Selection and Optimization of Turbines for Juba Barrage Hydropower Plant (Southern Sudan)  
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ABSTRACT: In this work an investigation was performed to select the appropriate, economical size and type of turbines for Juba Barrage proposed plan. Using charts and empirical formulae a suitable type and configuration were reached. According to the main site parameters, head and discharge, the turbine lies in the category of Bulb Kaplan turbine. Using different plant options the plant size was optimized with the aid of the flow duration curve and hydro help and ret screen software's, the annual energy was estimated, accompanied with economical analysis. Proposed new methodology for number of unit's selection was presented. The design discharge is 1400 m³/s and the rated head is 7.32 m. Total installed capacity is about 83 MW and the annual energy is about 533 GWh at 73% estimated capacity factor. The optimum number of units is 9 sets of hydro turbine /generator of bulb Kaplan machines. The runner diameter is 4.8 m running at 115.4 rpm. The specific speed is of the order of 919.3.  

KEYWORDS: Hydrology, Economics, Bulb Turbine  

INTRODUCTION  
The study area is located about 7 kilometers to the south of Juba city at longitude 31° 36′ 15″ and latitude 4° 46′ 15″, where, the main stream is divided into two channels forming Lologo Island with series of falls. These falls are not high enough to create the required head to drive turbines. A low head dam is to be constructed across the stream to create a suitable head. The project area has relatively sustainable high flows so it lends itself as run- of- river plant. The proposed lay out envisaged the construction of integrated dam/power house type. The dam shall consist of water intake, flood gates and retaining section. The water intake will lead the water into the turbines whereafter released to the stream. Flood gates are intended to spill extra discharges, beyond the turbine design flow. Fig 1 shows the possible project layout drawn to scale from the topography of the area.  

Fig 1: Project proposed layout
Flow Duration curve: The flow, duration curve, is defined as a presentation summarizing the potential of the stream flow, arranged in descending order from the historical records (Bonifica, 1983) or in other words it shows the relation between flows and length of time during which they are available. The flows are plotted as the ordinates and length of time as abscissa. These records of discharges were obtained from the Ministry of Irrigation based on ten day means for the years 1958 to 1982 and correlated with one year recent readings of Juba gauge station. The time flow, equaled or exceeded, was drawn according to the discharge available, from any point in the flow duration, the power output was calculated and an efficiency of 85% was assumed initially. The data of the stream potential are provided in table 1 using these data, the flow duration curve was drawn as shown in Fig. (2).

<table>
<thead>
<tr>
<th>Time Flow Equaled or Exceeded (%)</th>
<th>Flow m³/s</th>
<th>Time Flow Equaled or Exceeded (%)</th>
<th>Flow m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>2650</td>
<td>55%</td>
<td>1395</td>
</tr>
<tr>
<td>5%</td>
<td>1828</td>
<td>60%</td>
<td>1360</td>
</tr>
<tr>
<td>10%</td>
<td>1747</td>
<td>65%</td>
<td>1325</td>
</tr>
<tr>
<td>15%</td>
<td>1689</td>
<td>70%</td>
<td>1302</td>
</tr>
<tr>
<td>20%</td>
<td>1655</td>
<td>75%</td>
<td>1267</td>
</tr>
<tr>
<td>25%</td>
<td>1620</td>
<td>80%</td>
<td>1220</td>
</tr>
<tr>
<td>30%</td>
<td>1574</td>
<td>85%</td>
<td>1006</td>
</tr>
<tr>
<td>35%</td>
<td>1539</td>
<td>90%</td>
<td>779</td>
</tr>
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<td>40%</td>
<td>1511</td>
<td>95%</td>
<td>662</td>
</tr>
<tr>
<td>45%</td>
<td>1463</td>
<td>100%</td>
<td>578</td>
</tr>
<tr>
<td>50%</td>
<td>1411</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig 2: flow duration curve
Referring to the retscreen text book (Retscreen www. retscreen.net) , the possible power from the stream is expressed as follows :

\[ P = \rho g Q (H_g - (H_{hr} + H_{tail})) \eta_t \eta_g (1 - l_{tran}) (1 - l_{pras.}) \]  

(1)

From the same above mentioned reference also, the total energy potential, each 5% interval equals 5% of 8760 hours of the year and from the calculated power output the total energy is given by

\[ E(\text{KWh}) = \sum_{i=0}^{8760} [P_1 + P_2]/2 \times 5/100 \times 8760(1 - \text{g}) \]  

(2)

Scenarios for Different Alternatives Methodology

Based on topographic mapping and river flows, different scenarios were examined for different pool elevations and discharges, and the economical, less environmental impact were selected. Tables from 2 to 4 illustrate these alternatives together with the estimated area which will be inundated as a result of constructing a barrier across the stream. Alternative discharges of 1260 m$^3$/s, 1300 m$^3$/s, 1400 m$^3$/s, 1460 m$^3$/s, 1570 m$^3$/s, taken from the flow duration curve corresponding to time flow exceeded at 75%, 70%, 50%, 45%, 30% respectively. The mean stream flow was 1400 m$^3$/s, two flows below the mean and two above the mean were tested at three pool elevations (U.S.A Corp of Engineers 1976, William and Rand. J. D 1950, James 1954 and Bhatti, et.al, (2004) Economical analysis was carried out using ret screen and hydro help soft wares simulation tools (www.Hydrohelp.ca) and the affected area was estimated from the topographic map available.

**Table 2: Full supply level 460 m Gross Head (6m)**

<table>
<thead>
<tr>
<th>Q m$^3$/s</th>
<th>Power MW</th>
<th>Energy MWh</th>
<th>Cost Mill USD</th>
<th>Annual cost Mill USD</th>
<th>Revenue Mill USD</th>
<th>cost/kWh USD/kwh</th>
<th>Internal rate of return IRR%</th>
<th>Area affected km$^2$</th>
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</thead>
<tbody>
<tr>
<td>1260</td>
<td>49.34</td>
<td>312904</td>
<td>277.87</td>
<td>12.85</td>
<td>31.55</td>
<td>0.887</td>
<td>15.8</td>
<td>5.58</td>
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<tr>
<td>1300</td>
<td>53.15</td>
<td>339884</td>
<td>289</td>
<td>13.2</td>
<td>33.98</td>
<td>0.852</td>
<td>16.6</td>
<td>-</td>
</tr>
<tr>
<td>1400</td>
<td>57.37</td>
<td>366000</td>
<td>304</td>
<td>13.8</td>
<td>36.4</td>
<td>0.83</td>
<td>17.1</td>
<td>-</td>
</tr>
<tr>
<td>1460</td>
<td>59.5</td>
<td>383000</td>
<td>314</td>
<td>14.13</td>
<td>38.6</td>
<td>0.865</td>
<td>17.2</td>
<td>-</td>
</tr>
<tr>
<td>1570</td>
<td>64.5</td>
<td>412756</td>
<td>331</td>
<td>14.74</td>
<td>41.27</td>
<td>0.803</td>
<td>17.9</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 3 : Full supply level 462 m, Gross Head (8)**

<table>
<thead>
<tr>
<th>Q m$^3$/s</th>
<th>Power MW</th>
<th>Energy MWh</th>
<th>Cost Mill USD</th>
<th>Annual cost Mill USD</th>
<th>Revenue Mill USD</th>
<th>Cost/kWh USD/kwh</th>
<th>Internal rate of return IRR%</th>
<th>Area affected km$^2$</th>
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</thead>
<tbody>
<tr>
<td>1260</td>
<td>71.2</td>
<td>455310</td>
<td>314</td>
<td>14.13</td>
<td>45.5</td>
<td>0.69</td>
<td>22</td>
<td>8.9</td>
</tr>
<tr>
<td>1300</td>
<td>77.2</td>
<td>494100</td>
<td>333</td>
<td>14.82</td>
<td>49.36</td>
<td>0.67</td>
<td>22.7</td>
<td>-</td>
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<tr>
<td>1400</td>
<td>83.37</td>
<td>533000</td>
<td>423</td>
<td>15.54</td>
<td>53.6</td>
<td>0.65</td>
<td>18.1</td>
<td>-</td>
</tr>
<tr>
<td>1460</td>
<td>85.2</td>
<td>545000</td>
<td>446</td>
<td>18.82</td>
<td>54.5</td>
<td>0.819</td>
<td>17.5</td>
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<tr>
<td>1570</td>
<td>93</td>
<td>594000</td>
<td>476</td>
<td>19.85</td>
<td>59.4</td>
<td>0.79</td>
<td>18.1</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 4: Full supply level 464 m, Gross Head (10 m)

<table>
<thead>
<tr>
<th>Q m³/s</th>
<th>Power MW</th>
<th>Energy MWh</th>
<th>Cost Mill USD</th>
<th>Annual cost Mill USD</th>
<th>Revenue Mill USD</th>
<th>Cost/kWh USD/kWh</th>
<th>Internal rate of return IRR%</th>
<th>Area affected km²</th>
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<tbody>
<tr>
<td>1260</td>
<td>91</td>
<td>582000</td>
<td>442</td>
<td>18.68</td>
<td>59</td>
<td>0.759</td>
<td>19.4</td>
<td>10.5</td>
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<td>1300</td>
<td>100.4</td>
<td>642100</td>
<td>454</td>
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<td>64</td>
<td>0.707</td>
<td>21.2</td>
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<tr>
<td>1400</td>
<td>99.93</td>
<td>639000</td>
<td>413</td>
<td>17.66</td>
<td>63.9</td>
<td>0.64</td>
<td>23.7</td>
<td>-</td>
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<td>1460</td>
<td>107.8</td>
<td>659000</td>
<td>432</td>
<td>18.3</td>
<td>68</td>
<td>0.655</td>
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<td>1570</td>
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<td>729000</td>
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<td>18.99</td>
<td>72</td>
<td>0.617</td>
<td>25.4</td>
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</tr>
</tbody>
</table>

* calculated, Total Cost/Annual Energy
** Obtained through Topographic Map, and Back water Effect computation

**DISCUSSION**

**Design discharge:** As it is stated earlier, plant size based on economical analysis made for different options. Economical parameters were assumed and for the total cost including civil works + mechanical and electrical equipments, the internal rate of return was worked out using retscean and hydro help soft wares. Plotting discharge vs. internal rate of return (IRR), the highest IRR lies at 1300 m³/s, it is proposed to choose 1400 m³/s as a design discharge which corresponds to the mean stream flow, so as to make use of the flowing water otherwise it would be spilled if 1300 m³/s was selected. The total cost was slightly higher but it is justifiable due to the increased power production. The pool elevation chosen at 462m, corresponding to 8 m gross head (the river bed level here at 450 m), and the mean water depth about 4 meters; this is to limit the effective head at this range in order to minimize the environmental impact associated with flooding large areas. Fig. (3) shows plotting of design discharges vs. internal rate of return.

![Fig 3: Design discharge vs. internal rate of return](image)

**New methodology for number of unit’s selection:** Iteration is made for different number of units for the design discharge of 1400 m³/s at gross head 8 m, the units attempted from 6 to 13. These units were entered in hydro help software. Based on economical analysis and physical constrains, the most suitable one was selected. The
details are presented in Figs 4, 5, 6, and 7 and Table 5. Each attribute of the feasibility of hydropower plant namely total cost, installed power output, maximum efficiency and part load efficiency is given the score 8 for the best, and changing in descending order, and the number of units which obtain the highest score is selected, Tables 5 and 6 show these scenarios.

Fig 4: Number of units vs. total cost

Fig 5: Number of unit's vs. power output
Fig 6: Number of units' vs. maximum efficiency

Fig 7: Number of units' vs. part load efficiency

Table 5: Summary of plant number of units' selection

<table>
<thead>
<tr>
<th>Number of units</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Cost ratio</td>
<td>1</td>
<td>0.91</td>
<td>0.92</td>
<td>0.94</td>
<td>0.957</td>
<td>0.8</td>
<td>0.819</td>
<td>0.834</td>
</tr>
<tr>
<td>* Power ratio</td>
<td>0.98</td>
<td>0.98</td>
<td>0.977</td>
<td>1</td>
<td>0.997</td>
<td>0.995</td>
<td>0.993</td>
<td>0.991</td>
</tr>
<tr>
<td>* Max. Eff. ratio</td>
<td>0.98</td>
<td>0.99</td>
<td>0.986</td>
<td>1</td>
<td>0.9979</td>
<td>0.9972</td>
<td>0.9959</td>
<td>0.9947</td>
</tr>
<tr>
<td>* Part load Eff. ratio</td>
<td>0.97</td>
<td>0.973</td>
<td>0.966</td>
<td>1</td>
<td>0.9989</td>
<td>0.997</td>
<td>0.996</td>
<td>0.995</td>
</tr>
</tbody>
</table>

*These ratios are obtained by dividing each attribute by its corresponding maximum value in the record
Table 6: Units' selection final result

<table>
<thead>
<tr>
<th>Number of units</th>
<th>Cost ratio score</th>
<th>Power ratio score</th>
<th>Maximum efficiency score</th>
<th>Part load efficiency score</th>
<th>Total score obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>8</td>
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<td>10</td>
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<td>7</td>
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<td>7</td>
<td>23</td>
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<tr>
<td>11</td>
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<td>12</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>22</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>18</td>
</tr>
</tbody>
</table>

As it is presented by the tables above, and Fig. 8 and Fig 9 units obtained the highest score compared to others. This installation is an attractive one technically for the reason that the power output was higher and best efficiency of the turbines was achieved. The total cost was slightly higher due to the increasing cost of crane capacity to handle such large units and the volume of the excavation was also increased. Accordingly, nine units is assumed to be reasonable and if the river bed condition is good this will practically reduce the total cost.

Turbine selection and runner dimensions: The basic approach for the selection of turbine type, size and speed is head and flow rate, in this connection as previously worked out, the design discharge is to be maintained at 155.5 m$^3$/s per unit for all the nine units proposed plant and the gross head is to be kept at 8 m so as to reduce the area which may be flooded when the dam is raised higher than that limit. As a rule of thumb relatively high flows and heads below 10 m is covered by axial flow turbines in particular in this tailor made plant is Bulb Kaplan turbine (Esha 1998) as shown in the application chart (Fig. 9)
When the basic parameters of head and flow are fixed, the main dimension of the turbine can be worked out. Specific speed is the term which characterizes different types of runners, and if the rotational speed is estimated (Kpordze, 1983), specific speed can be calculated as follows:

\[ N_s = \frac{N\sqrt{Q}}{H^{1.25}} \]  \hspace{1cm} (3)

\[ N_{sOE} = \frac{N\sqrt{Q}}{E^{0.75}} \]  \hspace{1cm} (4)

Another version of specific speed is the SPEED NUMBER \([11]\) that refers to the best efficiency point. The equation for the speed number yields:

\[ \Omega = \frac{\omega \sqrt{Q}}{\sqrt{2gH}} \]  \hspace{1cm} (5)

The size of the turbine can be found by the capacity

\[ Q = \frac{Q^*}{(2gH)^{0.75}} \]  \hspace{1cm} (6)

It is convenient to introduce reduced velocities

\[ c_0 = c/\sqrt{2gH} \]
\[ u_0 = u/\sqrt{2gH} \]
\[ w_0 = w/\sqrt{2gH} \]

The reduced circumferential speed \( \omega_0 = \omega^*/\sqrt{2gH} \)

The capacity is reduced flow \( Q_0 = Q^*/\sqrt{2gH} \)

And the speed number

\[ \Omega = \omega_0 \sqrt{Q_0} \] \hspace{1cm} (Dimensionless) \hspace{1cm} (7)

Knowing the speed number the main dimensions are obtained. A large number of statistical studies on schemes has established a correlation of the specific speed and the net head for each turbine. Some of these correlations for bulb turbine units (CSK Kpordze 1983) are:

\[ N_{sOE} = 1.528 / H^{0.283} \]  \hspace{1cm} (8)

The relation of speed with power and head is given by

\[ N = 3558.983(P/H)^{0.4835} \]

Applying the above mentioned equations and statistical relations to the proposed project yields the following:

Rotational speed \( = 115.4 \text{ RPM} \)
Specific speed \( = 919.3 \)
Speed number \( = 3.14 \)
Bulb turbine diameter \( = 4.8 \text{ m} \)
Fig. 10 shows the cross section of a typical Bulb Kaplan turbine.

Fig (10) Typical power house cross section accommodating Bulb turbine (R.P.Saini 2001)

**Cavitation:** Cavitation problems and possibility of rough operation preclude generation below a minimum discharge and limited head range. The minimum discharge for axial bulb turbine is 0.35 of the rated discharge \(^{[10,3]}\) then the minimum for the proposed project is \(0.35 \times 155.5\) m\(^3\)/s = 54.4 m\(^3\)/s, taking 2% as leakage loss the minimum would be 57.5 m\(^3\)/s. This corresponds to 7.97 m head, which is the maximum generating head. The minimum discharge of the site is 57.8 m\(^3\)/s which is above the required minimum discharge. The minimum head required for the bulb turbine is 0.33 of the maximum head (CSK Kpordze 1983 and U.S.A Corp of Engineers 1976), this would be 0.33 \times 7.97 = 2.63 m, which is less than the available minimum head of 3.9 m.

**Turbine setting:** For free cavitation the turbine is to be set at a certain height reference to the tail water level, and the governing parameter is the cavitation number \((\sigma)\). It is commonly relating cavitation number with specific speed:

\[
H_s = H_a - H_v - \sigma H
\]  

\(^{(9)}\)

From the statistical studies \(\sigma = 0.097 \times 10^{-6} \times N_s^{2.479}\), for \(N_s=915.5\), \(\sigma = 2.13\)

Accordingly the turbine setting would be:

\[
H_s = 10.3 - 0.5 - 2.13 \times 7.97 = 7.13\ m
\]

**CONCLUSIONS AND RECOMMENDATION**

We conclude that the design discharge for the proposed project using economical analysis is performed and it seems to be very attractive for this installation since it achieves reasonable internal rate of return (IRR) 18.1%. The levelized cost of energy calculated by retscreen software \(^{[2]}\) is about 0.09 USD/kWh and the targeted power and efficiency is obtained. At the proposed gross head of 8 meters a suitable size of the plant is reached, which is 155.5 m\(^3\)/s as design discharge per turbine, the number of units is optimized at nine sets of bulb turbines producing 83 MW of power, taking in to consideration the environmental impact which limits the gross head at this range.

Minimum discharge and minimum head for satisfactory operation is satisfied. As this work is to be considered as pre-technical and economical study, the hill chart or the performance characteristic of the candidate turbine is required at the next phase of the study from the turbine manufacturer for efficiency guarantee and the limitations of discharge and head for reliable operation of the proposed hydropower plant.

**Nomenclature:**

Where:

\[
P \quad \text{[W]} \quad \text{power output watts} \\
\rho \quad \text{[kg/m}^{3}\text{]} \quad \text{density of water} \\
g \quad \text{[m}^{2}\text{/s]} \quad \text{acceleration of gravity} \\
Q \quad \text{[m}^{3}\text{/s]} \quad \text{discharge} \\
H_g \quad \text{[m]} \quad \text{gross head} \\
H \quad \text{[m]} \quad \text{rated head} \\
H_{hr} \quad \text{[m]} \quad \text{hydraulic losses} \\
H_{tail} \quad \text{[m]} \quad \text{tail water effect} \\
\eta \quad \text{[%]} \quad \text{turbine efficiency} \\
L_{\text{trans}} \quad \text{[%]} \quad \text{transformer losses}
\]
I_{pras} [%] parasitic electricity losses

Equ (2)

E Energy [kWh]
P1 and P2 = power output at time 1 and time 2 in [kW] respectively
5/100 Time difference [%]
L_t annual downtime losses [%]

Equ (3)

N_s: specific speed (dimensionless)
N speed [rpm]

Equ (4)

N_{SE} = is the specific speed energy based (dimensionless)

Equ (5)

Q* discharge at best efficiency [m^3/s]
\omega* rotational speed at best efficiency [rad/s]
H* head at best efficiency [m]
\sigma cavitation factor [-]

Equ (6)

c absolute velocity [m/s]
u circumferential velocity [m/s]
w relative velocity [m/s]

Equ (7)

H_s turbine setting height [m]
H_a absolute pressure [m]
H_v vapor pressure [m]

REFERENCES:

12. WWW. Hydrohelp.ca.