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Research Article

Technical & Economic Feasibility Study of Proposed Pump Storage Power Plants at Kuda Oya, Mul Oya, Gurugal Oya, and Dambagasthalawa

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Abstract

This paper presents a Technical and Economic Feasibility Study of proposed Pumped Storage Power Plants (PSPPs) at KM (Kuda Oya, Mul Oya), KMG (Kuda Oya, Mul Oya, Gurugal Oya), KG (Kuda Oya, Gurugal Oya), and Dambagasthalawa. Sri Lanka aims to transition away from a coal-dominant electricity sector within the next decade, aligning with sustainability goals outlined by the United Nations. In pursuit of affordable and clean energy sustainability, the Sri Lankan government has opted to shift its long-term energy policy towards renewable sources, departing from fossil fuels. Despite this shift, a significant portion of Sri Lanka's electricity consumption—approximately 600 MW from oil and 900 MW from coal—persists. The country now aims to source 80% of its energy from renewable sources, necessitating a focus on underutilized opportunities.

In selecting the best candidate sites for Pumped Storage Power Plant (PSPP) design, comprehensive hydrological and sedimentation studies play a pivotal role. In this endeavor, we endeavor to re-rank the selected candidate sites for pumped storage power plants considering technical & financial feasibility by conducting comprehensive hydrological and sedimentation studies. These studies are pivotal for assessing the feasibility and long-term viability of potential sites, aiming to select the most sustainable candidate site in every aspect. Therefore, the primary objective of this research is to conduct a thorough hydrologic study of the proposed KMG and Dambagastalawa pump storage power plants, focusing on identifying potential energy-saving opportunities in pumping when these plants operate as open-loop systems. This study will analyze the hydrology of the upper ponds of the Kuda Oya, Mul Oya, and Gurugal Oya (KMG) pump storage power plants, and the Dambagastalawa Oya pump storage power plant, assessing the potential reduction in pumping energy. Such insights are essential for optimizing the design and operation of PSPPs to ensure economic viability and sustainable energy generation.

Furthermore, this research addresses the importance of studying sedimentation in both the upper and lower ponds of the KMG and Dambagastalawa pump storage power plants. Sedimentation calculations will be performed to determine reservoir lifetimes, offering critical insights into the long-term feasibility and maintenance requirements of these projects. The findings of this study are expected to provide valuable guidance to policymakers, investors, and PSPP designers in selecting the most suitable sites for addressing Sri Lanka's peak power demands and urgent electricity needs. By emphasizing the significance of hydrological and sedimentation studies, this research underscores the importance of thorough site assessment in optimizing the design and operation of Pumped Storage Power Plants.

Introduction

United Nations introduced the Sustainable Development Goals 2030 agenda [1] to make a better and sustainable future for all. In 2015, September Sri Lanka and another 192 countries adopted the 2030 agenda for sustainable development.

To achieve SDG goal 7 which is affordable & clean energy, the Sri Lankan government made a policy with the objective of increasing the renewable energy share percentage of electricity generation up to 80% in 2041 [2]. Ceylon Electricity Board (CEB) would not be able to install a large number of economical fossil fuel power plants. Further, CEB forecast in 2030 maximum demand would be 4872MW [2]. It is almost double the current maximum demand. To fulfill this requirement CEB needs to increase the generation capacity immediately. Furthermore, CEB started to promote domestic roof-top solar systems and wind power generation where large hydropower generation capacity was almost absorbed [3]. Daytime power generation will increase and can create a positive gap between electricity generation and demand in the daytime.

If CEB can store excess and cheap power generated in off-peak and daytime, where generated power is greater than the demand, then it can use night peak and other necessary times where the generation cost is high. It is called as "Peak saving method". But solar power generation with a battery bank, is costly. CEB identified pump storage power plants are one of the suitable options for storing energy [3].

The first known use cases of pumped storage

Pumped Storage Power Plants (PSPP) were found in Italy and Switzerland in the 1890s, and PSPP was first used in the United States in 1930. A PSPP can primarily generate required electric power during the peak hours or day time and when the power demand is lower, water is pumped up from the lower pond to the upper pond using the excess electricity generation capacity of base-load thermal power plants. Consequently, water is circulated to generate electric power. PSPPs may be classified into "closed loop PSPP" type and "Open loop PSPP" type.

In "Closed loop PSPP", there is no natural inflow into the upper pond or the flow is negligible, and water pumped up to the upper pond is recirculated between the two ponds for power generation. In the "Open loop PSPP" type, the power plant is made with the natural inflow, and the water pumped into the upper pond is used for power generation. This would save energy used for pumping according to the capacity of natural inflow into the upper pond.

In addition to providing lower-cost peak-time power generation, a PSPP can also act as an emergency reserve during sudden outages in the system and also can be helped to withstand vulnerable blackouts. PSPP acts as an ideal fast response reserve assisting economic dispatch. Since PSPP can store electric power, it improves the quality of the electricity supply and the reliability of the sector as a whole through the improved provisions for frequency control and reactive power supply. Accordingly, a PSPP can improve the reliability of a power system. Owing to these advantages of PSPP it allows the power system to be developed with larger penetration of renewable energy sources in a flexible manner.

In a system inclusive of both thermal and nonthermal sources, PSPP acts as a steadfast intermediary in the overall system coordination. Studies have indicated the potential for PSPP in Sri Lanka considering various aspects as in Figure 1, Sri Lanka witnesses a peak demand for electricity during 1800 - 2100 hrs.

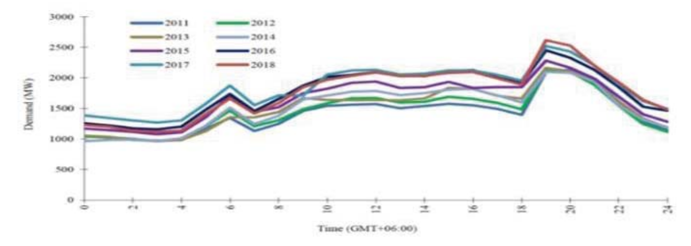

Figure 1: Load Curve in Sri Lanka.

It is estimated that 17% of the total energy is consumed during this time period [4]. Owing to this peaking scenario, Sri Lanka needs to find a mechanism to serve the fluctuating demand. This can be achieved by the use of PSPP. Since Norochcholai coal power plants are planned to be fully connected to the grid to cater to the base load, the introduction of PSPP would increase the efficiency of these large-scale coal power plants as well. Furthermore, the maintenance costs of certain types of gas-fired power stations increase sharply burdening the national economy when they are forced to reduce load at night. This is due to the fact that the thermal plants are much less able to respond to the sudden changes in electrical demand, potentially causing frequency and voltage instability. Pumped storage plants, like other hydroelectric plants, can respond to load changes within seconds.

Now, PSPP facilities can be found all around the world. According to the 2021 edition of the Hydropower Market Report, PSPP currently accounts for 95% of all utility-scale energy storage in the United States. America currently has 43 PSPP and has the potential to add enough new PSPP plants to more than double its current PSPP capacity [5]. Those are statistical data in a global context and unfortunately in a local context, Sri Lanka still did not have any PSPP. In 2009, the survey identified suitable locations and water streams to install pump storage plants including Kuda Oya, Mul Oya, Gurugal Oya & Dambagasthala Oya to fulfill the peak power requirement of the country. Moreover, in 2015, a survey was done by the Japan International Cooperation Agency, and the study aimed at propounding optimal power generation for peak power demand in Sri Lanka that will contribute to development and improvement in Sri Lankan economy and living standard in a quick and efficient manner through stable supply of electricity and relief of peak power shortage and Fluctuation in electric supply capacity according to season [6].

Methodology

The study aims to evaluate the technical and economic feasibility of pumped storage power plants (PSPP) at Kuda Oya, Mul Oya, Gurugal Oya, and Dambagasthalawa. This research analyzes site-specific data such as hydrology, geology, and sedimentation to determine the most feasible locations for PSPP installations. The feasibility study includes both manual calculations and HEC-HMS models [7], along with comprehensive sedimentation analysis. The study is based on catchment area calculations and data derived from 1:10,000 maps. The locations under study are Kuda Oya, Mul Oya, Gurugal Oya, and Dambagasthalawa pump storage power plants (Table 1). The map, as referenced in the study (Figure 2), provides a catchment area of the Gurugal Oya upper pond.

Economic feasibility analysis of KMPSPP, KGPSPP & DMPSPP

This study was performed as follows,

1. Catchment area calculation (upper ponds)
2. Collecting rainfall data
3. Runoff flow calculation (manually calculated and verified with HEC-HMS software)
4. Calculation of each pond's natural inflow
5. Pumping energy saving due to natural inflow

Sources and databases of data

The data for this feasibility study is sourced from several key repositories and databases:

- Ceylon Electricity Board (CEB) for power demand forecasts and PSPP performance metrics.
- Catchment Area Maps (1:10,000 scale) for determining the catchment areas of the upper ponds.
- Sedimentation data was calculated using the Dandy-Bolton formula and validated using reservoir storage data.
- Soil data was sourced from the Soil Map of Sri Lanka, identifying soil types for geological analysis.
- Hydrological calculations were verified using both manual calculations and the HEC-HMS model.

Catchment area calculation

The catchment area calculation performed in this study used 1:10,000 maps, with the map numbers referenced in Table 2 as '61/15' and '61/14.' These map numbers serve as identifiers for specific map sheets, which are commonly used for detailed topographical studies and hydrological assessments at each site (Table 3).

Rainfall data

Rainfall data from the catchment area were collected from the Meteorology Department for this study.

Table 1: Selected PSPP's Upper and Lower Ponds.

Pump Storage Power Plant (PSPP)	Upper pond	Lower pond
KM PSPP	Mul Oya	Kuda Oya
KG PSPP	Gurugal Oya	Kuda Oya
DM PSPP	Pattipola	Dambagastalawa

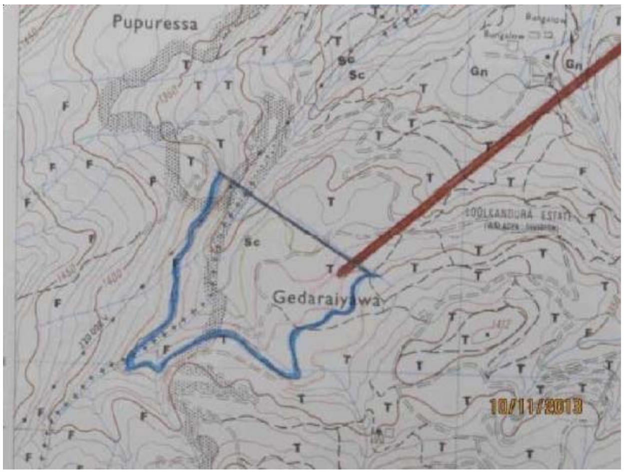

Figure 2: Marked map of the Catchment area of Gurugal Oya Upper pond.

Table 2: 1:10000 scale topographical Maps used for Catchment area Calculation.

Pond Name	Related 1:10,000 Map Nos
Gurugal Oya upper pond	61/15, 61/14
Mul Oya upper pond	61/15, 61/20, 62/11
Pattipola upper pond	68/15

Table 3: Calculated Catchment areas.

Location	Catchment Area(km^2)
Gurugal Oya Upper pond	4.2
Mul Oya Upper pond	14.86
Pattipola Upper pond	1.468

Runoff flow calculation (manually calculated and verified with HEC-HMS software)

Manual runoff calculations are performed using the Curve Number (CN) method [8]. This method, developed by the USDA Soil Conservation Service, is widely used for estimating direct runoff from a rainfall event based on land use, soil type, and hydrological conditions. The HEC-HMS [7] is a widely used software for simulating rainfall-runoff processes in watersheds [8]. This model is used to verify manual calculations. The flow chart (Figure 3) outlines the sequence of steps followed in the study, beginning with data collection and ending with the comparison of manual and model-generated results.

This HEC-HMS model (Figure 4) shows the estimated runoff depth based on the given input data.

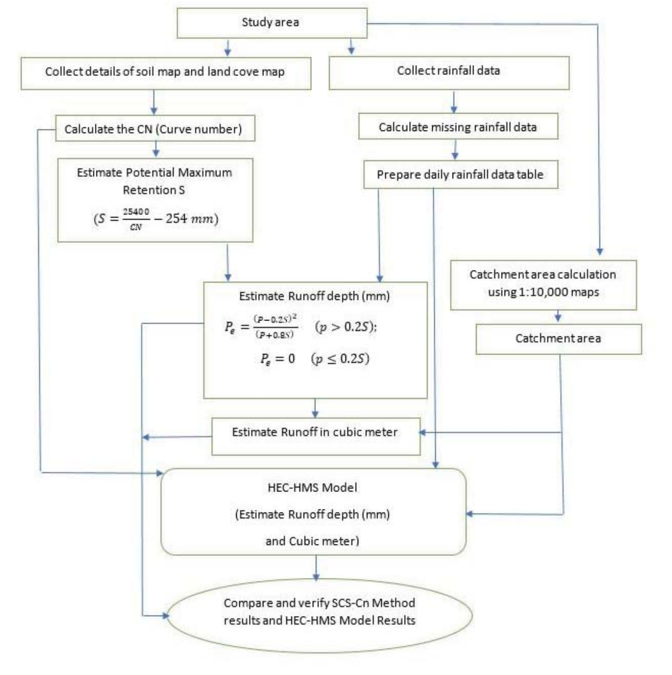

Figure 3: Methodology flow chart.

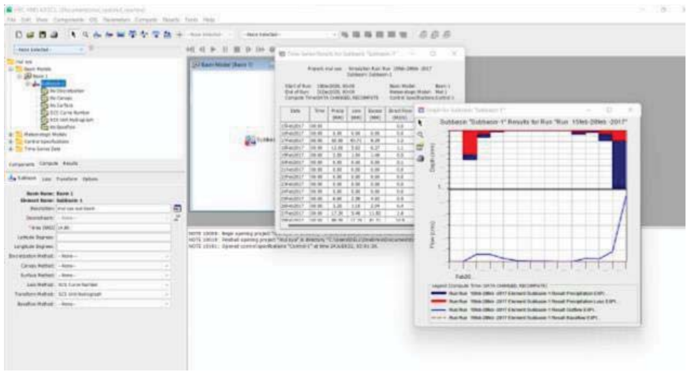

Figure 4: HEC-HMS Model.

Energy saving due to natural inflow (Pumping Energy Saving)

Finding the pump discharge rate (KM Pump storage power plant)

Basic design configurations based on Tharanga Wickramarathna's study [6].

Design Discharge = 80.2 m^3/s

Peak duration, Hours = 6 hr

Total discharge of water per day = 6 hr × 60 × 60 × 80.2 m^3/s = 1732320 m^3

If the power plant pump working hours are 18 hours,

Pump discharge = 1732320 $m^3/(18 \times 3600)$

Pump discharge = 26.733 m^3/s

Required penstock diameter for discharge

Assume the penstock Making Galvanized iron, Then $n = 0.016$

$D = 2.69 \times (n^2 \times Q^2 \times L/Hg)^{0.1875}$

$D = 2.69 \times (0.016^2 \times 80.2^2 \times 2320\ /\ 366.7)^{0.1875}$

$D = 4.18\ m$

Finding the discharge velocity

$D = (4 \times Q/V \times \Pi)^{0.5}$

$V = 4 \times Q/D_2 \times \Pi$

$V = (4 \times 80.2)\ /\ (4.18^2 \times 3.1416)$

$V = 5.844\ m/s$

Finding the pumping velocity

$V = (4 \times 26.733)\ /\ (4.18^2 \times 3.1416)$

$V = 1.948\ m/s$

Therefore, maximum discharge velocity = maximum pumping Velocity = 5.844 m/s

Finding the Reynolds number

$$Pomping\ power\ p = \rho \times g \times Q \times H_e \times \eta \times 10^{-3}\ MW$$

$$R_e = \frac{(1000\text{kg}/\text{m}^3 \times 5.844\, m/s \times 4.18m)}{0.001\text{N}/\text{m}^2}$$

$R_e = 2.44 \times 10^7\ kgN^{-1}m^{-5}S$

Finding pipe relative roughness factor

Pipe Relative Roughness Factor = $\varepsilon/ = 0.06\ mm/4.18 \times 10^3\ mm$ (steel Welded and Seamless $\varepsilon = 0.06$ mm)

Pipe Relative Roughness Factor

$= 1.435 \times 10^{-5}$

friction factor factor f = 0.009293

(Reference: Moody Graph)

Find the head loss due to Friction

$$h_L = f \times \frac{L}{D} \times \frac{V^2}{2g} = \frac{8fLQ^2}{gD^5\Pi^2}$$

$$h_L = 0.009293 \times \frac{2320}{4.18} \times \frac{5.844^2}{2 \times 9.81}$$

$h_L = 8.99\ m$

Find the total effective head

Total effective head for pumping

$= 366.7 + 8.99\ m$

$= 375.69\ m$

Total pumping energy calculation

Pumping power $p = \rho \times g \times Q \times H_e \times \eta \times 10^{-3}\ MW$

$P = 8.5 \times Q \times H_e \times 10^{-3}\ MW$

$P = 8.5 \times 26.733 \times 375.69 \times 10^{-3}\ MW$

$P = 85.36\ MW$

Yearly pumping energy $E = 85.36\ \text{MW} \times 24h \times 365$

$E = 747.753 \times 10^3\ MWh$

Yearly pumping Water Volume (closed loop)

$= 1732320\ m^{3}$/day × 365 days

$= 632.3 \times 10^6 m^3$

$$Yearly\ energy\ saving\ Because\ of\ Natural\ Flow$$

$$= \frac{747.753 \times 10^3\ MWh \times Yearly\ Inflow\ Volume}{632.3 \times 10^6\ m^3}$$

$$Year\ 2016\ saving\ Because\ of\ Natural\ Flow$$

$$= \frac{747.753 \times 10^3\ MWh \times 114799206.07}{632.3 \times 10^6\ m^3}$$

$= 13575.22\ MWh$

As above, calculations for pumping energy savings were performed for the KM Pumped Storage Power Plant using inflow volume data from 2016 to 2020, with results presented in Table 4. Similar calculations were conducted for the KG and Dambagasthalawa Pumped Storage Power Plants, with results shown in Tables 5,6.

Sedimentation & reservoir lifetime analysis

Sedimentation yield calculation: The Dandy-Bolton formula is often used to calculate the sedimentation yield. The formula uses catchment area and mean annual runoff as key determinants to give a yield value. It does not differentiate in basin-wide smaller streams and their characteristics. Dandy and Bolton's equation calculates all types of sediment yield, i.e. sheet and rill Erosion, Gully Erosion, channel Bed, bank erosion, mass movement, etc.

Sediment yield by the Dendy-Bolton formula For Q < 2:

$$S = 1280\ Q^{0.46}\,[1.43 - 0.26 log(A)] \quad (1)$$

For $Q \geq 2$:

$$S = 1965\ e^{-0.055}\,[1.43 - 0.26 log(A)] \quad (2)$$

Where;

Table 4: Mul Oya UP Yearly inflow volumes.

Year	Inflow Volume (cubic meter)
2016	11479206.07
2017	19106295.46
2018	27836772.45
2019	18116298.56
2020	14054416.54

Table 5: Gurugal Oya UP Yearly inflow volume.

Year	Inflow Volume (cubic meter)
2016	1875391.25
2017	3966168.224
2018	5333538.57
2019	4119010.557
2020	2682605.383

Table 6: Pattipola UP Yearly inflow volume.

Year	Inflow Volume (cubic meter)
2016	446818.8818
2017	1337846.147
2018	1518672.438
2019	1464600.085
2020	914216.538

Q (in) - Runoff

A (mi2) - Catchment Area

S (tons/mi2/yr) - Sedimentation Yield

Reservoir lifetime (Figure 5) is calculated manually by using the general formula given below and using Microsoft Excel to find reservoir lifetime.

$$Sediment\ Volume\ per\ 1\ year = \frac{Se\dim ation\ Load\ Per\ year}{(\gamma_{av})} \quad (3)$$

Cumulative Sedimentation Volume (m^3) = $\sum_{t=1}^{T}$ Sediment Volume (4)

Dead Storage Volume Balance (m3) = (Initial dead storage volume) – (Cumulative Sedimentation Volume) (5)

Annual Sediment load to reservoir (*Kg* = Sediment Yield (*Kg/Km*^{2} per year) * Catchment Area (*Km*^{2}) (6)

Using sediment yield data calculated with the Dendy-Bolton formula (Equations 1, 2, 3, 4, 5, and 6), the reservoir lifetime can be calculated.

Soil Analysis for KM, KG, KMG & Dambagastalawa PSPP

Utilizing the Soil Map of Sri Lanka, the identified soil group

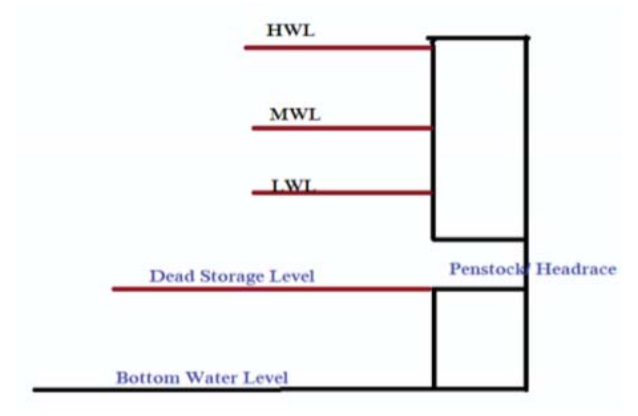

Figure 5: Lifetime of a reservoir.

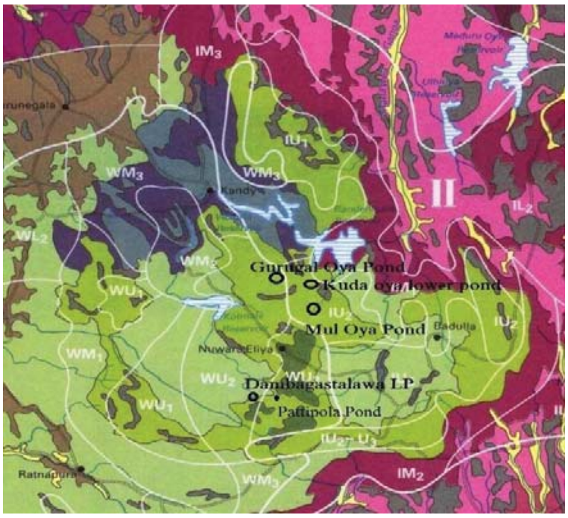

Figure 6: Sri Lankan soil map.

is Red Yellow Podzolic. Within this classification, specific soil types have been identified (Figure 6) [9,10].

Results and discussion

This section analyzes natural inflow, sedimentation rates, and soil composition for the Mul Oya, Gurugal Oya, and Pattipola reservoirs. The results highlight natural inflow's role in reducing energy needs, sedimentation's impact on reservoir lifespan, and soil considerations for construction. Together, these insights support the feasibility and sustainability of the proposed pumped storage systems.

Natural inflow results

Manual calculations were performed using the collected data and equations [7] to compute the runoff and inflow volume. The HEC-HMS model processes [8] the collected data and provides the results. A comparison of the results from the manual calculations and the HEC-HMS model is conducted for verification. The yearly inflow volume results for Mul Oya, Gurugal Oya, and Pattipola upper ponds are as follows (Tables 4-6).

Table 7: KM Pump storage power plant Energy Saving due to natural inflow.

year	Inflow Volume (cubic meter)	Yearly Energy Saving(MWh)
2016	11479206.07	13575.22
2017	19106295.46	22594.95
2018	27836772.45	32919.55
2019	18116298.56	21424.19
2020	14054416.54	16620.64

Table 8: KG Pump storage power plant Energy Saving due to natural inflow.

year	Inflow Volume (cubic meter)	Yearly Energy Saving(MWh)
2016	1875391.25	3540.83
2017	3966168.224	7488.32
2018	5333538.57	10069.98
2019	4119010.557	7776.89
2020	2682605.383	5064.89

Table 9: Dmbagastalawa Pspp Energy Saving Due To Natural Inflow.

Year	Inflow Volume (Cubic Meter)	Yearly Energy Saving(Mwh)
2016	446818.8818	641.69
2017	1337846.147	1921.33
2018	1518672.438	2181.02
2019	1464600.085	2103.37
2020	914216.538	1312.94

Table 10: Identified Soil Types.

Location	Soil Type
Gurugal Oya UP	Red Yellow Podzolic with mountain regosols
Mul Oya UP	Red Yellow Podzolic with mountain regosols
Kuda Oya LP	Red Yellow Podzolic with mountain regosols

Table 11: Reservoir Life time calculation and Results.

Reservoir	Result
Muloya upper Reservoir	Dead Storage Volume Zero between year 530 & 531. Therefore, reservoir life time is 531 Years.
Gurugal Oya_ Reservoir	Dead Storage Volume Zero between year 243 & 244. Therefore, reservoir life time is 244 Years.
Kuda Oya Lower Pond	Dead Storage Volume Zero between year 208 & 209. Therefore, reservoir life time is 208 Years.
Pattipola Reservoir	Dead Storage Volume Zero between year 368 & 369. Therefore, reservoir life time is 369 Years
Dambagasthalawa Lower Pond	Storage volume Zero between year 191 & 192. Therefore, reservoir life time is 192 Years.

Using inflow volume data from 2016 to 2020, the calculated energy savings for the Pumped Storage Power Plants due to natural inflow are tabulated below in Tables 7-9.

The identified soil types are tabulated in Table 10.

Using sediment yield data calculated with the Dendy-Bolton formula (Equations 1, 2, 3, 4, 5, and 6), the results are tabulated in Table 11.

Conclusion

Based on the calculations, it is evident that the annual energy savings attributed to the natural flow of upper ponds are substantial, averaging approximately 22,000 MWh for the KM PSPP, 7,000 MWh for the KG PSPP, and 1600 MWh for the DM PSPP. Leveraging this natural flow can significantly reduce pumping time, thereby enhancing plant efficiency. This presents an additional advantage for the plants in terms of operational cost reduction and overall sustainability.

Furthermore, the mathematical analysis indicates that the lifetimes of all reservoirs exceed expectations, ensuring long-term viability and stability for the PSPP. This underscores the robustness of the selected sites and reinforces their suitability for addressing Sri Lanka's energy demands in a sustainable manner.

One limitation of the study is the reliance on historical data for rainfall and inflow estimations. Climate change may alter precipitation patterns, which could affect future inflow rates and reservoir sedimentation. Additionally, the study does not fully explore alternative inflow enhancement methods, such as water diversion or artificial reservoirs, which could improve the system's reliability during dry periods.

This study highlights the viability of Pump storage power plants as a reliable solution for meeting Sri Lanka’s peak energy demands, emphasizing the role of natural inflows in reducing energy costs and optimizing system performance. With effective sedimentation management and soil stabilization techniques, these sites provide long-term, sustainable energy storage that aligns with Sri Lanka’s renewable energy goals. Moving forward, careful consideration of evolving hydrological patterns and environmental impacts will be essential to maintain the effectiveness of these systems.

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