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A Novel Approach of Exploring Water Value: A Study Based on Sri Lankan Reservoirs

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Abstract: Water, often perceived as a free natural resource, plays a crucial role in meeting societal needs and ensuring its preservation for future generations. The concept of water value highlights its importance, especially in reservoirs, where its value fluctuates based on demand and availability. This paper explores the intrinsic value of water amidst stochastic variations due to weather uncertainties and introduces a novel model for economic dispatch using Dynamic Programming (DP) and Stochastic Dual Dynamic Programming (SDDP) principles. Two new approaches for calculating water value are proposed, expanding beyond the traditional zero-value assumption relative to fuel cost. The first method estimates the water value based on the per-unit generation cost of the most expensive thermal power plant in the Daily Load Curve. The second method calculates the water value as the weighted average cost of variable thermal power plants in the economic dispatch schedule. Additionally, this research examines the water value in the context of both power generation and agriculture, comparing their respective impacts. The paper underscores the importance of incorporating water value concepts into decision-making processes while addressing potential challenges. The research is contextualised within Sri Lanka, highlighting its practical implications.

Keywords: Water value, Hydropower, Economic dispatch, Per unit generation cost, Stochastic

1. Introduction

Water is one of the basic needs of human beings, and accurately measuring its value is challenging. Although water is freely available in nature, it is often considered a zero-cost resource. However, this assumption is not entirely justified, as water may not always be readily available to meet our needs due to shortages of usable water, leading to potential crises in the future. Consequently, water management policies have been introduced in many countries to distribute water for various requirements. When water is insufficient to meet demands, various alternatives are utilised to accomplish necessary tasks. At this juncture, water value can be estimated based on the cost of these alternatives. While water may have been taken for granted when it was plentiful, its true worth becomes evident during times of scarcity. The rate of water replenishment largely depends on rainfall and large reservoirs play a crucial role in storing water for periods when rainfall is scarce. This phenomenon is seasonal in nature. During periods of heavy rainfall, water needs can often be met solely by natural precipitation, replenishing the reservoirs. However, when reservoir levels reach capacity, it signifies a state of saturation due to excess of water. Yet, when utilising stored water, careful consideration must be given to its current use versus its preservation for future needs. Sometimes, conserving water for use during dry seasons may prove more beneficial than immediate consumption.

The water value can be defined as the equivalent worth of water stored in reservoirs. In the context of electricity generation, the value of one kilowatt-hour (kWh) of electrical energy produced from hydropower is considered a representation of water value [1]. Similarly, in agriculture, the value of one kilogram of rice produced with water can be used as a reference. However, this determination is complex as rice is not the sole crop cultivated and water usage varies depending on the type of crop.

Current water management policies prioritise meeting the basic needs of living beings, including providing water for drinking and daily activities, followed by allocations for agricultural purposes. Subsequently, water is

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allocated for electricity generation. Due to this factor, hydropower plants are not operated frequently, leading to the utilisation of various other expensive power plants for electricity generation.

In the existing generation planning frameworks, the dynamic nature of water value is often overlooked, with a static, nationally averaged value being utilised. This research paper introduces a model for economic dispatch using SDDP principles and then presents two novel methodologies for water value estimation while offering a comparison to the traditional approach where water value is considered zero. These methodologies can calculate real-time water value by accounting for its dynamic behaviour influenced by various factors. Furthermore, the paper presents a quantitative analysis comparing the water value in agriculture to that in electricity generation. Ultimately, the study provides guidance on refining the water value in relation to different reservoir levels.

2. Literature Review

Water value estimation is related to Dynamic Programming (DP) techniques due to the uncertainty of weather and climate conditions [2]. On the utility side of the power system, an economic dispatch schedule is prepared for each quarter-hour time duration to ensure a continuous, qualitative power supply at a justifiable economic state. The Sri Lankan power system comprises numerous hydro and thermal power plants, each with distinct operational constraints. All constraints of every power station must be considered in the economic dispatch process.

DP techniques and their advanced versions support obtaining clear outputs in such problems [3]. DP techniques, based on Bellman's Principle of Optimality, solve complex, multi-stage problems by dividing them into simpler sub-problems, thus providing systematic approaches to find optimal solutions after considering all possible stages. In this context, DP can optimise the operation of hydroelectric plants by determining the optimal water release schedule to minimise costs while meeting the expected electricity demand. However, DP is computationally intensive for large-scale problems. To address this, advanced versions of DP, such as Differential Dynamic Programming (DDP) and Discrete Differential Dynamic Programming (DDDP), are utilised to obtain accurate solutions. These methodologies reduce computational complexity by focusing on local optimality. Furthermore, DP with Successive Approximations (DPSA) can optimise state variables in a one-by-one cyclic process by freezing the values of non-optimised variables at their previous semi-optimal values. Combining DPSA with DDDP can yield fast and optimal results [4].

Using the principles of DP and its advanced versions, a recursive equation for the minimum cost of operation (F_N) can be obtained as represented in Eq. (1), whereS_n is the reservoir storage at the n^{th}stage, andU_{N-1} denotes the water release at stage $n.R_n(S_n, U_{n-1})$is the return stage at stage n with respect to $S_n$andU_{n-1}.

$$F_N(S_N) = min[R_N(S_N, U_{N-1}) + F_{N-1}(S_{N-1})] \ldots (1)$$

Markov Chains provide a way to model the stochastic behaviours of inflow by considering the conditional probabilities of streamflow based on previous records, assuming that the streamflow of a given month is independent [5]. Using the conditional probability of streamflow at stage N falling into discretisation stage I, given that the inflow at stage $n+1$ is I_{n+1}^1, denoted by $P(I_N^1, I_{N+1}^1)$, Eq. (1) can be used to obtain Eq. (2).

$$F_N(S_N, I_{N+1}^1) = min\left[\sum_{i=1}^{K} P(I_N^1 I_{N+1}^1).\{R_N(S_N, I_N^1, U_{N-1}) + F_{N-1}(S_{N-1}, I_N^1)\}\right] \ldots (2)$$

The DDP and DDDP techniques are instrumental in finding an improved trajectory among discrete states within the neighbourhood of a trial trajectory. An algorithm can be developed to achieve this as shown in steps (i) to (vi) [4]:

i **Select a Trial Trajectory:** Choose a trial trajectory as close as possible to the optimal trajectory. This can be done with some insight into the actual operation of the system. It ensures convergence to the global optimum rather than a local optimum.

ii **Open Corridors:** Define corridors on state variables around this trial trajectory.

iii **Update Trajectory:** Obtain the updated trajectory using the conventional DP technique within the corridor.

iv **Iterate:** Repeat steps (ii) and (iii) until the updated trajectory remains the same as the previous trajectory. This will be the optimal trajectory for the given discretisation of the state variables within the corridor.

v **Increase Accuracy (if needed):** If added accuracy is required, narrow down the corridor by maintaining the same number of discretisation but with a smaller increment of the state variable. Repeat steps (ii), (iii), and (iv).

vi **Ensure Sufficient Accuracy:** If the accuracy is still not sufficient, repeat step (v).

In the data analysis stage, streamflow patterns should follow normal or log-normal distributions with a high goodness-of-fit index due to the large amount of statistical data required for the inflow. After suitable statistical distributions are obtained, discretisation is done with equal intervals of probability [3].

2.1 Cost Functions and Water Value

The process of hydrothermal dispatch involves sequential, stochastic and time-dependent optimisation [5]. It is assumed to be centralised, requiring generation decisions to be made in sequence due to the stochastic nature of inflows. Turbine decisions impact future water availability and the overall system cost, making it crucial to understand the relationship between immediate and future costs. By optimising the schedule of decisions, the sum of immediate and future costs can be minimised.

The immediate cost function provides information on the associated costs of thermal generation at time t, while the future cost function encompasses the expected costs of thermal generation from $t+1$, to the end of the time horizon. If the storage water volume increases at the end of t, future costs decrease because more hydropower can be utilised. Conversely, if less water is used at t, immediate costs increase. Figure 1 illustrates the derivations of both cost functions, showing that at the optimal solution, the values of immediate and future water are equal [6].

It is noted that the future cost function is convex with respect to the water storage volume at t. This can be explained by the fact that when the reservoir is at spill level, an additional unit of water implies an additional unit of spill, rendering the marginal value of water zero. Conversely, when the reservoir is empty, extra units of water can replace either expensive thermal power generation or energy rationing, thus increasing the marginal value.

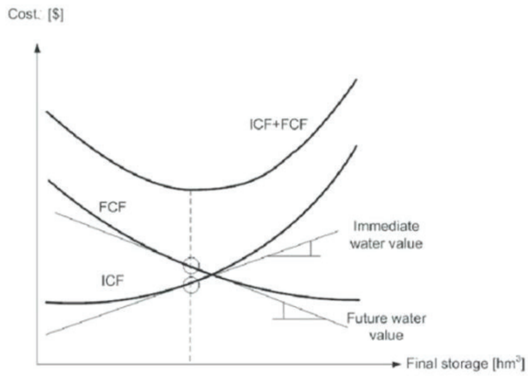

Figure 1 – Immediate and Future Cost Functions

3. Methodology and Analysis

For real-time water value calculation, the principles of Stochastic Dual Dynamic Programming (SDDP), an advanced version of DP, are used. SDDP has the capability to address large-scale multi-stage optimisation problems under uncertainty. Unlike other versions of DP, SDDP offers distinctive approaches by eliminating the need to enumerate different reservoir combination levels. The future cost function is estimated through Benders Decomposition, effectively handling probabilistic models of hydro inflow, renewable intermittency, demand variation and fuel price uncertainty [7].

Furthermore, SDDP contributes to long-term, medium-term and short-term optimisation by providing cost-effective operating policies. It facilitates the identification of real-time water value rather than relying on a single water value for the entire planning period [8]. To minimise the total cost over a planning horizon, an objective function can be introduced, as shown in Eq. (3) with Cost function at time t (C_t), state vector (x_t), Control vector (u_t, decision variables) and uncertainties (ω_t).

$$\min E\left[\sum_{t=1}^{T} C_t(x_t, u_t, \omega_t)\right] \quad \text{... (3)}$$

To simplify the calculations, the uncertainty (ω) is omitted.

Various constraints must be considered while preparing a model to calculate the water value.

Neglecting the losses,

$$Total\ Electricity\ Demand$$
$$= Total\ Hydro\ generation$$
$$+ Total\ Thermal\ Generation \quad ...\ (4)$$

The water storage of a reservoir at a particular state t can be characterised by several factors: the water storage at the end of state t (x_{t+1}), the water storage at the beginning of state t (x_t), incremental water inflow (y_t), water discharge(u_t)and water spillage (s_t), while neglecting evaporation.

$$x_{t+1} = x_t + y_t - (u_t + s_t) \quad ...\ (5)$$

It is essential to maintain x_{t+1} between the minimum ($\underline{x}_{t+1}$) and maximum ($\bar{x}_{t+1}$)storage levels of the reservoir.

$$\underline{x}_{t+1} \le x_{t+1} \le \bar{x}_{t+1} \quad \ldots (6)$$

Additionally, $u_t$should be less than the maximum allowable discharge level ($\bar{u}_t$) of the turbine.

$$u_t \le \bar{u}_t \quad ...\ (7)$$

Since water is free, the aim of the optimisation is to minimise the cost of thermal power generation. The objective function is a recursive function, which is a summation of immediate operation cost and future operation cost. Eq. (8) serves as a building block for DP, defining how costs propagate over time, which is more focused on a single stage$t$ and its immediate successor $t + 1$, providing a local view of the cost structure. Expected operation cost at state t ($A_t(X_t)$) and its future operating cost $A_{t+1}(X_{t+1})$ is taken as a recursive function with a discount factor of γ.

$$A_t(X_t) = E[\min(C_t) + \gamma A_{t+1}(X_{t+1})] \quad ...\ (8)$$

3.1 Algorithm for Economic Dispatch Inputs

Economic Dispatch Inputs

Quarter hour predicted electricity demand, Existing Power Plant details, Irrigation release agreements

Initial State Variables

x_o: initial water storage levels in reservoirs, Capacities of existing hydro and thermal power plants and their per unit generation cost details

State Transition Parameters

y_t: Water inflows into the reservoirs at each time step, s_t: Water spillage at each time step, u_t: Water released from reservoir at each time step

Constraints

Eqs. (4), (5), (6), (7).

Uncertainties and Stochastic Elements

ω_t: Probability distribution for uncertainties like inflow and demand

Step 1
Generate initial schedule.
Sort thermal power plants according to the ascending order of unit cost.

Step 2
Generate options for next schedule. (Number of options = 2^I) [4]
Remove the impossible conditions of loads. (e.g., - $P_{min} < P < P_{max}$)

Compare the different conditions of each power plant and choose/ ignore according to the conditions/ constraints.

Step 3
Employ all the options available.

Step 4
Sort options of quarter-hour total cost in ascending order and computation time.

Take first 100 options as the current option. (100 options are chosen due to the conditions of computation)

Step 5
Repeat 2,3,4 steps until the time finish.

Form a tree structure. (Figure 2)

Step 6
Find minimum total cost at $t = T$.

Reach the backward till it reaches initial position. ($t = 0$)

The path from initial position to final least cost position provides optimum dispatch schedule.

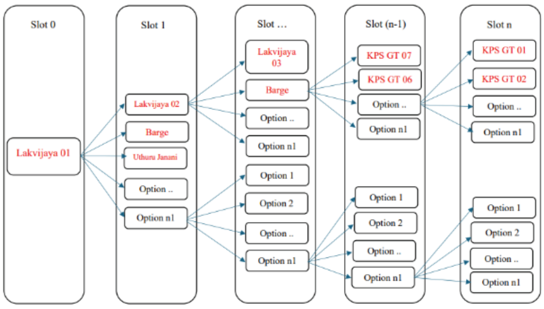

Figure 2 – Sample Tree Structure for the Algorithm

Output

An optimal economic dispatch schedule for each 15 min.

3.2 Water Value Analysis

After obtaining the output of the algorithm in Section 3.1, three methods are introduced to assess the water value. Figure 3 shows the demand variation for a selected month, providing insight into the electricity demand fluctuations during that period. The year 2019 was chosen as the sample year for the calculations because it is the most recent year that can be used as a reference for the regular electricity pattern in Sri Lanka. The years 2021 and 2022 were affected by the Covid-19 pandemic, followed by the economic crisis impacts that lasted until mid-2023, during which planned long-term electricity interruptions occurred.

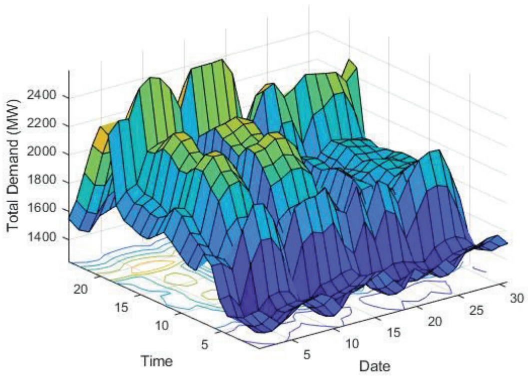

Figure 3 – Sri Lankan Monthly Electricity Demand (March 2019)

The results obtained from the algorithm introduced in Section 3.1, illustrated in Figure 3, are used to calculate the per unit generation cost. During the per unit generation cost calculation stage, hydropower plants are assigned their respective water values, while thermal power plants are assigned their per-unit generation costs, primarily dependent on fuel costs. The three different water value assessment methods are described in the sections of 3.2.1 to 3.2.3.

3.2.1 Assigning Zero Value to Water, Considering the Zero Fuel Cost of Hydropower

This is the traditional approach to evaluating water value, where water is assigned a value of zero due to its zero-fuel cost. Figure 4 illustrates the resulting generation costs after assigning a zero value to water for the electricity demand shown in Figure 3.

Figure4 reveals an irregular observation wherein, during peak evening hours (6 pm to 10 pm), the generation cost unexpectedly reaches its lowest point. This anomaly contrasts with the expected pattern of costs increasing with total demand. The phenomenon occurs because low-cost hydropower plants are utilised to handle peak loads, displacing expensive thermal power plants typically operational during the daytime. Consequently, with water value set to zero, overall generation costs decrease during peak times.

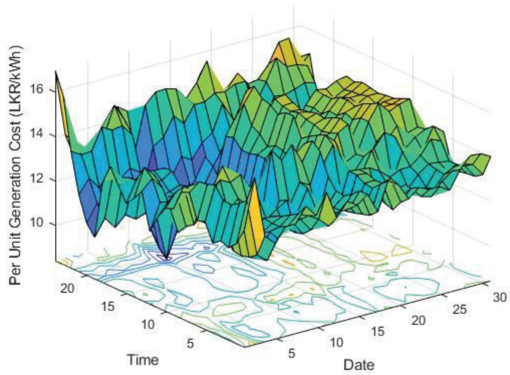

Figure 4 - Per Unit Generation Cost of March 2019 Calculated by Assigning Zero Value to Water, Considering the Zero Fuel Cost of Hydropower

This traditional approach of water value assessment contradicts the concept discussed in this research paper. Moreover, in this zero-cost method, capacity costs are neglected, posing challenges in covering the operating and maintenance expenses of power stations.

3.2.2 Assigning the Per Unit Generation Cost of the Most Expensive Thermal Power Plant in the Economic Dispatch Schedule as the Water Value

This method employs a graphical avoided cost-based approach, relying on the dispatch schedule. The Daily Load Curve is plotted based on the daily economic dispatch schedule, following the merit order starting from the baseload. Typically, power plants with low operational costs occupy lower positions on the Daily Load Curve. However, this may not always be evident in the dispatch schedule due to various constraints, including water management policies.

In this methodology, the thermal power plant positioned highest on the Daily Load Curve is identified, and its per-unit generation cost is designated as the water value.

This method considers the highest marginal cost (i.e., the cost of producing an additional unit under current operating conditions) among all the thermal units in operation. If hydropower is used, the savings come from shutting down or reducing the output of the most expensive generator currently in operation, which, by definition, is the costliest thermal unit.

Therefore, the cost savings due to the use of hydro at that moment are equal to the marginal cost of the most expensive unit. Hence, it is justifiable to use this method to assign a value to the water.

As the share of hydropower increases in total demand, the percentage of thermal energy decreases, and vice versa. Capacity limitations between two thermal power plants or between a hydropower plant and a thermal power plant may restrict the increase in hydropower share. In such cases, where a hydropower plant is sandwiched between two thermal power plants on the Daily Load Curve, resulting in a decrease in hydropower share and an increase in thermal share, the per-unit cost of the thermal power plant located above the hydropower plant is designated as the water value.

To cite an example, a selected date is considered, and the Daily Load Curve for that date is plotted in Figure 5. For simplicity, entire power plant complexes are treated as a single power plant to mitigate complexity.

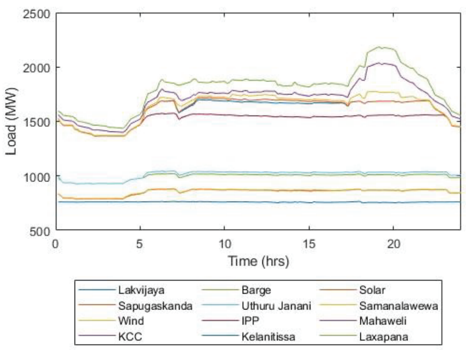

Figure 5 - Daily Load Curve of 2019.03.30 According to the Economic Dispatch Order

Based on Figure 5, it is observed that the Kelanitissa Thermal Power Plant operates as the most expensive thermal power plant between the hours of 5 am and 11:15 pm. Therefore, the water value for that period is taken as 46.07 LKR/kWh [9], which represents the per unit generation cost of the Kelanitissa Thermal Power Station. When it is not operating, Independent Power Producers (IPPs), which belong to the private sector, operate as the most expensive power plants. Upon examining the dispatch schedule for the date, it is identified that the Sojitz power plant operated at the highest position of the Daily Load Curve during the periods when Kelanitissa was not in operation. Hence, the per unit cost of the Sojitz Power Plant, which is 23.15 LKR/kWh [9], is taken as the water value for the slots between 12 am and 5 am, as well as 11:15 pm to 11:45 pm.

The water value estimated by this method, for March 2019 is illustrated in Figure 6, while the generation cost, calculated using the water values shown in Figure6, are depicted in Figure 7.

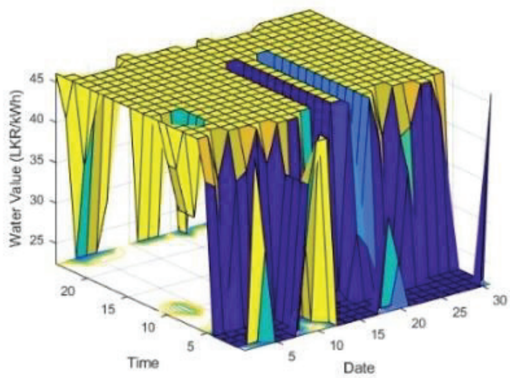

Figure 6 - Water Values of the Month of March 2019, Calculated by Assigning the Per Unit Generation Cost of the Most Expensive Thermal Power Plant in the Economic Dispatch Schedule

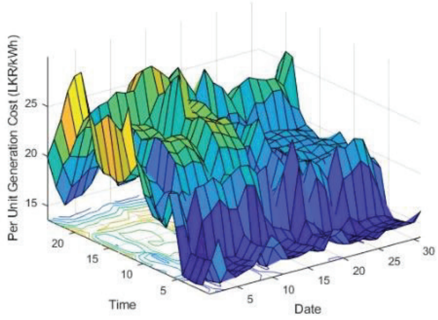

Figure 7 - Per Unit Generation Cost Calculated by the Water Values Obtained in Figure 6

3.2.3 Assigning the Weighted-Average Cost of Variable Thermal Power Plants in the Economic Dispatch Schedule Based on their Contribution to the Total Generation

This method assumes that the value of a resource is equivalent to the cost of alternative options that must be used when the resource is unavailable to perform the same task [10][11]. When water resources are unavailable, more expensive thermal power plants must be utilised to generate the required amount of electricity. The weighted average cost of these thermal power plants is then used to represent the water value, with the weighting based on each plant's contribution to electricity generation.

The generation cost of thermal power plants primarily fluctuates based on fuel costs. In this calculation, the baseload is excluded from the weighted average calculation because the power system cannot operate without the baseload. Therefore, only the variable thermal power plants are considered for the calculation. Figure 8 represents the water value calculation for a selected month using the weighted-average method, while Figure 9 illustrates the generation cost calculations using the water values of Figure 8.

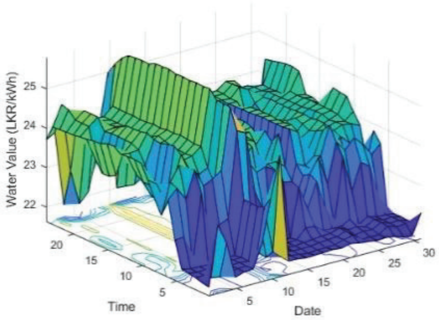

Figure 8 - Water Values of March 2019, Calculated by Assigning the Weighted-Average Cost of Variable Thermal Power Plants in the Economic Dispatch Schedule based on their Contribution to the Total Generation

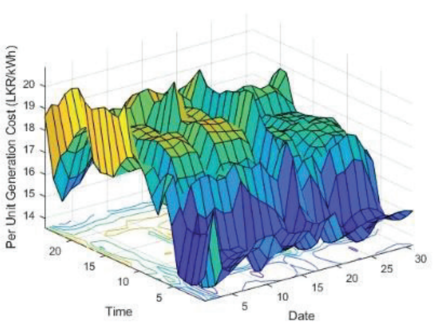

Figure 9 - Per Unit Generation Costs Calculated by the Water Values Obtained in Figure 8

4. Water Value in Agriculture

Presently, water management policies of Sri Lanka prioritise agriculture over power generation. This study particularly focuses on rice production due to its status as the country's staple food and its high-water demand. The seasonality of paddy cultivation is evident as it occurs during the Yala and Maha seasons.

Maha season (October to February), coincides with the northeast monsoon, typically experiences high rainfall to the dry zone (cultivation area), leading to high water availability in reservoirs and rivers. During this period, water value tends to be low due to the abundant supply, as reservoirs often reach their spill levels. In contrast, the Yala season (March to September) relies on the southwest monsoon, which brings less rainfall to the dry zone, resulting in low reservoir inflows and high competition for water between agricultural and electricity sectors. Consequently, water value during the Yala season increases due to the scarcity and greater demand for both irrigation and hydroelectric generation.

For instance, in the Mahaweli River basin, the water stored in reservoirs like Kotmale and Victoria during the Maha season is often reserved for irrigation during the Yala season when rainfall is limited. The water release strategy during the Yala season must carefully balance the needs of downstream paddy fields and power stations. In this context, the water value increases, as water becomes a limiting factor in sustaining agricultural production, especially in key rice-growing areas such as Anuradhapura and Polonnaruwa. Studies have shown that water shortages during Yala can lead to reduced agricultural output, underscoring the critical role of water management in determining its value during this dry period.

A case study conducted by the International Water Management Institute (IWMI) on the Mahaweli project has illustrated that hydropower plants can operate at near full-load capacity in Maha Season [12], while irrigation water needs are met with minimal constraints. However, during Yala, the reduced inflows result in prioritisation of agricultural needs, with electricity generation often curtailed. This scenario highlights the dynamic nature of water value, shifting between seasons based on availability and sectoral demands.

By integrating such seasonal considerations into water management, a more refined pricing mechanism can be developed to reflect the varying value of water for both agriculture and electricity generation throughout the year.

The water requirements for paddy fields vary depending on the stage of cultivation, with the initial weeks being crucial. If the necessary amount of water is not supplied during the first two weeks, the entire crop is at risk. As the crop matures, the importance of water decreases. This indicates that the significance of water in agriculture fluctuates with the growth stages of the crops. According to recorded statistics from the Irrigation Department, the Kaltota scheme reported the highest water duty, reaching 7 feet per acre per season, while the general case is recorded at 4 to 5 feet per acre. It is calculated that producing 1 kg of paddy requires 3,000 to 4,000 litres of water, yielding 700 grams of rice [13][14].

The cost of rice production for fields associated with irrigation systems and rainfed systems is 23.17 LKR/kg and 32.38 LKR/kg, respectively, with more than 80% of gross paddy coming from irrigation-based agriculture. The rice production costs include labour costs, machinery costs, fertiliser costs and other associated expenses.The subsequent calculations in this research paper assume that the cost of rice production is equal to the water value, neglecting other associated expenses. The per capita rice consumption in Sri Lanka is 107 kg/year [15], with a population of 22 million. However, the entire agriculture of the Mahaweli region does not rely solely on water releases at the Polgolla and Minipe basins, as rainfall, groundwater and stored water from reservoirs also play a role.

Regarding the utilisation of Mahaweli water, it is estimated that 11,016 MCM of water flows to the sea annually [16]. Initially Mahaweli water is used for electricity generation at Kotmale and Upper Kotmale power plants owing to the locating at the earliest position of the river. A portion of this flow is diverted at Polgolla to the northern part of the country, with the remaining water flowing through Victoria, Randenigala and Rantembe reservoirs. The water diverted north at Polgolla is used for agricultural purposes in the Mahaweli H, L and Huruluwewa zones and for power generation at Ukuwela and Bowatenna power stations [16], while also meeting basic human needs. The total rice production in the Mahaweli H, L and Huruluwewa zones was recorded as 197,125 Mt in 2019 [17]. The water release to this area from Polgolla was 1,110.176 MCM [16]. Assuming that the entire agriculture was based on water released at Polgolla and neglecting the incremental flow, rainfall and existing reservoirs, the water value of agriculture can be calculated as 0.178 kg/m^3. With a cost of 23.17 LKR/kg for irrigation-based rice production, the cost per cubic meter of water usage is 4.12 LKR/m^3.

The remaining water, which is not diverted at Polgolla, flows through Victoria, Randenigala, Rantembe and other downstream reservoirs, serving the Mahaweli B, C, D, E and G zones by diverting the water at Minipe and Moragahakanda anicuts [16]. The total rice production in these zones amounts to 398,393 Mt [17], with a water release of 1,583.446 MCM [16] at Minipe and Moragahakanda. The water value is calculated as 0.252 kg/m^3, and the cost of water usage is 5.84 LKR/m^3.

Moving forward, these calculations should be expanded to a seasonal level, as rice production and water release are not equal in the Yala and Maha seasons. Seasonal rice production of Mahaweli Zones in 2019 was recorded as 336,316 metric tons during the Yala season and 344,388 metric tons during the Maha season [17].

The previous calculations were based on annual statistics rather than seasonal data. However, it is important to note that Mahaweli is not the sole rice supplier in the country. In 2019, the total rice production of Mahaweli Zones was 680,704 Mt, with a production value of 15.8 billion LKR [17]. In contrast, the total rice production of the country in 2018 was 3,930,000 Mt, costing 118 billion LKR [18]. These statistics reflect local rice production costs, but it should also be noted that the government imports rice to maintain the country's food security. In the same year, 200,400 Mt of rice was imported at a cost of 14.1 billion LKR [19], which amounts to 70.43 LKR/kg.

In the same year, the Ceylon Electricity Board (CEB) spent 99.4 billion LKR on 585 million litres of oil and 47 billion LKR on 2.2 billion kilograms of coal to produce 7,502 GWh of electricity from CEB-owned thermal power plants. Additionally, 2,875 GWh of electricity was generated from Independent Power Producers (IPPs) [20]. These statistics indicate that the costs associated with electricity generation surpass the combined costs of domestic rice production and imports.

5. Water Value at Reservoir Level

Current water value estimations provide a single national-level figure. However, a deeper analysis reveals that water value fluctuates not only based on seasonal and time-of-day factors but also varies by location.

Considering the flow of the rivers, it can be inferred that the water value of upstream reservoirs is higher than that of downstream reservoirs. In the context of the Mahaweli River, the Kotmale and Upper Kotmale reservoirs are located at the initial stages. After utilising the water at these reservoirs, it is returned to the river in a different state. The same drop of water then flows through Polgolla and follows one of two paths: Ukuwela-Bowatenna or Victoria-Randenigala-Rantembe. These reservoirs form a cascading system, where the outflow from Victoria serves as the inflow to Randenigala, and the outflow from Randenigala feeds Rantembe. Consequently, it is justifiable that the water value of each reservoir differs due to incremental inflows. For instance, a drop of water at Victoria holds more value than at Rantembe, as it is utilised sequentially at Victoria, Randenigala and Rantembe.

However, in this analysis, the electricity generation rates of each power plant are considered. Different power plants have varying generator ratings, which influence the amount of electricity that can be generated from 1m^3 of water. Table 1 provides details on the water discharge rates of the turbines and the rated electricity generation capacities of their generators [21].

The water value at reservoir levels provides combined benefits across different sectors, making it difficult to isolate the individual benefits for electricity generation or agriculture.

6. Discussion

The water value varies with season, date and time, yet these fluctuations are often overlooked in utility calculations, resulting in inaccurate generation cost estimates. Therefore, incorporating real-time water value assessments is imperative for precise generation planning. Water resources are finite and allocated based on priority orders, including basic needs, agriculture and power generation.

Table 1 - Discharge Rates and Electricity Generation Rates of Different Hydropower Stations

Hydro Complex	Power Station	Discharge rate (Q) (MCM/GWh)	Rate of Generating Electricity (kWh/m^3)
Mahaweli	Ukuwela	5.40	0.19
	Bowatenna	8.10	0.12
	Kotmale	1.80	0.56
	Victoria	2.00	0.50
	Randenigala	5.10	0.20
	Rantambe	12.7	0.08
Laxapana	Canyon	2.24	0.45
	Wimalasurendra	1.98	0.51
	Laxapana (old)	0.94	1.06
	Laxapana (new)	0.82	1.22
	Polpitiya	1.60	0.63
Samanala	Samanalawewa	1.30	0.77
	Kukule Ganga	2.10	0.48

Source: CEB System Control Centre

Forecasting water availability is inherently uncertain due to factors such as rainfall and environmental conditions. Consequently, accurately estimating reservoir inflow undervarious environmental scenarios is essential.

Moving forward, it is crucial to discuss the practical implications of these findings on planning processes. Specifically, how seasonal and time-of-day dependent electricity costs can inform pricing methodologies. Presently, electricity consumers face time-of-day production costs, where fixed costs (e.g.- generation, transmission and distribution) are separated from energy-related costs in pricing structures. Following payment of fixed costs, the energy component directly reflects production adjusted for losses, assuming uniform losses throughout the network.

Sri Lankan energy sector was introduced Standing Power Purchase Agreements (SPPAs) in 1996 to procure electricity from Independent Power Producers (IPPs). Initially, the tariff was set at 2.90 LKR/kWh, and after one year, two tariff schemes were introduced for the dry and wet seasons. The dry season, spanning from February to April, was distinguished from the wet season, covering the remaining four months [22]. This tariff structure was established based on the cost savings from operating thermal power plants due to the generation of electricity from small power plants.

This methodology remained in place for a decade, and the tariff variations during this period are depicted in Figure 10. A similar approach could be adopted to procure electricity from the private sector, aligning with the seasonal variation of water value.

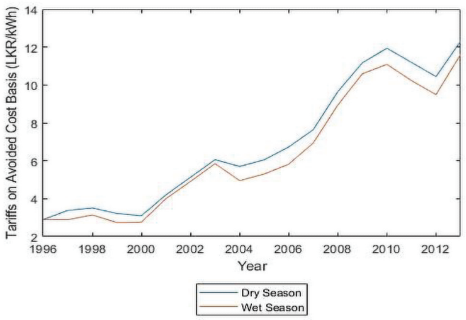

Figure 10 - Seasonal Tariff on Avoided Cost Basis (1996-2013)

At times, in accordance with water management policies, costly thermal power plants are operated to conserve water for future needs. However, amidst fluctuations in water value, it becomes apparent that importing rice at a certain price per kilogram may prove more cost-effective than utilising expensive thermal energy sources for power generation, aimed at preserving hydro resources. This proposition, however, sparks debate, particularly considering Sri Lanka's robust agricultural sector. The reliance on rice imports not only jeopardises the country's food security but also threatens the livelihoods of millions of families dependent on agriculture. This vulnerability was starkly evident during the Covid-19 pandemic when disruptions in import and export channels left the nation grappling with food shortages.

Another drawback lies because water value is an operational economic parameter, and it is not justified to change the long-term decisions at design stage. An economic analysis is performed for every engineering project during the design stage. Based on this analysis, future development plans are formulated. However, altering the master plan could disrupt all existing plans. Therefore, any modification to the initial plan necessitates a comprehensive reassessment to mitigate potential disruptions and ensure the continuity of development efforts.

Given the significant role of agriculture in sustaining livelihoods and ensuring food security, it is imperative to reconsider the reliance on rice imports. Instead, there is a compelling case for updating Sri Lanka's water management policies to prioritise and facilitate hydropower generation.

It would be ideal if the water management policy could be adjusted to allocate more water for electricity generation without compromising the country's food security. One potential approach to update the current water management policy is to implement initiatives that monitor real-time water usage and value fluctuations, enabling data-driven decision-making for future policy adjustments. Additionally, investing in infrastructure improvements, such as expanding water storage capacity (reservoirs) and enhancing water distribution systems (canals), can yield significant benefits for both electricity and agricultural sectors.

By doing so, the nation can harness its abundant water resources more effectively while simultaneously safeguarding its agricultural sector and promoting food self-sufficiency.

7. Conclusion

Accurate estimation of generation costs is crucial in the energy economics sector for developing tariff structures aimed at maximising profit within the power system. The energy costs of hydropower plants play a pivotal role in calculating generation costs. Traditionally, water value has been considered negligible, which is an unjustified assumption.

The water value is influenced by various factors, including seasonal variations, specific dates and times of the day.

This research paper introduced an innovative approach for economic dispatch process using SDDP principles. This approach is developed after a thorough analysis of the advantages and limitations of traditional DP technologies and their modified versions.

Two novel methods for real-time water value assessment are proposed, challenging the conventional practice of assigning either a zero or constant value. The first method considers the per-unit generation cost of the highest variable thermal power plant on the Daily Load Curve. The second, deemed the optimal approach, assumes that the cost of backup energy, rather than water, represents the water value, with the weighted average value of variable thermal power plants in the dispatch schedule serving as the water value.

Furthermore, this paper pioneers the evaluation of water value on a per-reservoir basis, moving away from the practice of using a single national value. It also initiates both quantitative and qualitative comparisons of water value for agricultural use versus power generation.

Finally, the practical implications of these findings are discussed, including their potential application in power system planning and the challenges that may arise in practical implementation.

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