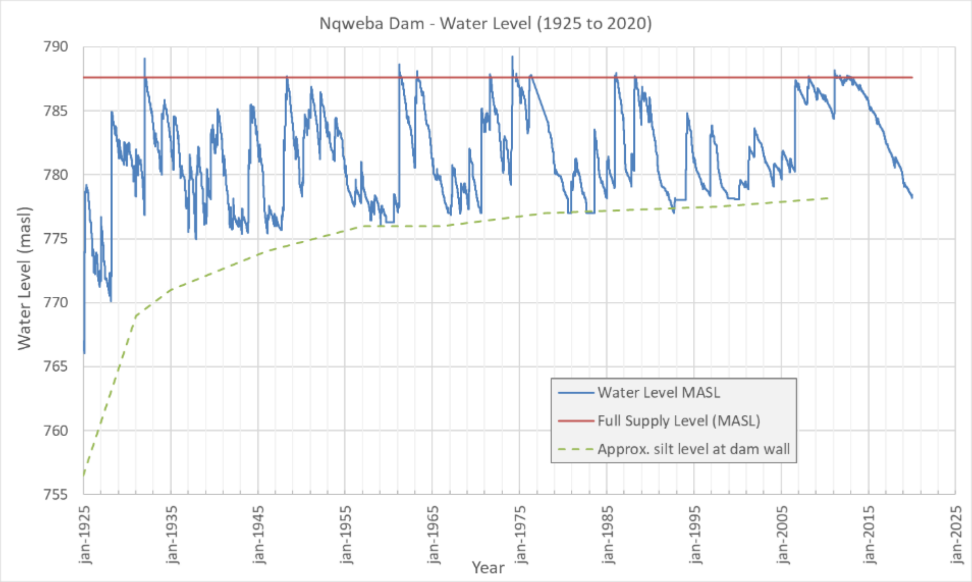


Fig. 1. Time plot of recorded reservoir water levels at the Nqweba Dam with the approximate observed increase in bed level due to sedimentation at the dam wall (green dotted line).

Fig. 2. Cracked sediment surface in the Nqweba Dam during the recent water crisis (left photograph by Reuters end 2019 and right photograph by Ellis, October 2019).

2 Water requirements of Graaff-Reinet

The population of Graaff-Reinet was 35 672 as published during the 2011 South African census and it is estimated that the population growth from 2011 to 2019 was 1.9 % per annum. This agrees with the current water demand of 3.3 million m^3/a (9 ML/d) and a 1.8 % historical growth in water use during the past decade. It is estimated that the future water demand growth will continue at a rate of 1.8 % pa to 5.6 million m^3/a (15 ML/d) in 2050 based on the recent growth in population. The current 9 Ml/d is the Average Annual Daily Demand (AADD) and should be supplied by both the Nqweba Dam and the existing boreholes. The existing water treatment works has a capacity of 16 Ml/d.

The water losses in the distribution network of Graaff-Reinet was 40 % in 2017, but is now estimated at 38% in 2020 i.e. 3.4 Ml/d of the current water use of 9 Ml/d is lost. The system is relatively old and a long-term loss of 30% can be expected from the distribution network. One of the first mitigation measures to consider should therefore be to upgrade the pipe network to reduce the system losses from 38% to 30%.

The water requirements of Graaff-Reinet are met by water supply from Nqweba Dam when it has water, and from ground water (boreholes). The water quality of Nqweba Dam is apparently better than from the boreholes (less saline) and therefore the town prefers use from Nqweba Dam whenever the dam has water. The priority to use Nqweba Dam water also stems from the principle to limit evaporation from the reservoir by using it.

The historical firm yield of Nqweba Dam is estimated at 1.9 million m^3/a (5.2 Ml/d), but originally in 1925 the firm yield was 5 million m^3/a (13.7 Ml/d) for a 1:50 year risk of failure in supply, which was more than the current water requirement of the town. The decrease was caused by reservoir sedimentation. The current dam has a firm yield that can only supply 58% of the current water requirement.

The total current groundwater resource has a developed supply of 4.9 Ml/d (3.4 Ml/d during droughts). Additional boreholes were planned during the drought of 2019 to supply an additional 4.4 Ml/d (3.1 Ml/d during droughts) but the pipelines have not yet been constructed. The combined supply is 9.3 Ml/d (6.5 Ml/d during droughts) which means that Graaff-Reinet has a current shortfall of 9-5.2-3.4 = 0.4 Ml/d in 2020 (4%) and 15-1.1-6.5 = 7.4 Ml/d in 2050 (49%). Therefore additional ground water sources and/or Nqweba Dam mitigation measures must be implemented to increase firm yield and assurance of the water supply to the town to provide for current and projected future (2050) demand.

3 Reservoir sedimentation

The Nqweba Dam has lost 33 million m^3 of its original Full Supply Capacity (FSC) of 78.8 million m^3. The observed mean annual storage loss of the original FSCs in South African reservoirs due to sedimentation is 0.37% per annum [1]. However, the observed Nqweba Dam storage loss per year is 0.51% pa by year 2011, which is significantly higher than the average for SA. This is still lower than the global mean annual storage loss due to sedimentation of 0.8 % pa though [1].

A decrease in sediment loads have been observed at the Nqweba Dam, from 0.72 million t/a (1940-1950) to 0.22 million t/a (2000-2011). A similar trend was found on the Lower Orange River before the construction of major dams [2]. Soil conservation was partly responsible but it is believed that land use change and farming practises lead to the decrease in sediment loads. With a catchment area of 3 668 km^2, the current sediment yield is therefore 60 $t/km^2.a$ which is relatively low for South Africa. A two-dimensional hydrodynamic model was used to predict the reservoir sedimentation by the year 2050, as shown in Fig. 3. It was assumed that the observed mean sediment load of 0.22 million t/a would increase by 10% by year 2050 due to extreme flood peaks and climate change.

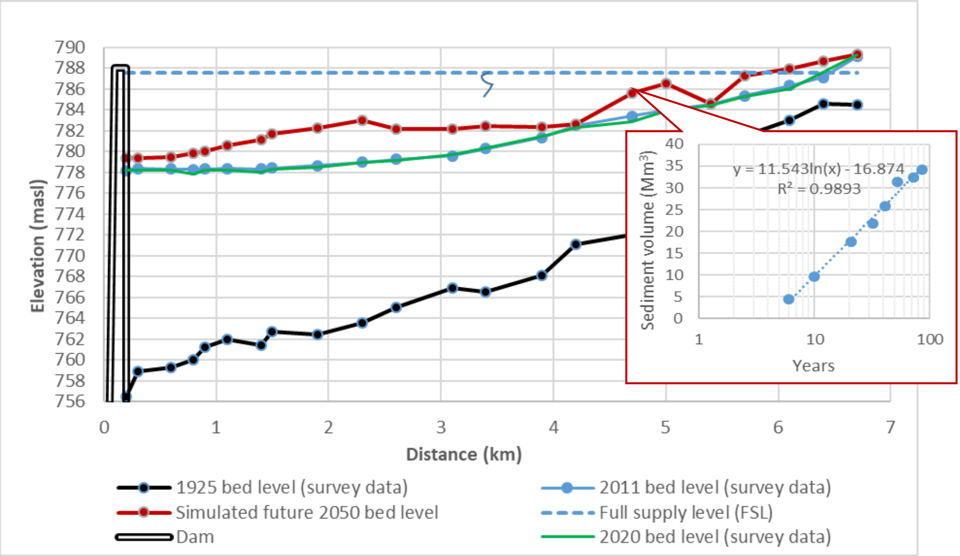


Fig. 3. Longitudinal profiles of the 2020 (surveyed) and 2050 (predicted) bed levels along the Nqweba Dam due to accumulative sediment in the Nqweba Dam.

4 Possible reservoir sedimentation mitigation measures

4.1 Sediment sluicing or flushing

When the storage capacity to mean annual runoff (MAR) ratio of a reservoir is less than 0.03, especially in semi-arid regions, sediment sluicing or flushing may be done during floods and through large bottom outlets. However, the Nqweba Dam capacity to MAR ratio exceeds 0.2 and therefore not enough excess water is available for flushing. Other reservoir sedimentation mitigation measures are required.

4.2 Dredging

Dredging the accumulated sediment deposits from the Nqweba Dam is seemingly obvious but expensive. If financially feasible, it could be a long-term solution that can be maintained in future by continuously performing maintenance dredging on any additional sediment deposits with time. The fine silt and clay dredged sediment would be suitable for clay brick manufacturing [2]. Although the income generated from brick manufacturing may not be significant, it has a social benefit to the local community at Graaff-Reinet. Six different dredging options were identified:

1. Dredging a 8 m deep channel with 1:8 side slopes and 20 m base width along the original river channel (best-practice guidelines as per Dredging Africa (Pty) Ltd)
2. Dredging to the original 1925 bed with 1:8 side slopes and 50 m base width
3. Dredging to within 2 m of the original 1925 bed levels based on practical limitations of the practical dredging equipment (e.g. Royal IHC Beaver 40)
4. Dredging as in option 1 but with the abstraction of 50% of the seepage water trapped in the settled sediment body, assuming it to be a feasible aquifer to utilise.
5. Dredging as in option 1 but with the abstraction of 25% of the seepage water trapped in the settled sediment body sediment body
6. Dredging as in option 1 but with a deeper section dredged at the dam wall and with the abstraction of 25% of the seepage water trapped in the settled sediment body.

While Dredging Option 4 would be the cheapest, it represents the upper limit whereby 50% of the seepage water trapped in the settled sediment can be abstracted, while the 25% proportion of options 5 and 6 is considered more realistic. The potential use of the aquifer in the settled sediment was assumed feasible for this study but this (as well as the aquifer in the river bed alluvium underlying the settled sediment) should be investigated in more detail to confirm this assumption.

4.3 Off channel dam

Off-channel dams have been used widely in South Africa, often to overcome the problems of sedimentation experienced at dams on rivers with large catchment areas and high sediment loads. An off-channel dam at Graaff-Reinet will increase the combined storage capacity and firm yield of the system. Water supply to the off-channel dam is usually pumped in South Africa by oversized pumps larger than the mean annual water supply from the dam in order to pump more flow during the rainy season and floods. The off-channel dam should have a small catchment area to limit sedimentation.

Several possible sites were identified for an off-channel dam (OCD). While several dams were closer to the Nqweba Dam than 16.5 km, it was found that the most feasible site (OCD1 -refer Figure 4) was the deepest dam that would provide the largest increase in storage capacity and smallest surface area. Two scenarios were initially considered for a 20 m (14.4 Mm^3) and 30 m (38.1 Mm^3) high embankment dam at OCD1 as well as different discharge capacities, which were optimized for the best firm yield benefit at the lowest cost.

Option 1: Pump abstraction from the upper Sundays River to OCD1 (refer Figure 4)

Water is stored in OCD1 by abstracting water from the Sundays River by pumping via a pipeline to OCD1 and from the Broederstroom (which flows past OCD1) by a gravity diversion canal. When the water stored in OCD1 is required, it is released down the Broederstroom to the Nqweba Dam. It was assumed that it would cheaper to release water down a river than by pipeline but there are seepage and evaporation losses.

Option 2: Transfer scheme from Nqweba Dam to OCD1 (refer Figure 4)

Raw water is stored in OCD1 by pumping directly from the Nqweba Dam via a pipeline to OCD1 (via the Water Treatment Works i.e. WTW) during the rainy season and releasing water back along the pipeline to the WTW at Nqweba Dam under gravity when it is required during the dry season. The Broederstroom diversion is also used as in Option 1.

Option 2 is cheaper than constructing a new river abstraction works and would maximize the yield since most of the sediment would be trapped in the Nqweba Dam before pumping. Option 2 also has the potential benefit of hydropower generation when water is released back along the pipeline to the WTW under gravity. However, electricity generation from the OCD transfer scheme will not be continuous and may not be considered a reliable source of income.

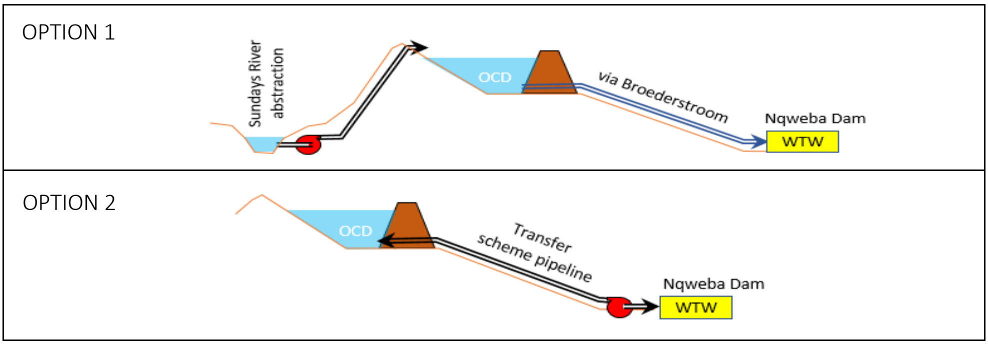


Fig. 4. Schematic illustration of Option 1 and Option 2 for the off-channel dam storage.

4.4 Inter-basin transfer scheme

The Orange-Fish River transfer scheme was built to divert water from the Gariep Dam to the Great Fish River in the Eastern Cape Karoo. Part of this transfer scheme is the tunnel which conveys water from the Gariep Dam to Teebus Spruit. For this alternative scheme, water could be pumped from the tunnel outlet at Teebus Spruit to transfer water to the WTW at the Nqweba Dam in the Sundays River catchment through a 163 km long pipeline. However, the availability of water for Graaff-Reinet from the Orange-Fish River transfer scheme would have to be negotiated with the South African Department of Water and Sanitation (DWS). Hydropower generation could also help recover some of the pump costs by taking advantage of the 399 m differential head.

4.5 Dam raising

The feasibility of raising the Nqweba Dam FSL by different heights was investigated to increase its firm yield. However, the benefit is limited because the surface area (subject to evaporation) increases almost linearly with the increase in reservoir capacity. The 3 m raising is considered the most feasible raising option in terms of dam safety and cost because it has a storage capacity similar to that of the original design.

Raising of the Nqweba Dam wall should preferably be done without affecting the Safety Evaluation Discharge (SED) flood surcharge water level, because this would require expensive modifications to the dam wall, if it is assumed that the current dam is safe for the SED. Dam raising could be achieved in the following ways without compromising the SED level and dam safety:

- A 1 m raising of the ogee spillway if its piers and road are removed;
- A 2 m raising of the Full Supply Level (FSL) if the ogee and piers are replaced by a Piano Key Weir (PKW) spillway;
- A 3 m raising with fusegates or automated control gates.

Amanziflow Projects (Pty) Ltd proposed that 6 of their TOPS gates and 34 release gates could be implemented to open automatically to release large floods in response to the rising water level in a dam (without affecting the SED level) and close to maintain the increased FSL. The Amanziflow release gates are a type of safety fuse gate that operate in conjunction with the TOPS gates to release surplus water in the event of an extreme high flood level. However, they do not detach from the structure like traditional French fuse gates and can be reinstated to their closed position after a flood. The gates are designed to fail (i.e. open) successively for different floods based on the increasing water levels, typically commencing at the Recommended Design Discharge (RDD).

4.6 Anti-evaporation technology

Perhaps a more controversial but effective solution is to reduce the water losses from evaporation, particularly because the reservoir is characterized by a large surface area (1026 ha) with high evaporation rates (S-pan MAE of 1934 mm and MAP of 356 mm).

Shade balls are an innovative modular reservoir cover used in California and Israel which are capable of reducing evaporation by 80-90%. Unlike standard shade covers, the balls allow rainfall to be harvested and can accommodate increasing or decreasing water levels. In 2008, approximately 400 000 black HDPE shade balls with a 10 cm diameter were deployed on the Los Angeles Reservoir with the main objective of preventing the formation of the carcinogenic chemical, bromate, which forms naturally when bromine reacts with chlorine in sunlight. However, it was found that the balls were also saving water by limiting evaporation. Mekorot in Israel tested the shade ball system in 2014 and concluded that up to 94% of evaporation can be reduced, with an average reduction in the overall water temperature by 4-6°. Other benefits included reduced algae growth and chlorine costs. The EvaSpheres are an example of an anti-evaporation technology that has been optimized for South Africa with a total cost of R866/m^2 (1USD to 18.5ZAR at the time of the study).

Floatovoltaics or modular solar panels floating on pontoons is becoming increasingly popular because they have the benefit of cooling the panels and saving space on land. They have been implemented on over 100 dams worldwide and are particularly popular in Japan. They also have the added benefit that they are able to reduce up to 80% of evaporation and earn an income from the energy generation. New Southern Energy (NSE) installed the first commercial floating solar park in South Africa on one of the reservoirs at Marlenique Estate, Franschhoek in 2019. The capital costs for anti-evaporation technology is very expensive but solar panels could potentially recover the costs or make a profit from the solar energy generation if it is sold to Eskom.

If floating balls or solar panels were to be placed for 2.9 km upstream of the Nqweba Dam wall (where no vegetation would affect it), an 80% reduction in evaporation for a maximum surface area of 171 ha could nearly double the firm yield. Implementing anti-evaporation covers on the Nqweba Dam has certain risks that could ideally be mitigated by instead placing the floating balls or solar panels on the off-channel dam. Spilling of the balls or panels during large floods would not require special consideration because the scenarios with the transfer scheme to the off-channel dam scenarios should be optimized such that spilling would never occur to minimize pump costs. Furthermore, public access to the off-channel dam can be prohibited to control vandalism and safety without seizing public recreational areas at the Nqweba Dam.

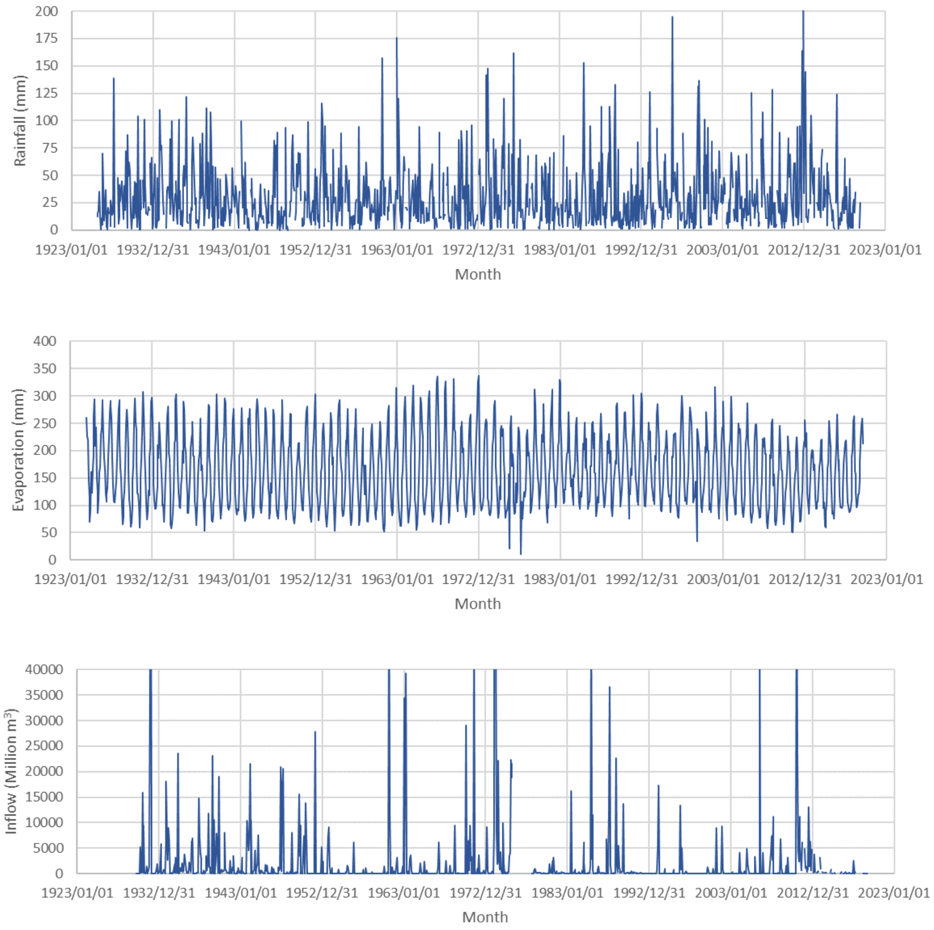
5 Firm yield and unit cost analysis

The different scenarios proposed to increase the Nqweba Dam's firm yield were ranked by a Net Present Value (NPV) cost analysis. The scenarios should ideally be capable of delivering Graaff-Reinet's water demand but the most economically feasible scenarios have the lowest unit cost or *average cost per incremental firm yield* (R/kL).

The average incremental firm yield is calculated as the increase in the 1:50 year firm yield compared to the "Do Nothing" scenario and is taken as the average between current and future firm yields. The "Do nothing" scenario is the historic firm yield for the current development scenario with a 45.7 million m^3 FSC. The future firm yield is based on the reduced FSC of 33.9 million m^3 due to the anticipated reservoir sedimentation. The current and future firm yields for the different scenarios were calculated by adjusting the reservoir capacity and their corresponding elevation-capacity-area relationships. The firm yield analysis was then done by applying the same assumptions and the same monthly inflow, evaporation and rainfall data used to calculate the historic firm yield (Fig. 5).

The capital, operation and maintenance costs were calculated as NPV over 30 years at a real interest rate of 4% based on some of the following assumptions:

- Fastest practical dredging rate of 2 million m^3/a at a unit cost of R44.50/m^3
- 7 MPa plaster clay bricks can be sold at a net profit of R0.20/brick
- Pump / turbine costs R17 700/kW which are increased x50% for building civil costs
- Energy costs at Eskom's RuraFlex rate of R1.20/kWh and R1.67 HomePower rate
- Ductile iron pipeline at R720/m for a 0.2 m nominal diameter to R5050/m for 0.8 m
- Average property value of R5664/ha for the region
- OCD construction, excavation, fill and compaction costs of R274/m^3
- RCC concrete construction, labour and civil works R 5 000/m^3
- Unit demolition and disposal costs R2 622/m^3
- Amanziflow TOPS gate at R2.58 million and release gate at R0.234 million
- Shade balls cost R866/m^2 while floating solar panels cost R2960/m^2 which can generate 1 MW/ha energy
- Operation and maintenance of different components
    - Civil (pipes; buildings) is 0.5% per annum of the civil capital cost
    - Mechanical/electrical is 4% per annum of the M&E capital cost
    - Annual operation/admin costs is 1% per annum of total construction costs
- 15% VAT, 30% P&G's and 10% contingencies were included in life cycle costs.



Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Demand	0.09	0.09	0.10	0.11	0.08	0.08	0.08	0.07	0.06	0.06	0.08	0.09

Fig. 5. Monthly rainfall, S-pan evaporation, inflow and demand distribution at Graaff-Reinet.

Table 1 shows a summary of all the scenarios in terms of average incremental firm yield, total cost and income, as well as the unit cost. The best scenarios within each category is highlighted. Based on the unit costs without the potential sale of solar power, the following scenarios are ranked from cheapest to most expensive:

1. Dredging Option 6 (R207/kL)
2. Great Fish – Sundays Transfer Scheme (R264/kL)
3. OCD1 20m or 30m (R389/kL or R512/kL)

Table 1. Summary of all scenarios to increase the firm yield at the Nqweba Dam.

Scenario		1:50 Firm yield (2020)	1:50 Firm yield (2050)	Average increase in firm yield	Total NPV cost	Income NPV	Unit cost	Unit cost including income
		(Million m^3/a)			(Million R)		(R/kL)	
Base case (1925-survey)		4.951						
Do nothing (2011-survey)		1.885	0.384					
Dam raising	1m raise by gates	2.290	0.804	0.413	257	0	123	624
	by PKW	2.290	0.804	0.413	97	0	624	235
	by ogee	2.290	0.804	0.413	65	0	235	158
	2m raise by gates	2.290	0.804	0.413	486	0	158	1176
	by PKW	2.455	1.111	0.648	109	0	111	168
	by ogee	2.455	1.111	0.648	707	0	749	1090
	3m raise by gates	2.455	1.111	0.648	585	0	168	903
	by PKW	2.455	1.111	0.648	679	0	1090	1047
	by ogee	2.620	1.111	0.731	846	0	125	1157
	4m raise by PKW	2.620	1.111	0.731	793	0	801	1084
	by ogee	2.620	1.111	0.731	979	0	929	1339
	5m raise by PKW	2.620	1.111	0.731	901	0	1157	1232
	by ogee	2.697	1.111	0.769	1107	0	1030	1439
	10m raise by PKW	2.697	1.111	0.769	1385	0	1272	1800
	by ogee	2.697	1.252	0.840	1704	0	1072	2029
Dredging	Option 1	3.038	3.038	1.904	460	2	242	241
	Option 2	4.244	4.244	3.109	832	2	268	267
	Option 3	3.590	3.590	2.456	978	2	398	397
	Option 4	4.006	4.006	2.872	507	2	177	176
	Option 5	3.550	3.550	2.415	505	2	209	208
	Option 6	3.865	3.865	2.731	565	2	207	206
OCD1 20m Option #1	0.5cmps	2.565	1.671	0.984	1146	0	1166	1166
	1cmps	2.913	2.028	1.336	1305	0	977	977
	5cmps	3.390	2.757	1.939	2500	0	1290	1290
	10cmps	3.508	3.562	2.401	3951	0	1646	1646
	5cmps (no BS)	2.725	1.790	1.123	1252	0	1115	1115
OCD1 30m Option #1	0.5cmps	2.674	1.692	1.048	1992	0	1900	1900
	1cmps	2.991	2.285	1.504	2154	0	1432	1432
	5cmps	3.930	4.209	2.935	3363	0	1146	1146
	10cmps	4.269	4.650	3.325	4827	0	1452	1452
	5cmps (no BS)	3.791	4.053	2.787	3195	0	1146	1146
OCD1 20m Option #2	0.25cmps	4.596	3.882	3.105	1233	6	397	395
	0.5cmps	4.590	3.947	3.134	1374	6	438	436
	1cmps	4.515	3.941	3.093	1644	6	532	530
	2cmps	4.402	3.938	3.035	2170	6	715	713
	0.25cmps (no BS)	4.597	3.872	3.100	1207	6	389	387
OCD1 30m Option #2	0.25cmps	5.476	4.918	4.063	2138	19	526	522
	0.5cmps	5.784	5.316	4.415	2289	19	518	514
	1cmps	6.011	5.609	4.676	2570	19	550	546
	2cmps	6.192	5.803	4.863	3113	19	640	636
	0.5cmps (no BS)	5.774	5.287	4.396	2253	19	512	508
Other	OCD3 20m Option 2	3.155	2.375	1.631	385	0	236	236
	OCD6 20m Option 2	3.150	2.204	2.464	426	0	2	173
	Great Fish - Sundays Transfer	3.815	2.314	1.930	819	310	424	264
Anti-evaporation technology	Shade balls on Nqweba Dam	4.045	1.923	1.850	1992	0	1077	1077
	Solar panels on Nqweba Dam	4.045	1.923	1.850	6812	6672	3683	76
	Shade balls on OCD1 20m #2	5.900	5.346	4.489	3070	0	684	684
	Solar panels on OCD1 20m #2	5.900	5.346	4.489	7721	6311	1720	314
	Shade balls on OCD1 30m #2	8.312	7.697	6.870	5461	0	795	795
	Solar panels on OCD1 30m #2	8.312	7.697	6.870	13439	10693	1956	400
	Shade balls on OCD3 20m #2	3.424	2.670	1.912	820	0	429	429
	Solar panels on OCD3 20m #2	3.424	2.670	1.912	1892	1611	989	147

**no BS refers to off-channel dam scenarios excluding the Broederstroom diversion*

6 Combination of scenarios

The following combined scenarios were considered to maximize the firm yield and to minimize the unit cost (R/kL):

- Combo A: Anti-evaporation technology on the Nqweba Dam with Dredging Option 6
- Combo B: Anti-evaporation technology combined with a 3 m raising of the Nqweba Dam with automatic control gates
- Combo C: Dredging Option 6 with a 3 m raising with automatic control gates
- Combo D: 30 m high OCD1 (Option 2 transfer scheme - 0.5 m^3/s pump capacity for 2618 hours per year without the Broederstroom diversion) combined with a 3 m raising of the Nqweba Dam with automatic control gates
- Combo E1: 20 m high OCD3 (Option 2 transfer scheme - 0.25 m^3/s pump capacity for 596 hours per year without the Broederstroom diversion) with Dredging Option 6
- Combo E2: 30 m high OCD1 (Option 2 transfer scheme - 0.5 m^3/s pump capacity for 2651 hours per year without the Broederstroom diversion) with Dredging Option 6
- Combo F: Anti-evaporation technology on the 30 m high OCD1 (Option 2 transfer scheme - 0.5 m^3/s pump capacity for 1 028 hours per year without the Broederstroom diversion) combined with 3 m raising of the Nqweba Dam with automatic control gates
- Combo G: Anti-evaporation technology on the 20 m high OCD3 (Option 2 transfer scheme - 0.25 m^3/s pump capacity for 171 hours per year without the Broederstroom diversion) with Dredging Option 6.
- Combo H: Dredging Option 6 combined with a 3 m raising with automatic control gates and the Great Fish – Sundays transfer scheme

A final comparison of the recommended and combined scenarios (of a total of 65 scenarios evaluated) is given in Fig. 6 to increase the firm yield at the Nqweba Dam. The scenarios are also ranked from cheapest to most expensive unit cost (excluding income).

The average incremental firm yield targets are based on Graaff-Reinet's demands of 0.2, 1.9 and 4.0 million m^3/a for the years 2020, 2035 and 2050 respectively, the assumption that 1.24 million m^3/a can be supplied by existing boreholes, as well as the firm yield for the "Do-Nothing" scenario of 1.89, 1.13 and 0.38 million m^3/a for the years 2020, 2035 and 2050 respectively.

Dredging Option 6 is the most economical scenario to satisfy Graaff-Reinet's current and future (2035) demand (an averaged representation of current and future cases). It is also capable of delivering the largest increase in the average incremental firm yield of the cheapest scenarios. However, Combo H (Dredging Option 6 + Great Fish to Sundays River Transfer) has the cheapest unit cost to satisfy the future (2050) demand if the availability of water from the Orange-Fish River transfer scheme can be negotiated with the DWS. Should the Great Fish to Sundays Transfer not be possible, the off-channel dam scenarios OCD1 30 m Option 2 and Combo E2 (OCD1 30 m Option 2 + Dredging Option 6) are capable of returning the highest firm yield (without any anti-evaporation technology). OCD3 may be a cheaper alternative to OCD1 but it is not a sustainable solution because it cannot reach the future (2050) demand when combined with other scenarios.

Combo F (which is essentially Combo D with anti-evaporation technology) has the highest average incremental firm yield. However, given the uncertainty in the dam safety issues, the 3 m dam raising by automatic control gates is not proposed at this stage without further investigation. If it were found that the Nqweba Dam would not have stability issues, the 3 m raising would potentially have the cheapest unit cost but also the smallest yield benefit.

The most expensive (i.e., relative large initial capital cost) scenarios are those with anti-evaporation technology, which require large capital costs. However, scenarios combined with the floating solar panels on OCD1 are the most attractive and lucrative because they can increase the water supply by reducing evaporation losses and because a net profit could potentially be made. Subsequently, the scenarios with solar panels are ranked in terms of unit cost including income potential. Note that the average income potential is shown for the two cases where (a) all electricity is sold and (b) only Graaff-Reinet's electricity demands are satisfied.

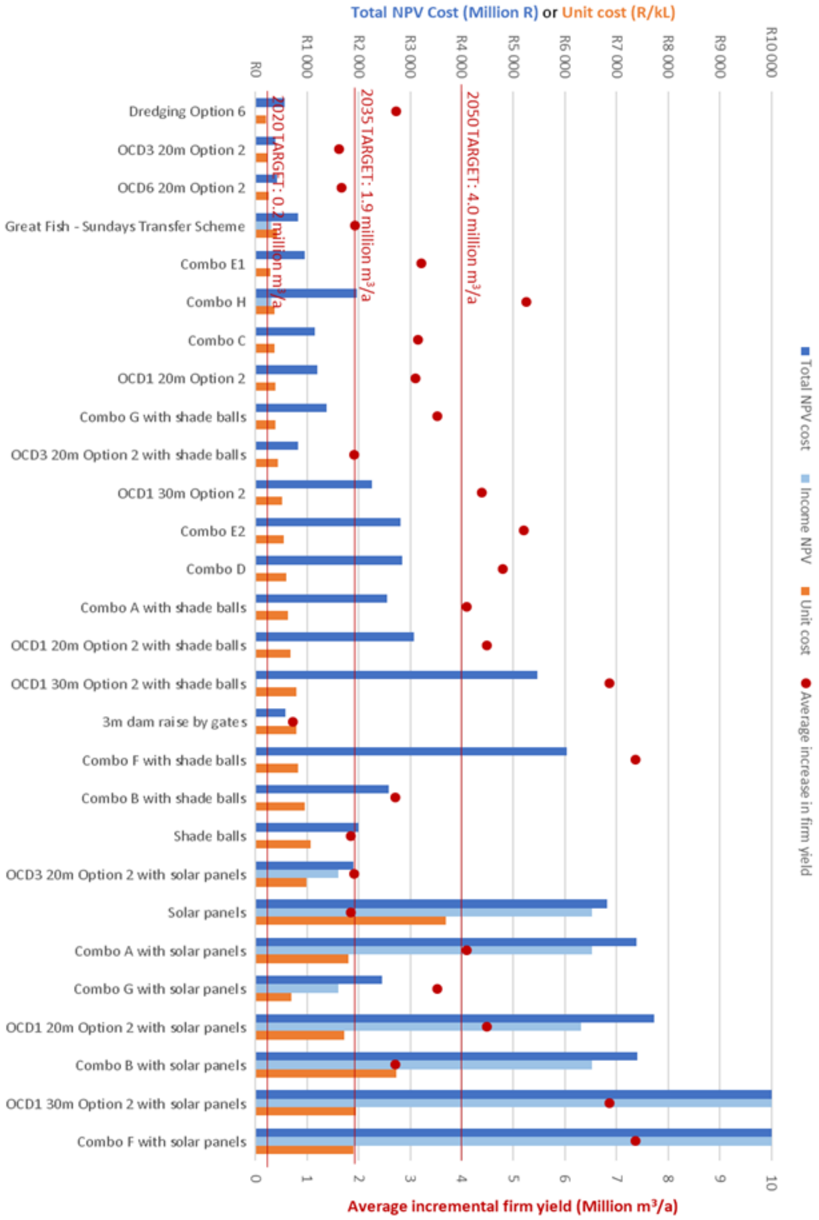


Fig. 6. Comparison of optimized and combined scenarios to increase Nqweba Dam's firm yield.

7 Phasing of scenarios

It can be concluded that a combination of scenarios is required to meet the water demands of Graaff-Reinet. However, it is possible that their benefit can be realized if their implementation is phased to achieve the current target now and the future target later. For example, dredging can be implemented to achieve the 2020 target, followed at a later stage by the construction of an off-channel dam to meet the 2035 target and finally, the implementation of an anti-evaporation floating cover on the OCD in the future when the concept of anti-evaporation is less novice.

Fig. 7 demonstrates how phasing could be implemented for different scenario combinations (including 30% losses in the pipe network and groundwater supplied by existing boreholes). In future, the existing groundwater must be used continuously with the Nqweba Dam and not alternating between the two sources (as was done in the past) such that the target firm yield of the system can be achieved.

Therefore, considering the firm yield requirements, feasibility in terms of unit costs, capital costs and possible income, the two recommended combinations of alternatives and phasing could be:

1. Dredging Option 6 (R207/kL), with further detailed investigation of the aquifer water use during droughts as well as the implementation of the Great Fish to Sundays Transfer Scheme from 2048 (R264/kL) including cost recovery from hydropower.
    a. If the additional future boreholes are drilled and maintained to supply a total of 2.4 million m^3/a of groundwater, Dredging Option 6 would be able to support Graaff-Reinet with enough additional water until 2059 (under drought conditions).
    b. If the Great Fish to Sundays Transfer Scheme is not possible, the off-channel dam scenario OCD1 could be considered as suitable alternatives to upgrade the Dredging Option 6 scenario after 30-40 years.
2. OCD1 Option 2, which could be phased in dam height from 20 m in 2020 (R389/kL) to 30 m in 2048 (R512/kL).
3. Anti-evaporation technology have high capital costs but floating solar panels implemented on the OCD1 can increase the firm yield and potentially generate net profits if electricity is sold to Eskom.

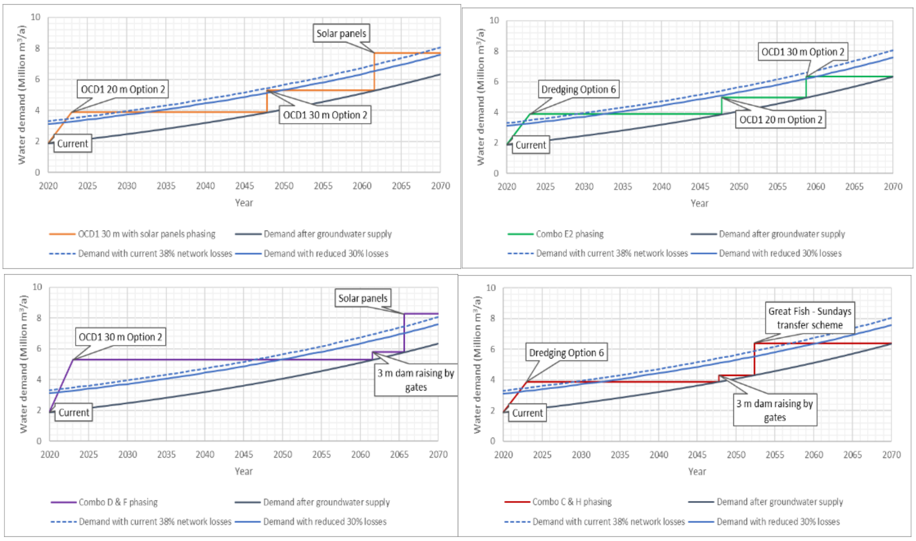


Fig. 7. Water demand and possible phasing of scenarios.

8 Conclusions and recommendations

The Nqweba Dam has lost approximately 42% of its original FSC since its construction in 1925. The dam supplies the town of Graaff-Reinet and due to the growing population at 1.9% pa it was realised in 1995 that the water use should change from irrigation to 100% potable use. However, the current water requirement of the town is 3.3 million m^3/a and during 2019 the dam ran dry. The historical firm yield of Nqweba Dam is estimated at 1.9 million m^3/a (5.2 Ml/d), but originally in 1925 the firm yield was 5 million m^3/a (13.7 Ml/d) for a 1:50 year risk of failure in supply, which was more than the current water requirement of the town. Urgent short and medium term measures were sought to solve the water crisis. The following scenarios were found to be the most beneficial at restoring the dam's firm yield, and are ranked based on unit costs:

1. Dredging Option 6 (R207/kL)
2. Great Fish – Sundays Transfer Scheme (R264/kL)
3. OCD1 20m or 30m (R389/kL or R512/kL)

It is proposed that a combination of the scenarios are implemented in a phased manner to ensure the feasibility of meeting Graaff-Reinet's future water demands.

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