Ngonye Falls hydropower project on the Zambezi in Zambia – the challenges and opportunities

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Abstract

The Ngonye Falls at Sioma in Zambia on the Zambezi River represents a significant opportunity to develop a hydropower station with a mean annual flow of 1097m^3/s a fall of around 23m and a scheme that was first proposed at this location in the 1960s. However, constructing an intake on the river at this location is complex since the river is 3km wide and heavily braided approaching the falls. Previous project layouts had an intake structure situated on the left most channel, with the assumption that sufficient flow could be abstracted from this channel. When 2D hydraulic modelling showed this was not the case, the scheme became undersized and suboptimal. Further studies by Mott MacDonald have shown that a low 3m high weir across the head of the falls could divert sufficient flow for a proposed 180MW hydropower plant significantly increasing the output of the scheme by a factor of 4. The potential for upstream flooding is proposed to be mitigated using over 0.5km of 3m high pneumatically controlled flap gates within the weir. Using this gate configuration has allowed the headpond to be controlled at a set water level meaning that changes to the upstream flooding conditions can be controlled within acceptable limits. The new configuration will also ensure full control over the distribution of flow into the falls area in order to maintain their visual and ecological benefits. Thus, the proposed scheme design has carefully balanced the potential environmental and social impacts with commercial constraints to maximise generation.

1. Introduction

The Western Power Company (WPC) is a Zambian IPP and is currently developing a hydropower project at Ngonye Falls which lies at 987m asl on the mighty Zambezi River about 320km upstream of the more well-known Mosi-o-tunya (Victoria Falls) (see Figure 1). The project is using development funding from InfraCo Africa (part of the Private Infrastructure Development Group PIDG) and the Development Bank of Southern Africa (DBSA). The Ngonye Falls HEP project is a run-of-river scheme using the potential of these falls by passing water from above the cascade through hydropower turbines before returning water to the river four kilometres downstream.

1.1. Zambia Electricity Sector Overview

Zambia has an open, regulated market that allows for participation of private generation, transmission and distribution. It is an Operating member of the Southern African Power Pool (SAPP) represented by ZESCO, the state owned vertically integrated utility. ZESCO owns and operates 80% of the generation capacity with the remainder shared amongst five IPP's who sell their power to ZESCO under long term PPA's, creating a single buyer model by default (Chimbaka, 2017).

The current total installed generation capacity is approximately 2.9GW (ERB, 2017), with hydro power accounting for 83% of the capacity. The balance of the generation mix comprises Coal thermal (10%), Heavy Fuel Oil (HFO) (4%), Diesel (3%) and Solar PV (less than 1%).

National electricity demand is largely driven by the mining industry which consumes approximately 51% of the total consumption with residential (domestic) and other sectors contributing 34% and 15% respectively. The peak demand on the system is approximately 2.2GW. Conservative energy consumption forecasts by the SAPP expect an average annual increase of about 3.8% up until 2030 (Southern African Power Pool, 2017), a slight increase from 2.4% experienced between 2006-2016.

Figure 1: Location Map showing the Western Province of Zambia (green shading) and the wetlands/dambos (light blue shading)

1.2. Western Province Electricity Supply

Power is currently supplied to Western Province over a weak 66kV lateral line that spans over 300km across the province and terminates at Mongu town with 68km and 195km spurs to Kalabo and Kaoma respectively. The line is tapped from the Sesheke 220/66kV bulk-supply substation which in turn is supplied by the 108MW Run-of-river Victoria Falls Hydro-power station via a 224km 220kV line.

The reliability and quality of supply to the Western Province is compromised by the insufficient capacity on the 66kV line due its considerable length. This has led to a suppressed local demand that currently stands at 5MW (during peak) attributable to voltage instability at Mongu and associated feeder lines.

With a population of approximately one million (Central Statistical Office, 2013) and an average load of around 12MW, the Western Province per capita energy consumption per annum of 100kWh/capita is about 9 times smaller than the national average of 894kWh/capita. This underscores the Province's considerably low levels of development in comparison to the country average.

1.3. Sesheke-Mongu 220kV Transmission Line and SAPP Export

In view of the capacity challenges and in line with the 6th National Energy Policy (NEP) goal to achieve 60% of electricity access by 2030, the Government of the Republic of Zambia (GRZ) has set out to enhance power supply and access to electricity in the Western Province through a large-scale electrification effort. To this end, ZESCO has committed to the procurement and construction of the 320km Sesheke-Mongu 220kV transmission line with a spur to Shangombo town near the Angola border. The line route passes within 5km of the proposed project powerhouse and will have a provision for a connector to the project substation for power evacuation.

ZESCO currently exports power to Namibia under a 50MW firm PPA via an 11km 220kV interconnector between the Sesheke Substation in Zambia and the Zambezi HVDC Converter station in Namibia. Hence, this new Sesheke-Mongu transmission line gives the Ngonye Project direct access to the Nampower transmission network via this substation. ZESCO has also expressed intentions to supply power to the isolated eastern Angolan grid from a bulk supply substation located at Shangombo.

1.4. Ngonye Falls Project Inception

The Ngonye Falls scheme was first studied in December 1968 on behalf of GRZ by Watermeyer, Legge Piesold & Uhlmann plus Merz and McLellen. At the time, the demand in the Western Province was only 2.7MW, rising to about 3.3MW by 1970. As such, only a small scheme was investigated for development in three phases of 4MW each, for a total capacity of 12MW.

In 2011, these studies were brought to the attention of the WPC team through an associate who was involved in the initial investigations. WPC recognized the potential of the scheme to supply power to the Province whose demand had since increased to 10.5MW, and the same year, embarked on comprehensive program of technical, environmental, and economic studies to define the feasibility of the project. Multiconsult UK was appointed in July 2012 to complete the feasibility study of the project. The resulting draft Technical and Economic Feasibility study (TEFS) proposed a 45MW scheme at a tariff of 13-14 USc/kWhr in 2020. Consequently, there were concerns that at this size, the project would have difficulty in achieving an economic tariff.

Under this backdrop, WPC appointed Mott MacDonald as the project's Owners Engineer (OE) in July 2016 to provide project review and other OE services through to Financial Close, including optioneering, feasibility studies, tender design, GI supervision, procurement advice and other related services.

1.5. Ngonye Falls and their hydropower potential

Ngonye Falls provide a unique opportunity for hydropower. While the drop across the falls is only 23m, the cascade is situated downstream of the Barotse Floodplain, a shallow alluvial basin consisting of extensive areas of floodplains, swamps and lakes, fed by the Lungúe Bungo, Zambezi, and Kabompo rivers (World Bank, 2010), the second largest wetland in Zambia and a designated Ramsar site (see Figure 1). The floodplain is over 200km long and 30km wide with only a shallow grade to the south. These wetland areas are locally known as dambos and are characterised by the presence of shallow pools fed by perennial water and surrounded by gently undulating grasslands. These dambos have a significant influence on attenuating runoff from the upper part of the catchment (Gupta, 2007) and increase the level of evaporation and infiltration to groundwater, which maintains baseflow in the dry season. In addition, the dambos result in a time lag of between two to three months between peak rainfall and peak runoff. This smoothing of the hydrograph provided by the falls and flood plain allows for similar utilisation of the annual flow as would be provided by a large reservoir.

Figure 2: Ngonye Falls from the air looking downstream

The falls themselves are formed by a horizontal layer of hard silicified sandstone (also known as silcrete), which overlays weaker layers of weathered and partially weathered sandstone. This geology creates a very wide and shallow river above the falls (almost 3km wide at its maximum) whilst below the falls, a narrow gorge is formed (typically 200m wide). Above the falls the river braids into a series of channels interspersed by islands. These channels discharge over a series of separate falls which each have their own character, some having a vertical face whilst others are more cascades. A distinctive large left channel takes a significant proportion of the river around the larger islands and was likely the original channel prior to the cutback of the falls to their current location.

One hydraulic feature caused by the wide river channel above the falls and the narrow gorge below the falls is the way the head across the falls decreases as flows increase. This is because the river water level rises more slowly above the falls (due to the very wide river channel) than below the falls (due to the narrow gorge). Hence, during the high flow season the available head decreases until the falls are mostly submerged. As such, the hydropower potential is optimal during mid-year flows.

Ecologically, the upstream channels are judged to be a nearly pristine habitat that supports a wide variety of species, although no critically endangered species have been identified. Because of this habitat and the aesthetic appeal of the falls, it is important that any future hydropower scheme is constructed sensitively with as much of the fall's habitat retained.

1.6. Site Access

Initially, the Ngonye project site could only be accessed from Sesheke town via 130km of intermittently good gravel track which proved challenging during the pre-feasibility stage. However, between 2013 and 2016, GRZ worked to upgrade the track to bituminous all-weather standard in fulfilment of the National Development Plan (NDP) (GRZ, 2011) which prioritized the development of rural transport infrastructure. The works included the extension of the M10 main road to Mongu from Sesheke, passing in close proximity to the project site and the construction of a new bridge over the Zambezi just downstream of the proposed powerhouse. Consequently, the project is now accessible by all-weather road from both the north and south.

Notably, the well maintained 1500km all-weather Trans-Caprivi highway connects the M10 at Katima (Sesheke) to the Walvis Bay seaport in Namibia; the nearest deep-water port to the project site. As such, the ease of delivery of major electrical and mechanical equipment during the construction phase has been considerably improved.

1.7. Project Alignment and Implementation

The timing and location of the project position it well to help achieve both near and long-term socio-economic development and energy self-sufficiency targets set out by GRZ and ZESCO in the NDP and Power System Development Master Plan (PSMDP).

The socio-economic development components include; 1) approximately 3100 jobs be created during peak construction phase with considerable direct and indirect benefits at the district and provincial level, 2) tangible and sustainable benefits to local communities from the project through a Community Development Fund that will be set up to identify projects which are community led, accountable and best match the needs of those communities as well as 3) by increased access and quality of power supply to local communities

The energy sector development benefits will include; 1) alignment with GRZ's goal for Zambia to achieve energy self-sufficiency and becoming a net power exporter to the SAPP and East African Power Pool (EAPP) markets by bringing additional generation online, 2) the project is ideally located to offset power flows and corresponding transmission losses from Southern Zambia to Western Zambia and neighboring power export markets and 3) an economic tariff providing good business case to ZESCO and other potential off-takers in the region.

1.8. Envisaged scheme layout

Figure 3 shows the layout of the proposed scheme as it is currently envisaged which includes a set of low weirs, embankments and barrage forming a headpond, an intake, canal leading to a forebay and powerhouse, tailrace and a switchyard plus a 220kV loop-in-loop-out connection to the proposed transmission line.

2. Rethinking the headworks and P&E Modelling

2.1. Reviewing flow diversions

Previous iterations of the project, back to its original inception in 1968, looked at left bank schemes developing only the left-hand river channel above the falls. These schemes abstracted flow from this channel and returned it to the river downstream, utilising the relic river channel for conveyance before dropping back into the main river channel some 3 or 4 km downstream. The most recent iteration was designed to divert a maximum of 386 m^3/s and generate 45MW (Multiconsult, 2016) but required a tariff that was unlikely to be economic.

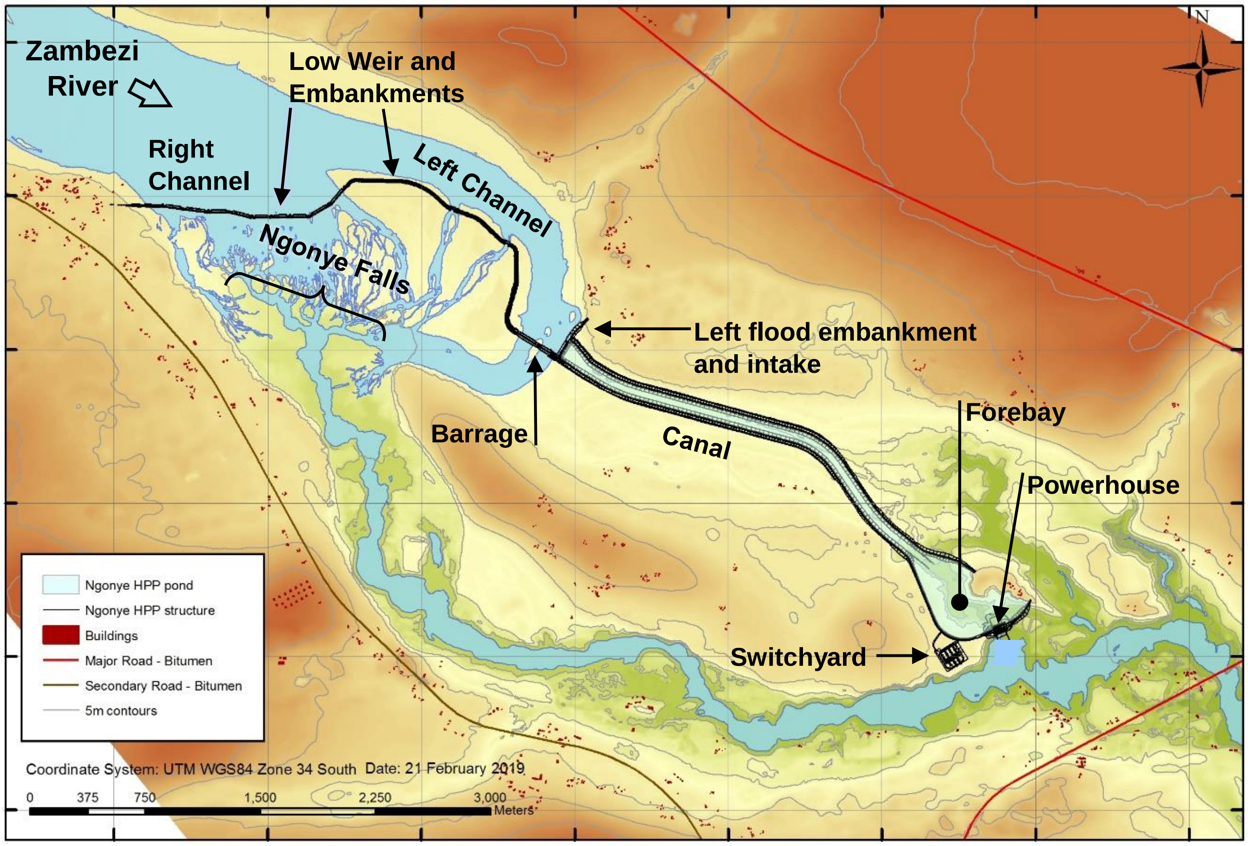

Figure 3: Overview of the Ngonye Falls Hydropower Project

On review, it became apparent that the early designs were limited by the flow that could be diverted from the left channel. While a barrage positioned across this channel would assist with this diversion it was limited by the size of this channel analogous to a proportional weir. Building a higher barrage in the left channel simply pushed more flow through the right channel which was shown using 2D modelling.

Mott MacDonald further investigated the limitations of the left channel in 2017 and concluded that any modifications, such as localised dredging, would have limited effect in improving flow diversions. It was realised that to benefit from the economies of scale, the scheme would need to be optimised for the higher design flows and this opened the study to a much wider range of alternatives.

Consideration was then given to a low weir across the entire width of falls and additional studies were initiated to investigate its feasibility. The 2D hydraulic model that had been developed for the 2016 study was revisited and modifications made to assess the height and configuration of a weir required to optimise the power output of the scheme. The weir was located as far upstream of the falls as possible to retain as much of the inter-channel and island habitat as possible.

2.2. Environmental Flows

During the development of the 2016 scheme layout, environmental studies had been ongoing to set the Environmental Water Requirements (EWR) for the falls. The environmental consultants, Ecotone, used a bottom up approach to understand the flora and fauna within the falls area and provide sufficient flows in each season to keep habitats intact, maintain fish passage and the amenity of the falls area for the local stakeholders. As any diversion of water from one or more channels would impact availability in the rest, each major channel across the falls was evaluated separately. This resulted in six individual EWR flows for channels across the falls and a number of fish passage structures (ladders and rock ramps) to compliment them. The resulting total EWR was substantially increased from $10m^3/s$ to over $48m^3/s$ in the left channel alone and highlighted the difficulty in providing enough water for habitat maintenance in such a wide, shallow river reach.

Flows were also assessed per season and the requirements were varied by month to respond to the requirement to increase flows for spawning fish and ensure flows in the affected area were more proportional to the seasonal flows currently experienced. The required EWR was incorporated into the revised 2D modelling and optioneering to arrive at a scheme that met the environmental requirements while increasing the diversion of water for generation resulting in a more efficient use of the available resource.

2.3. Hydrology and P&E Modelling

As part of the update to the scheme, the hydrology was revisited and updated. The project is very fortunate to have a substantial amount of data stretching back to 1924/1925 for gauges at Mosi-o-tunya (Victoria Falls) which was used to derive a 91-year flow series for the Ngonye scheme based on a strong correlation between the two stations. This exceeds what might normally be expected for a hydrological investigation for a hydropower scheme. It has been confirmed that the records at both stations are reliable.

Power and energy modelling was then carried out using the updated flow series, the environmental water requirements and a range of options for water diversion from the falls. For all cases, flows were extracted from the left channel and while increased water levels provided by the inclusion of a low weir improved flow diversion, the size of the scheme was still dictated by the capacity of the left channel. The power and energy modelling showed that with the higher water levels the diversion could be increased from 386m³/s to 1,100m³/s and four bulb units were proposed for the powerhouse.

To improve the generation capacity, the weirs were proposed to be set at 990m asl and provided with flood gates to enable the scheme to operate with a constant headpond level. This required some level of flow control at the weirs and flood gate options were investigated to provide both flood control and flood relief.

On first inspection there were some curious aspects to the power and energy results which showed years with higher annual flow but less energy generation. The overall reason was that energy generation was dependant on the overall shape of the hydrograph (in particular its width) and not its peak. This is because at high flows, flooding of the downstream gorge and consequent reduction in head across the scheme leads to a reduction in generation. At very high flows, generation ceases because the net head falls below the 10m threshold set for the turbines.

The final, combined rated capacity of the four turbines proposed (rated at 49.1MW each) is 196.4MW. However, the maximum output estimated in the power and energy model is approximately 189MW (with a nominal plant output of 180MW) and this is primarily due to the tailwater level effect giving a gross annual average energy for the project of 887GWh. The increased output of the scheme, being upsized from 45 MW to 189MW improved the overall feasibility of the scheme and allowed for the upsizing of the headworks and conveyance to improve the diversions and facilities that it required.

An assessment of climate change risks to the scheme has been carried out based on the process set out in the World Bank’s ‘Climate Resilience and Natural Disaster Guidelines for the Hydropower Sector’ Phase 2 Initial Analysis (Steps 2.1 – 2.2) (Mott MacDonald, 2017). This seeks to understand if climate is a dominant factor in the project economics based on a screening of the ‘worst case’ climate change scenario and consideration of the impacts of other factors such as hydrological variability and upstream irrigation demand. It has been found that hydrological variability plays a dominant role in affecting the climate conditions in the financing period, with climate change acting as a ‘risk multiplier’. A climate change stress test of downside scenarios using the power and energy and financial model showed that, because of the unusual characteristic of the project where high river flow does not necessarily result in high energy production, even though climate scenarios might reduce river flows, there is not the same level of reduction in energy generation from the project and the project economics were shown to be robust even under the worst-case scenarios of climate change.

2.4. Geological Setting of the falls

As the scheme now extended across the width of the river, the site conditions for placement of weirs, fish passes, and access needed to be assessed. Difficulties encountered in early investigations and understanding the processes involved had led to differing interpretations of the geology and, as the scheme was being upsized, another round of site investigation was carried out including intrusive investigation across the main falls, along conveyance structures and at the powerhouse that had been relocated.

The falls are formed by a horizontal layer of hard silicified sandstone (also known as silcrete), which overlays weaker layers of weathered and partially weathered sandstone of the Kalahari Group Sediments of Cretaceous age.

The underlying weaker sandstone erodes at a faster rate than the overlying more resistant cap causing undermining and eventual collapse of the cap. This process is further complicated and accelerated by continued settlement and fracturing of the cap which allows increasing water ingress through the cap causing accelerated erosion of the underlying sandstone. Eventually erosion and undermining become sufficiently advanced to cause complete collapse of the overlying silcrete leading to toppling of the cap and regression of the falls.

An analysis of available aerial imagery from 1982 through to present day indicates that the falls have remained stable over this time period. The undermining and regression process is summarised below and in Figure 15 (read comments in number order).

The somewhat fragile nature of the falls and lack of competent basement rock requires the headworks to be founded on the silicified capping layer. While the structures proposed are generally low, care will need to be taken during design and construction to minimise the disruption of this cap to prevent acceleration of the erosive processes already in place.

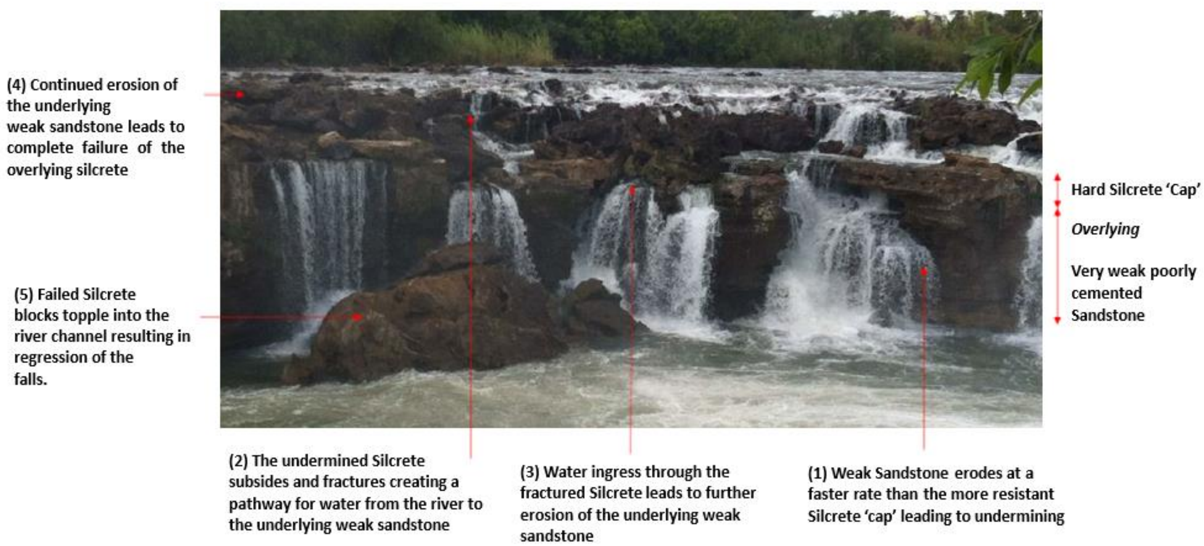

Figure 4: Active processes at the Ngonye Falls

2.5. Minimising the impact of upscaling

While upscaling the scheme has obvious benefits in generation, the larger scheme will inevitably have higher impacts on the area and limitations were applied to the scheme to minimise upstream impacts and preserve the unique habitat of the falls. These included a limitation on the height of the weirs, which were set by scale of upstream impacts. It also included the limitations on the flows diverted for generation set by the ecological requirements to maintain habitats for flora and fauna which in turn provide social benefits such as the maintenance of important fishing grounds. The visual appeal of the falls was also considered as the falls are visited regularly by tourists prepared to extend their trip up-river from Livingstone.

In order to provide the maximum flood relief while maintaining the headpond at 990masl for as much of the season as possible, flood gates were proposed to regulate the flows throughout the year. To both regulate the water levels and minimise upstream flood impacts, over 900m of flood gates will be required. Traditional radial gate type solutions would be very costly with their mechanical actuation and control mechanisms potentially exposed to damage from overtopping expected during higher flood events and hence a more innovative solution was sought.

The feasibility of pneumatically controlled steel flap gates was investigated. These gates, controlled via compressed air lines imbedded within the concrete structures, are able to be installed in over 100m runs and provide actuation via a neoprene bladder which is inflated behind the gate to lift it. The system fails in the open (down) position and being an overshot flap gate, is able to deal with debris without blocking. The flap gates would also be utilised to provide controlled environmental flow releases in the intermediate channels.

While smaller installations have been carried out for hydropower in Africa, this would be the largest worldwide if installed. The layout and scale of these structures is indicated in Figure 5.

Figure 5: Visualisation of the moveable flood gates and environmental water release weir structure

2.6. Adopted headworks layout

The headworks design currently proposed comprises a 3.5km long headworks control structure consisting of:

- A total length of 900m of ≈3m high pneumatically controlled steel flap gates for flood release across the right falls which is set back upstream of the falls by ≈100-500m so that they are not visible from below the falls. This is formed of 680m of 3m high gates and 230m of 2.2m high gates.
- A total length of 100m of EWR flow control structures within the right weir and the various channels upstream of the falls to release the environmental flow requirements and regulate the headpond to the 990m level. This consists of five EWR structures each 10m long within the main weir and two 25m long structures within intermediate channels situated between the larger islands.
- Sections of low connecting concrete weirs between the moveable weirs
- Low overtopping connecting embankments across the islands along the falls
- 7 radial gates in a barrage structure and non-overtopping embankment within the left channel of the falls
- An access track on or beneath the weirs and embankments to provide access for maintenance or tourism
- Non-overtopping left and right-bank flood embankments to prevent flood bypass
- Intake structure connecting the river and canal

3. Waterway and Powerhouse Layout Challenges and Improvements

Diverting close to three times the original flow from the left channel required the design of the conveyance canal and powerhouse to be revisited.

3.1. Canal and forebay

The previous powerhouse location was considered both vulnerable at high flows and difficult to cofferdam during construction. An alternative location was sought and the natural creek, previously the old river channel, some 1.5 km further down river was chosen which enabled the powerhouse to be located further away from the river and made use of the creek for both forebay and tailrace. Previous options had proposed using this old river channel including damming of the entire area.

The 2.9 km conveyance canal was upsized to accommodate the larger flows of 1100 m^3/s and concrete lined to reduce conveyance losses. A range of alignment options were investigated, and the canal moved further north to improve the cut and fill balance, to avoid the existing wildlife park boundaries and heritage features including a locally important tree and a rock cutting that had attempted, unsuccessfully, to provide navigation up-river by King

Litunga Lewanika in the early 1900s. The canal is 'parkable' and has currently been designed not to require a spillway for surge events or flood flows which would otherwise need to be of considerable size.

A forebay has been created from the natural topography at the revised powerhouse location and is approximately 0.6km long. Certain embankments are required to create this forebay. All are concrete faced structures, with the embankments adjacent to the powerhouse being concrete faced rock-filled dams and the others being concrete faced embankment dams made from granular fill. These are shown in Figure 6 below as a visualisation of the forebay, powerhouse and switchyard area.

Figure 6: Visualisation of the forebay, powerhouse and switchyard

4. Conclusions and future project direction

4.1. Conclusions

The review of the scheme has shown that by revisiting early design assumptions followed by evolving scheme layouts can identify opportunities for improvements that may have previously been ruled out or not considered. It is also noted that project optimisation is a dynamic process that needs to adapt to changing drivers and/or constraints, with this process needing to be revisited from time to time to ensure that a scheme remains optimum. It has highlighted the benefits of independent review and value of challenging previous studies with new thinking.

The scheme redesign has not been without difficulties and has presented unique challenges in understanding the complexity of the falls and headworks needed and the power potential they are able to provide. Challenges remain in the design of the final configuration within varied, and in places unfavourable, geotechnical conditions. However, as a result of the scheme upsizing, the project is now forecast to generate gross annual average energy of 887GWh with an improved tariff and is hoped to provide vastly improved benefits to the Western Province of Zambia.

4.2. Future project direction

The Project is targeted to achieve Financial Close in Q1 2020. The critical milestones yet to be finalized in the Project development schedule include: the EPC tender process and contract negotiation– Q1|Q3 2019; approval by ZEMA of the Environmental and Social Impact Assessment ("ESIA") Q3-2019; agreement of a full Power Purchase Agreement ("PPA") with ZESCO and following confirmation of the tariff; and the debt financing process – Q2|Q3 2019.

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