Ingula Pumped Storage Scheme, Design and Construction

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SYNOPSIS. Due to the anticipated high growth in peak demands, Eskom has commenced the construction of the 1332MW Ingula Pumped Storage Scheme which is scheduled for completion in 2013. This paper describes the role of pumped storage schemes, gives an overview of the Ingula project and then considers the particular environmental challenges of the scheme and their mitigation, with particular emphasis on the design of the upper dam to minimise impacts on an important wetland area.

INTRODUCTION

Eskom is the national electricity company for South Africa. It manages its capacity expansion programme through the Integrated Strategic Electricity Plan (ISEP) which aims to meet anticipated future power and energy demands as economically as possible. The ISEP addresses supply side options, demand side management options and demand forecasting. The current generation system is predominantly coal fired, with some gas fired, nuclear, imported and local hydro-power and pumped storage schemes. Eskom is now also investigating various renewable technologies including wind and solar power.

Until recently Eskom has had a surplus generation capacity, with some plant mothballed. The combination of economic growth and a major domestic electrification programme have resulted in an increase in both base load and peak demands and there is now insufficient generation plant to give a safe margin in capacity. The initial response was a ‘return to service’ programme, refurbishing and upgrading existing power stations. Eskom is now undertaking a substantial new-build programme including two major coal fired plants and the Ingula Pumped Storage Scheme. The combined effect will add almost 30% to the existing 42GW generation capacity.

THE ROLE OF PUMPED STORAGE SCHEMES

A pumped storage scheme stores energy in the form of water pumped to an upper reservoir during off-peak periods and recovers energy by discharging through a hydropower turbine to a lower reservoir during peak electricity demand periods. The process is then repeated to suit the daily and weekly demand cycle, with no net loss of water other than evaporation and leakage from the reservoirs. It is actually a net consumer of energy as it returns approximately 3kWh of energy for each 4kWh required for pumping. It is most useful where the main generation system is coal or nuclear plant, which is relatively inefficient in tracking sudden load changes, and there is a significant difference between the low demand (typically night or weekend usage) and peak demand (typically morning and early evening usage).

Pumped storage schemes supply power during peak demands, improve the power factor of the system, provide black start facility, and "smooth" the load demand curve to be supplied by coal fired and nuclear stations. If major load change or generation loss is experienced in the system, pumped storage units can be activated very rapidly to compensate.

THE INGULA PUMPED STORAGE SCHEME

Scheme Layout

The US$2 billion Ingula scheme is located within the Little Drakensberg mountain range of South Africa. The distance between the upper and lower reservoirs is in the order of 6km and the elevation difference is approximately 470m. The rated generating capacity is 1,332MW and the energy storage capacity is 21,000MWh (15.8 generating hours).

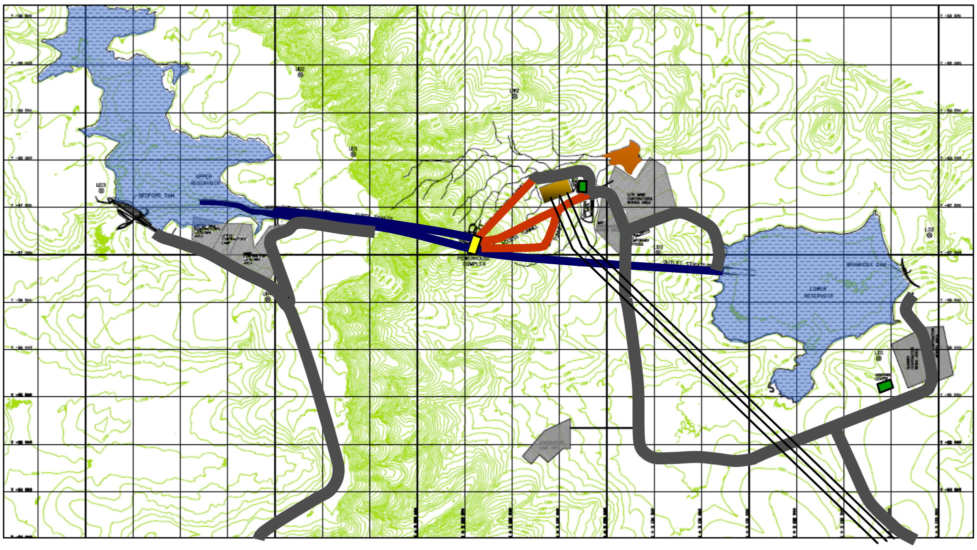

Figure 1. Scheme layout

The principle components of the project are shown in Table 1 below.

Table 1 : Ingula PSS, Principle Components

Bedford Dam	CFRD, live storage 19.2 Mm^3, embankment length 810m, height above foundation 51m, fill volume $1Mm^3$, spillway capacity $200m^3/s$, outlet capacity $71m^3/s$.
Headrace Intake Structure	49m high tower with intake screens, stoplogs and gates to two tunnel openings 6.6m high x 5.5m wide.
Low Pressure Headrace	2 no, 6.6m dia concrete lined tunnels 873m long, plus 185m long, 5.1m dia steel lined penstocks
Headrace Surge Shafts	2 no, 16.5m diameter, 191m deep, pre-stressed concrete lined
High Pressure Headrace	2 no, 5.1m diameter steel lined penstocks, 1081m long, inclined at 1V : 2.2H, reducing to 2.5m diameter at spiral casing, maximum transient pressure 730m
Power Station	Machine Hall: 26m span x 55m deep x 182m long. Transformer Hall: 18m span x 22m deep x 175m long.
Power Plant	4 no reversible Francis pump turbines, each 333MW, operating at 433m to 490m head. Rated flow $85m^3/s$ per machine.
Tailrace Surge Chambers	2 no, 20m diameter, 109m high
Tailrace Tunnel	1 no, 9.4m diameter, 2340m long concrete lined tunnel.
Tailrace Outfall Structure	43m high tower with stoplogs to two openings, each 10m high x 4.3m wide.
Bramhoek Dam	RCC dam with GERCC facing, live storage $19.2Mm^3$, length 310m, height above foundation 38m, concrete volume $103{,}000m^3$, spillway capacity $715m^3/s$, outlet capacity $75m^3/s$.
Tunnel system	Over 40 tunnels and shafts up to 9m diameter, for access, services, construction, drainage and ventilation.
Roads, buildings and infrastructure	57km of new or upgraded asphalt surfaced roads, quarry for 2Mt of dolerite aggregate, operations buildings, water supply and waste water treatment systems, offices and construction facilities, accommodation camps for workforce of up to 4,000.
Power Transmission	Switchyard and 400kV powerlines to connect to national grid.

Powerhouse complex

The underground machine hall accommodates the main inlet valves, the pump-turbine, motor-generator units and their auxiliary equipment. It also includes a control room, ablutions, battery room, workshops, etc. It is served by two, 265t overhead cranes with auxiliary hooks and a small 8t crane below the larger cranes. The Transformer Hall is parallel and adjacent to the Machine Hall, with a network of tunnels to service the complex, as shown in Figure 2 below.

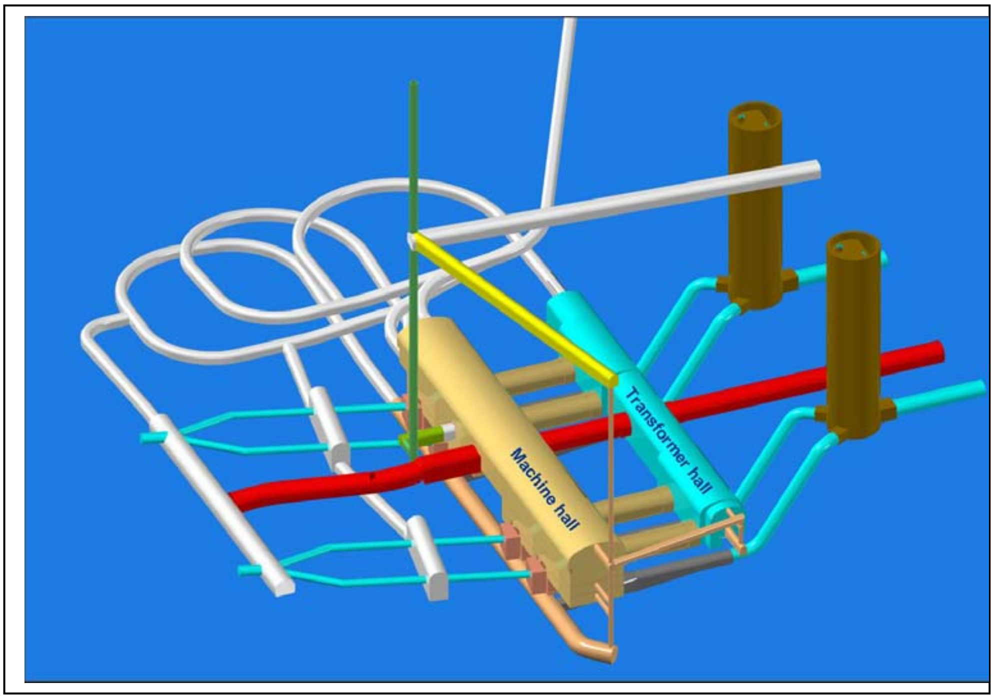

Figure 2. Powerhouse complex

Geology

The area is underlain by sedimentary rocks of the Ecca and Beaufort Groups, which have been intruded by dolerites of the Karoo Dolerite Suite. The sedimentary rocks comprise horizontally bedded mudrocks, siltstones and sandstones. In the vicinity of the machine and transformer halls, thermal effects from dolerite intrusions have altered the mudrock into a massive rock (shale) with relatively good uniaxial compressive strengths.

Eskom built the nearby Drakensberg Pumped Storage Scheme in similar geology in the 1970s with a separate valve hall to minimise the span of the machine hall cavern at around 17m. At the Ingula scheme the main inlet valves are housed in the Machine Hall. This, coupled with larger machines, resulted in a rather large span of 26m. Although this is feasible, systematic rock support is required, comprising pattern bolting with tensioned anchors.

The high pressure headrace tunnel is located below a spur from the escarpment, which hydrofracture testing showed to have relatively low horizontal insitu stresses, requiring steel lining through this section.

ENVIRONMENTAL ISSUES

Environmental significance of the site

Authorisation for the project to go ahead was requested and granted in 2000, only to be immediately withdrawn by the government following a large public outcry and pressure from conservation bodies and NGOs. The basis of the withdrawal was the ecological importance of the area, and the hydrological importance of the two catchments affected by the scheme.

The scheme is built across an escarpment which is the continental watershed between the Vaal and Tugela River systems, which are responsible for a large bulk of available water in the country. The majority of the ecological importance of the Ingula scheme lies on the upper area which is home to a large wetland complex situated downstream of the Bedford Dam. The wetland provides a continuous water supply to the Wilge River throughout the year, due to the excellent water retention properties of its peat soil. Peat can very quickly absorb up to one thousand times its weight in water and then release it slowly. This makes it ideal for keeping water flows stable, which helps prevent floods and relieve droughts. Peatlands are considered the largest and most effective terrestrial carbon sinks in the world. Bedford Dam will flood 5% of this particular wetland.

The wetland provides safe breeding grounds for various bird species, and pasture and refuge for a range of animals. Antelope present include the threatened Oribi, plus Grey Rhebok and Steenbok. Over 230 bird species have been identified on site. These include all three crane species, Bald Ibis, Cape Griffons and White Winged Flufftail, all of which nest on or in the vicinity of Ingula. These birds all fall within Critically Endangered, Endangered or Vulnerable categories in South Africa and are all protected species. It is estimated than only 200 White-winged Flufftails, breeding in two wetlands in Ethiopia, still exist in the world. The Flufftails migrate to nine wetlands in South African during summer, and have been sighted at Ingula. The continued conservation of these wetlands is vital to the survival of this species in the region.

Environmental Mitigation Measures

To mitigate the impact of the Ingula project, Eskom purchased an additional eight thousand hectares of land, and will manage this land as the Bedford Wetland Park (BWP) to the benefit of the White Winged Flufftail and other species. This should ensure the correct management of the previously mismanaged farms and wetlands, and the restoration of the area to a pristine condition. A positive Record of Decision (RoD) was issued in December 2002, including the above as conditions, and setting additional environmental conditions for the construction and operation of Ingula Pumped Storage Scheme.

The original Interested and Affected Parties (I&APs) that had raised concerns over the project were brought into partnership with Eskom to ensure that these concerns were addressed and managed in a responsible manner. This 'partnership' body comprises BirdLife South Africa (BLSA), Eskom and the Middelpunt Wetland Trust (MWT) as the principal members. By working with NGOs in a Partnership, Eskom is able to ensure an unbiased overview of the project, and ensure environmental objectives are met. Both BLSA and MWT are now actively involved in the project, at a strategic and operational level. Alongside the Partnership the Ingula Advisory Committee: Conservation (IACC), was formed to monitor day to day activities in the project and to interact with project staff accordingly, with representation from various governing bodies and NGOs.

Detailed studies were carried out on the hydrology, wetlands, fauna and flora, avifauna, invertebrates, socio-economics, agriculture and archaeology of Ingula. These were supplemented by additional research by specialists which formed the basis for compiling an encompassing Environmental Management Plan (EMP), as well as informing ensuing processes in terms of unique project design, stakeholder and landowner relations, land management and long term conservation.

Arising from these studies, and the EMP, a number of specific environmental measures have been adopted. These include:

- Wetland protection: The dam outlet works were designed to facilitate releases mirroring the virgin catchment runoff. A low weir ensures uniform flow releases into the wetland, obviating erosion.
- Landscape aesthetics: The design of the dam blends in with the natural surroundings, and borrow pits are developed below the minimum operating level (MOL).
- Habitat and nest site protection: artificial cliffs will be created in which the colony of Bald Ibis birds can roost and nest.
- Maintaining natural river flows: during construction and operation, water is released from the dam at a rate, quantity and quality as close as possible to the pre-construction flow.
- Fossil and archaeological recovery: fossilised plants and animals, dating to around 255 million years ago, have been recovered from the Bedford Dam excavations. Relics of the Bushman habitation of the area have been recovered from the reservoir basin.

- Creation of the Conservation Area: conservation programmes to eradicate alien invasive plants, rehabilitate the landscape, remove grazing livestock and return the area to indigenous wildlife are being implemented during the construction period and will be continued for the lifespan of the scheme.

DESIGN AND CONSTRUCTION OF BEDFORD DAM

Dam Design

Bedford Dam is a 51m high Concrete Faced Rockfill Dam (CFRD), with the embankment constructed from locally quarried sandstone, and a 300mm thick reinforced concrete upstream face. At each abutment the dam is changed to a clay cored rockfill embankment to avoid extensive sections of short facing slab. The transition is achieved with a retaining wall between sections of embankment. The CFRD makes best use of the local materials – an abundance of rock and limited amounts of clay, and meets the environmental requirement of blending in with the natural environment as far as possible.

The catchment of 11.5km² is small in relation to the dam, and the mean annual runoff is less than 10% of the live storage volume. All normal flood releases are discharged through the outlet works, and all natural floods up to the PMF can be absorbed within the reservoir freeboard capacity. The emergency spillway is therefore primarily provided in case of extreme mal-operation of the scheme and over-pumping of the system.

The design and construction of the dam is in accordance with modern CFRD practice and the main points of interest relate to the particular conditions arising from the environmental constraints. The remainder of this paper therefore focuses on these aspects, in particular the hydraulic design of the outlet works, landscape aesthetics, habitat replacement and fossil recovery. Note that the design and construction of the Bramhoek Dam is covered by a separate paper and is not addressed here.

Outlet Works Release Capacity

The environmental release requirements for Bedford Dam were defined with the objective of maintaining the present biophysical features of the downstream wetland. The critical requirements impacting on the release system design can be summarised as follows:

- Flood releases will coincide with the actual rainfall event as closely as possible.
- Flood releases in any one day will not exceed the total volume of the 1 in 2 year flood (approximately 80 000m^3).

- The reservoir must have capacity to hold, irrespective of its instantaneous level, all floods smaller than the 1 in 100 year flood (maximum volume to be held is 470 000m^3).
- The energy of released floods must be dissipated, with no consequential erosion of the wetland.
- The wetland has to be saturated annually by 0.5m.

On the basis of the above, the outlet works must cater for the range of normal river flows (10 to 50 l/s), and flood flows up to 50m^3/s. This latter flow is sufficient to meet flood discharge requirements and to inundate the wetland by 0.5m. This indicated release range must be possible with water at any level in the dam, from Minimum Operating Level (MOL) to Full Supply Level (FSL).

Outlet Works Arrangement

The outlet works comprise a 42m high inlet tower, high and low capacity conduits under the embankment and an outlet structure at the downstream toe. Access is from the embankment via a 48m span steel bridge. The outlets discharge into a hydraulic jump stilling basin, followed by a stilling pond which distributes low velocity flow to the wetland.

Due to the frequent mixing of live storage in a pumped storage scheme, stratification of the stored water is not anticipated. A single level intake was incorporated in the design of the low capacity outlet and a single bottom level intake was provided for the high capacity system. The outlet works consist of a high capacity 3m diameter conduit controlled by two radial gates, 1m high x 2.1m wide, and a low flow system drawing water from higher in the reservoir via a 1m diameter conduit. This discharges through flow control valves of 100mm, 200mm or 500mm diameter. The capacities of the two systems overlap to allow the precise selection of any required discharge across a broad range of flows.

The original concept for the outlet included a weir in the river downstream to distribute flow evenly onto the sensitive wetland. The final design incorporates a sunken stilling pond with a long discharge sill at river bed level, against the lower left abutment outside the wetland. This is much more practical to construct and less destructive to the wetland.

Optimisation by Computational Fluid Dynamics (CFD) Modelling

Hydraulic modelling was carried out to ensure the fully effective and optimal function of the proposed environmental stilling basin and pond. CFD modelling was adopted, rather than a physical scale model, on the basis that it is now a cost effective and flexible tool for design optimization of complex hydraulic systems. The three dimensional modelling covered the entire release system from upstream of the intake tower to beyond the wetland area itself. In order to reduce the complexity of the simulation models and the computational time for each analysis, the modelling domains were split into two main regions:

- Region 1: This consisted of the trash racks, the intake tower and the conduit and ended at the radial flood release gates.
- Region 2: This model started at the outlet of the radial flood gates and ended in the wetland, downstream of the stilling pond.

Region 1 Modelling

The domain for the trash rack model consisted of a large volume of water surrounding the trash rack inlet and the entire internal wetted area of the outlet system from the trash racks to the radial gates that open up into the stilling basin area (see Figure 3).

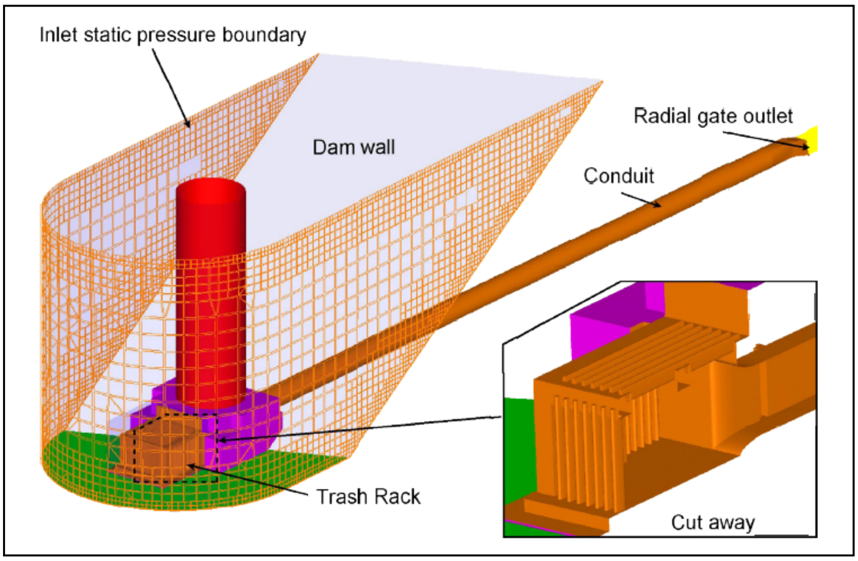

Figure 3. Domain modelled for Region 1

Different geometries were evaluated for the trash rack intake optimisation. The main differences between the original and final geometries are:

- Slanted roof section to reduce velocities through the top trash racks (see Figure 4)
- Levelling the floor of the inlet with the floor of the conduit section
- Larger intake radius in the vertical plane to reduce entrance losses

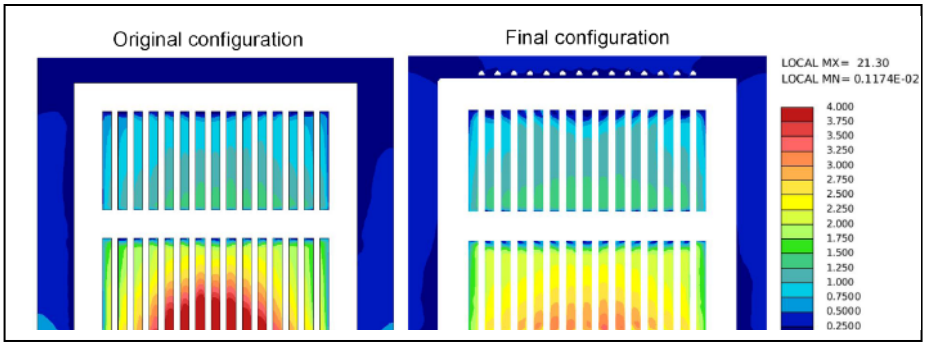

Figure 4. Comparison of velocities passing through the top horizontal trash racks

Region 2 Modelling

The wetland details were not included in the simulation but an additional volume was added downstream of the stilling pond in order to improve the boundary condition in this area. The outlet works model comprised:

- The outlet gates that open up into the stilling basin
- The stilling pond which feeds water back into the wetland

It became evident that the geometries of both the stilling basin and the stilling pond could be modified to improve energy dissipation. For this reason a separate steady state model was used to optimise the stilling basin geometry before performing the final transient free surface calculations.

Stilling basin optimisation

The initial simulation of a single gate outlet was performed for a flow rate of $70m^3/s$. Energy dissipation in the stilling basin was insufficient with localised high velocities of up to 15m/s leaving the basin. The revised works consisted of dual gates each with a width of twice the height of the opening giving a shallower water depth as the flow exits the gate.

Figure 5 shows the free surface and velocity vector plot for the $70m^3/s$ case with both gates 100% open. The position of the hydraulic jump is visible and the step in the stilling basin significantly improves the energy dissipation. The flow entering the stilling pond is smoothed by the wave suppressor. The free surface calculations were performed using transient analyses and the plots presented are snap shots during the transient event.

Stilling pond optimisation

It is important that stilling pond reduces the velocity of the water to below 1 m/s before releasing it into the wetland and that the shape is such that flow is always outward into the wetland and that no flow recirculates. The initial design was such that a number of recirculation zones formed due to flow separation at the entrance to the pond. A number of steady state models of the pond were therefore evaluated in order to optimise the flow distributions entering and leaving the pond, see Figure 6. The final geometry resulted in a much smaller area that needed to be excavated. Figure 7 shows the layout of the original outlet works and stilling pond on the left and the optimised geometry on the right of the figure.

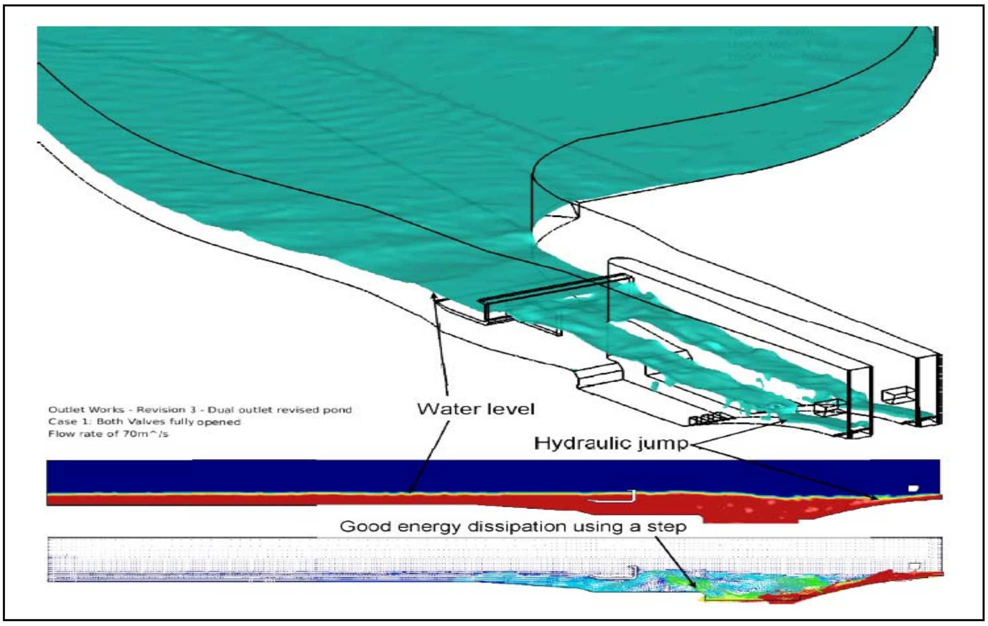

Figure 5. Free surface and velocity vector plot showing the position of the hydraulic jump

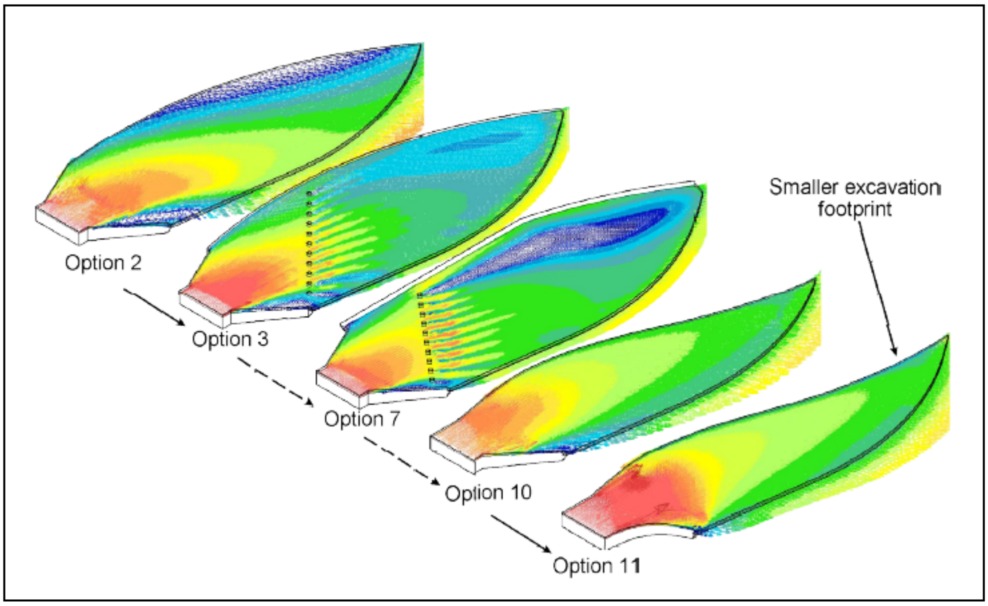

Figure 6 Geometries evaluated for optimisation of the pond

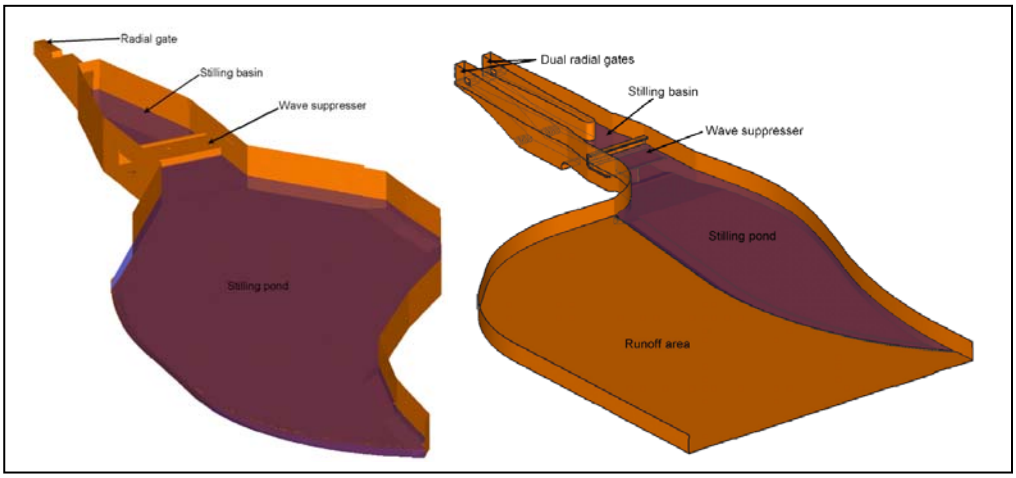

Figure 7 Original (left) and optimised (right) geometry for outlet works

<u>Landscape Aesthetics</u>

No requirement was set in the RoD to re-vegetate the downstream embankment slope as sandstone outcrops appear naturally in the area and the dam downstream face will be formed by packing sandstone boulders against a controlled slope. It is however required to develop all quarries and borrow areas as far as possible below the dam MOL.

Figure 8 Artist's impression of completed embankment

Eskom appointed a landscape architect to comment on the dam layout during the initial design stages. Due to the flowing natural contours in the area it was decided to curve the left flank of the dam to fit in to the landscape. This resulted in a minimal increase in embankment material quantities. Figure 8 provides an artist's impression of the completed embankment.

Habitat and nest site protection and replacement

Since very early on during the design process after completion of the geotechnical investigation, it was known that the upper right flank of the dam is very permeable and that deep excavation work would be required to remove the permeable material. This excavation cut would extend far into the right flank and above the dam crest level. Instead of merely backfilling this excavation cut it was decided to use this area to replace the Bald Ibis roosting sites that will be inundated by the dam. The alternative was to blast new cliffs especially for this purpose. Birdlife South Africa, one of the Interested and Affected Parties at Ingula, was consulted during the design process and Figure 9 gives an indication of how the relocated nesting sites should look once constructed. No access is provided to this area and the nests will be tucked away in the far right hand side of the dam.

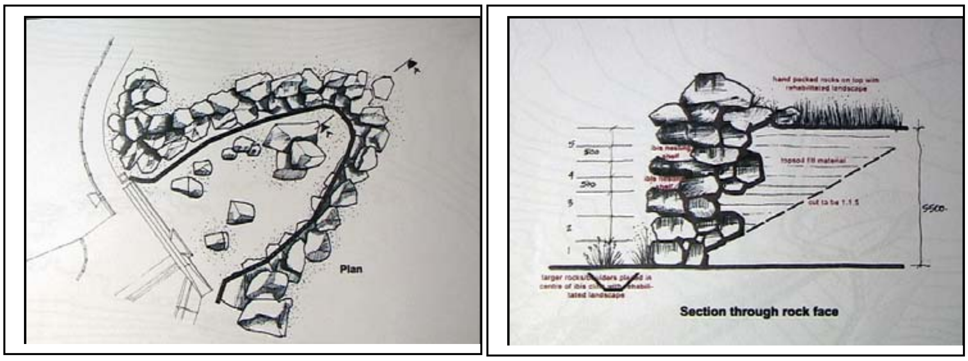

Figure 9 Artist's impression of Bald Ibis roosting sites

Fossil and Archaeological Recovery

A paleontological survey is performed after every site blast and on completion of excavation works. Several sites were identified where fossils occur. The sites are recorded and the fossils, if significant, are removed with assistance from the Contractor. Most of these are estimated to be approximately 255 million years old. The delays in removing the specimens could be costly to the project, but the onsite palaeontologist has an understanding with the contractors, and all steps are taken to remove the fossils as quickly as possible.

To date at least 40 sites are recorded where fossilised bone and wood were found. Remains of the vertebrates discovered are of exceptional quality and it was possible to collect some of the most complete skeletons of animals recorded up to date in South Africa. The skull of at least one predator was found. A very well preserved skull of a plant-eating reptile, possibly *Dicynodon lacerticeps* was discovered followed by the further discovery of a very well preserved, possibly articulate skeleton of an unidentified vertebrate, *Oudenodon*. If so, this will be the first recording of this animal in the North Eastern part of the Free State. At least five other skeletons were discovered and removed.

The vertebrate fossil remains will be housed at the National Museum in Bloemfontein. It is envisaged that it will be returned on loan to the visitor's centre at Ingula for educational purposes.

Figure 10. Tree fossil discovered in conduit cut and tusk of Dicynodon.

Caves are present in the upper watercourse that will be inundated by the Bedford Dam. These were historically used by the San (Bushmen), and in later years as a refuge during the Boer War. The caves were inspected by archaeological specialists, and cave paintings and artefacts have been documented and removed to National Museum in Bloemfontein for record keeping purposes.

CONCLUSION

The Ingula Pumped Storage scheme is situated in an extremely sensitive ecosystem. Eskom is, however, managing the project development process in a responsible manner to the long term benefit of the environment. We believe that the implementation demonstrates that it is possible to achieve both essential infrastructure development and environmental gains in an appropriately managed project.

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This paper draws on information given in a series of papers presented at the SANCOLD biennial conference, November 2009, as referenced below, and the authors' contribution is gratefully acknowledged.

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