INTEGRATED WATER-ENERGY-CARBON NEXUS: A MIXED-METHODS APPROACH TO EVALUATING HILLY RUNOFF POTENTIAL IN UNLOCKING A SUSTAINABLE FUTURE

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ABSTRACT: *This study evaluates the potential of harnessing renewable energy and producing clean water from hilly runoff resources in Sarawak, with the overarching aim of contributing to a sustainable green future. A mixed-methods approach was adopted, combining field experiments, an extensive literature review, and policy analysis. The findings indicate that Sarawak's current water demand of 2,060 million litres per day (MLD) could be fully met through hilly runoff, which has an estimated clean water potential of 8,000 MLD and an associated in-Stream Energy capacity of 4.3 MW. Experimental trials conducted in Lundu confirmed that clean water can be produced without chemical dosing or carbon emissions, requiring only 0.55 kWh/m³ of renewable hydropower and thereby reducing emissions by 0.35 kg CO_2eq/m^3. The adoption of such a system could prevent approximately 793.1 tonnes of monthly sludge discharge, eliminate chemical use at a rate of 10 mg/L of water, and deliver substantial savings in public health and environmental management costs. Despite these advantages, policy gaps and limited technical capacity in implementing green technologies remain significant barriers. Overall, the study concludes that hilly runoff represents a viable and sustainable pathway towards water and energy security in Sarawak, provided that regulatory frameworks and technological constraints are effectively addressed*

Keywords: Hilly Runoff Resources, Clean Energy, Clean Water, Economic Sustainability, Environmental Sustainability, Mitigating Climate Change, Sustainable Clean Future,

1.0 INTRODUCTION

Water production and supply to meet the domestic and commercial water demand of Sarawak is depending on traditional coagulant dosing powered by grid electrical energy, which are associated with polluted sludge formation and carbon emission despite Sarawak is blessed with hilly runoff water and in stream micro hydro energy. A few case studies and research outcome of pilot studies reveal that green technology have been used successfully to produce clean water from hilly runoff and inherent potential energy of water with zero coagulant dossing and zero carbon emission [1–4].

Building on this background, the authors propose a sustainable clean energy and water solution for Sarawak, designed as a strategic roadmap for policymakers, government agencies, and researchers engaged in shaping energy and water management strategies. The aim of this work is to advance the development of a green and sustainable future for Sarawak. This study is further motivated by the need to disseminate successful case studies on green technologies applied in clean water production, thereby supporting the transition of Sarawak's water industry towards a carbon-neutral and pollution-free model.

2.0 Method of Literature Review

The core methodology involved a comprehensive literature review, supplemented by experimental work, case study analysis, and statistical data. The literature review specifically focused on Sarawak's rainfall characteristics, sources of in stream hilly runoff and energy potential, applicable green technologies for clean water production, economic activities in Sarawak, and the benefits of integrated water-energy systems. A systematic search yielded 55 peer-reviewed articles, books, and web-based information published from 2010 to 2025, covering foundational studies and recent advancements in renewable energy-water purification integration and policy.

2.1 Potential of Water Resources and Challenges in Sarawak

Sarawak, which benefits from an average annual rainfall of approximately 3.5 metres, is experiencing increasing pressure on its water resources, with current demand estimated at 2,060 million litres per day (MLD) and projected to reach 2,400 MLD by 2030 [5]. A critical challenge in this context is the persistently high rate of Non-Revenue Water (NRW), which averages 43% across the state [5, 6]. Traditionally, water supply systems in Sarawak have relied on fossil-fuel-based operations and chemical dosing treatment methods, both of which contribute to environmental degradation and greenhouse gas emissions. In response to these challenges, the state government has introduced four pilot plants supported by Universiti Malaysia Sarawak employing green technologies to treat hilly runoff water without chemical additives and with zero carbon emissions. These pioneering initiatives are designed to gradually replace conventional treatment facilities, reflecting Sarawak's strategic commitment to sustainable water management. Furthermore, they underscore the state's ambition to emerge as a regional leader in the deployment of innovative, low-carbon, and environmentally responsible water solutions.

2.2 Green Technology for Green Energy Production at Zero Carbon Emission

Green technology refers to the application of science and technology to develop environmentally friendly products and services, primarily associated with zero carbon emissions. It encompasses cleaner production processes that enhance efficiency, improve operational performance, and reduce waste through the substitution of fossil fuels [3, 7]. A core objective of green technology is to promote a green economy, mitigate climate change, and ensure environmental sustainability [8]. It seeks to decrease reliance on fossil fuels for electricity generation, thereby reducing carbon emissions and air pollution [9],

Studies demonstrate that green technology enhances energy efficiency, leading to reduced energy consumption and lower carbon emission rates per unit of output, thereby supporting green economic growth [10–12].

Renewable energy sources such as solar, wind, hydroelectric power, and green hydrogen play a central role in achieving net-zero emissions and slowing climate change [13, 14]. The water production industry, heavily dependent on fossil fuels and chemical dosing, is a major emitter. Research highlights that adopting green technologies in water and energy sectors significantly reduces carbon intensity and pollutant discharge [15–18]. However, it is founded that a 1.0% increase in clean energy use could contribute to a 3.0 % increase in green economic growth [19], [20]. Overall, green technology underpins the transition to a zero-carbon economy[21–23].

2.3 Micro Hydro Energy for Water Filtration in Sarawak

Micro-hydropower represents an abundant source of clean energy in Sarawak, supported by the region's high annual rainfall of approximately 3.5 metres. Despite this natural advantage, the sector remains underutilised. The hilly runoff not only presents a viable renewable energy resource but also offers potential as a sustainable water source. These runoff resources could be harnessed simultaneously for energy generation and clean water production, providing an integrated solution to address both energy and water security. However, studies have reported that such resources remain largely untapped due to barriers including limited technological capacity and inadequate policy frameworks [23, 24]. To advance towards a sustainable and green future for Sarawak, it is recommended that micro-hydro projects be strategically implemented with integrated clean water production facilities, thereby maximising resource efficiency while reducing carbon emissions [25].

2.4 Barriers and Challenges to Utilizing Hilly Runoff Water and Energy in Sarawak, Malaysia

A few barriers have been reported in utilizing hilly runoff resources in Sarawak [26, 27]. The rugged terrain, remote locations, complexity in constructing water intake and implementing micro-hydropower systems [28]. Accesses to green technologies insufficient local expertise and limited access to spare parts, land-use conflicts are also reported [28–30]. Policy-wise, inadequate institutional coordination and limited financial incentives discourage private sector participation [26, 30] Overcoming these obstacles requires enhanced data collection, capacity building, stakeholder collaboration, and targeted policy reforms [26, 30].

2.5 Problem Statement: Hindrances to Clean Water Production from Hilly Runoff in Sarawak

Sarawak receives abundant annual rainfall; however, the state continues to face challenges in meeting its projected water demand of 2,060 MLD [5, 6]. Conventional river-based water sources, supported by traditional treatment plants, remain the dominant mode of water supply. These systems are highly energy-intensive, relying on fossil fuels and dependent on chemical coagulant dosing. In contrast, catchments of hilly runoff remain largely underutilised despite their potential as sustainable water sources. Pilot studies conducted in the Lundu district have demonstrated that hilly runoff can be effectively utilised to produce clean water without the need for fossil fuel energy and chemical dosing [3, 31]. Project reports further highlight that, while promising, the adoption of hilly runoff for water supply requires overcoming several barriers, particularly those related to infrastructure, technological capacity, and policy frameworks [7, 32]. This paper has been developed to critically address these challenges and to propose strategic solutions for advancing sustainable water management in Sarawak.

Research Questions

2.6.1 What is the total volume of water (m^3) and the potential energy (kW) available from hilly runoff in Sarawak?

2.6.2 What are the requirements for chemical dosing (mg/L) and the corresponding energy consumption rate (kWh/m^3) in producing potable water from hilly runoff resources?

2.6.3 To what extent is the utilisation of in stream hilly runoff water and energy both economically viable (in alignment with SDG 8) and environmentally sustainable (in alignment with SDG 13)?

2.7 Broad Objective

This study seeks to provide a comprehensive evaluation of the water and energy potential embedded within hilly runoff areas in Sarawak. The results are structured into three subsections to ensure a clear, systematic presentation of the research outcomes.

2.7.1 Objective One: To determine the water and energy resources available in in-stream hilly runoff.

2.7.2 Objective Two: To assess the coagulant dosing and energy consumption rate associated with the production of clean water from in-stream hilly runoff.

2.7.3 Objective Three: To analyse the economic and environmental impacts of utilising in-stream hilly runoff water and energy in the context of Sarawak's sustainability goals.

3.0 Research Methodology

A specific research methodology with experiment has developed to achieving the study's goal. In respect to the three objectives, three difference methods have been designed which are explained in the following subsection sections.

3.1.1 Experimental Setup and Procedure

Secondary datasets covering **2010–2025** were obtained from institutional databases, government reports, and published studies. These data were used to estimate the water availability and hydro-energy potential of in-stream hilly runoff in Sarawak (Objective One).

3.1.2 Experimental Design

Pilot-scale (25m^3/day) experiments were conducted to determine coagulant dosing requirements and energy consumption for clean water production (Objective Two). A gravity-driven filtration system, operated using the inherent potential energy of the in stream runoff, was employed. Trials were performed under two conditions: (i) with coagulant application and (ii) without coagulant application. A schematic of the setup is shown in **Figure 1.0**.

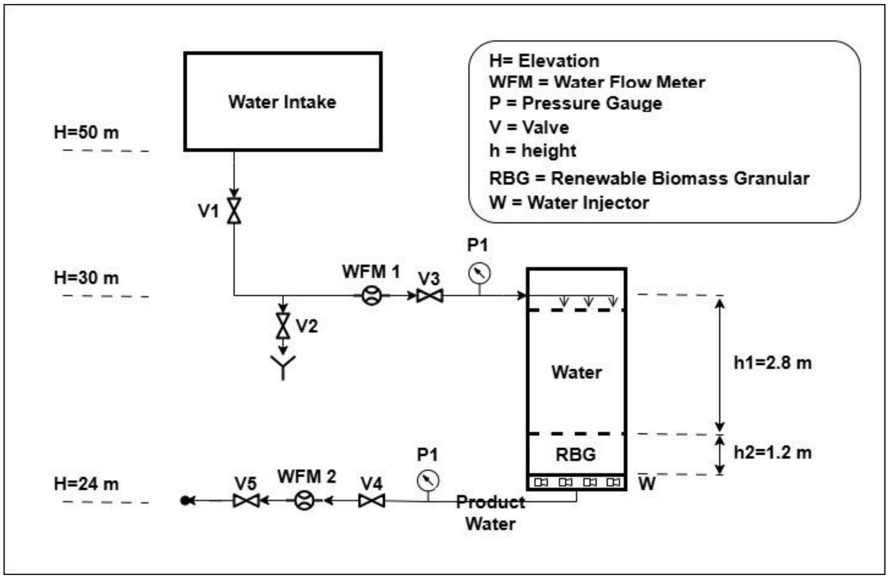

Figure 1.0: Schematic Diagram of Experiment

3.1.3 Data Collection and Analysis

Water quality parameters, coagulant dosing rates, and energy consumption were measured during each trial. Data analysis was carried out in two stages:

a) Assessment of the effects of chemical dosing on economic and environmental outcomes.
b) Estimation of hydro-energy consumption, expressed as kilowatts per cubic metre ($kW \cdot m^{-3}$).

Details of experimental procedures, measurement protocols, and statistical methods are provided in Section 4.2**.**

3.1.4 Literature and Case Study Integration

To address Objective Three, experimental results were Integrated with findings from peer-reviewed case studies on in-stream runoff for water and energy applications. Additionally, credible web-based sources (2025) were reviewed using academic databases and institutional repositories. This evidence was used to evaluate the economic and environmental sustainability implications of in-stream runoff utilisation in Sarawak.

3.2 Theoretical Framework

Required mathematical equation to estimate the relevant parameters are listed in this section. The equations present here in Table 1.0 are proven to be useful for water and energy analysis.

Table 1.0: Mathematical Equation

Average TSS Separation efficiency = $\frac{Total\ TSS\ separation\ Efficiency}{Total\ Experimenatl\ run}$	Eq.(1)
TSS Separation efficiency(∏) = $\frac{\textbf{TSS in product water}(\frac{mg}{L})}{\textbf{TSS in feed water }(\frac{mg}{L})}$	Eq.(2)
t(statistics) = $\frac{\beta-\mu}{\sigma/\sqrt{n}}$ Where, β mean of population, n is samples size, with a specified theoretical mean μ.	Eq.(3)
Average TSS = $\frac{Total\ TSS\ in\ Water}{Number\ of\ Sample\ (N)}$	Eq.(4)
Potential hydro energy (Pwatt) = ρ η gHQ ρ(Water density) = **1000 kg/m³** g(Acceleration due to gravity) = **9.81 m/s²** H(Average head) Q(Flow rate) **m³/s** η (System efficiency= 0.65-0.80	Eq.(5)

4.0 Data Analysis and Research Findings

This study provides a comprehensive evaluation of the water and energy potential of hilly runoff in Sarawak. The findings are presented in three subsections (Sections 4.1, 4.2, and 4.3) to ensure a clear and systematic presentation of the research outcomes.

4.1 Water and Energy Potential of Hilly Runoff in Sarawak.

His section examines the availability of in stream hilly runoff resources and their associated energy potential in Sarawak. The analysis draws upon secondary datasets sourced from credible institutional and published records, as outlined in Section 3.1**.**

4.1.1 Water Potential in Hilly Runoff

The hilly regions of Sarawak serve as critical natural catchment areas, capturing rainfall and channelling it through an extensive river network that underpins the state's water supply. Sarawak receives an average annual rainfall of approximately **3,500 mm**, which constitutes a major component of its renewable water resources [27], [33]. Elevated areas situated above **300 m** represent nearly 37% of the state's land area and retain approximately 25% of the annual rainfall. This generates a considerable volume of instream runoff, thereby contributing significantly to the hydrological potential of the region [35,36]. The spatial distribution of rainfall and runoff potential is illustrated in Figure 2.0**.**

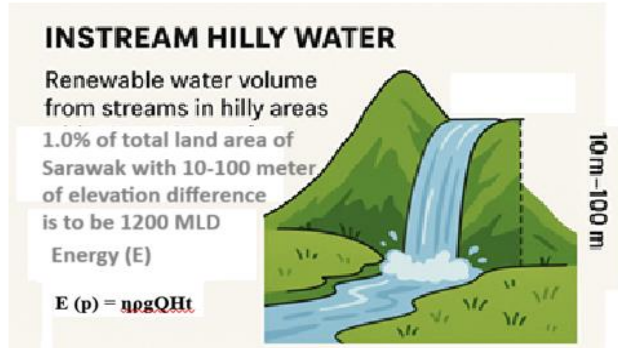

Figure 2.0: Source of Instream Hilly Runoff water and Energy

As illustrated in Figure 2.0, rainwater originating from higher elevations flows towards rivers under the influence of gravity. The potential energy stored at higher altitudes is converted into kinetic energy as the water descends, representing a primary source of hydropower [33]. The estimated water potential from hilly runoff is summarized in Table 2.0.

Table 2.0: Rainfall Characteristics and Estimated Runoff Potential in Sarawak

Parameter	Value / Description	Estimated Runoff Potential	Reference
Annual rainfall range	4,600–5,000 mm	~8,000 MLD (Million Litres per Day)*	[2], [33], [34],
Average annual rainfall	~3,500 mm		
Proportion of hilly land area (>300 m)	~37% of Sarawak's total land area*		
Annual runoff volume	Rainfall in hilly regions contributes ~184.186 billion m³		
Accessible area for water harvesting (assumption)	0.1% of total hilly land between 10–100 m elevation		

***Data Limitations:** Precise data on rainfall distribution specifically over the 37% hilly area is not readily available through general web searches. More accurate figures would require detailed meteorological data and geographical information system (GIS) analysis is required for Sarawak. Rainfall distribution across Sarawak is spatially non-uniform. Estimates are based on average conditions in hilly catchments.

.The analysis indicates that hilly regions in Sarawak, which receive substantial annual rainfall, generate an estimated 184.2 billion m³ of runoff annually. Even under a conservative assumption that only 0.1% of the hilly area is accessible for harvesting, the potential water yield is approximately 8,000 MLD. These findings highlight a significant untapped resource that could support sustainable water supply planning and small-scale hydropower development, offering valuable insights for both policymakers and researchers.

4.1.2 Instream hilly Water Energy Potential in Sarawak

Sarawak's hilly terrain, characterised by high rainfall and dense stream networks, offers considerable potential for in-stream micro-hydropower development. The successful implementation of pilot projects in the region has demonstrated its technical and operational viability. Harnessing this resource could play a significant role in advancing rural electrification, particularly for small enterprises and agricultural activities. The estimated potential is presented in **Table 3.**

Table 3: Potential Micro-Hydro Power Sites in Sarawak

Source inn Sarawak Malaysia	Category	Number of Sites	Instream Hilly Runoff Energy Potential	References
Local Authority Survey	Micro Hydropower	104	10,200 **kW**	[25–27, 37, 38]
Reconnaissance Study	Micro Hydropower	22	5,300 **kW**	
Existing Installed Capacity	Micro Hydropower	27	740.3 **kW**	
Micro Hydro Energy Potential in Sarawak			≈ 16,240 KW	
Reference to Table 1,0 estimated Hydro Energy Potential at 100-meter elevation of hilly area at the flow rate 8000.0 MLD			≈ **4.299,562 kW**	

Referring to Figure 2.0 and Table 2.0, Sarawak receives averaging 3.5 m annually, which significantly increases instream water flow. Around 37% of the state's land area consists of hilly terrain that functions as a natural reservoir, generating an estimated 184.186 billion m³ of runoff annually [3], [37]. This runoff also carries hydropower which summarised in Table 3.0 and Equation (6

kW ≈ 4. 3 MW. Eq. (6).

4.2 To assess the coagulant and energy consumption to produce clean water from instream hilly runoff

This study assessed the economic and environmental impacts of coagulants dosing and the utilisation of instream potential energy in clean water production from hilly runoff. To achieve this, 30 experimental runs were conducted as shown in Figure 1.0. The require energy to operate the filtration was calculated using Equation (5). Equations (1)–(5) were applied to calculate average TSS concentrations and separation efficiency. A summary of the laboratory results, estimated TSS-related values, and energy consumption rates is provided in Table 4.0.

Table 4: Experimental data on Instream Hilly Runoff Water filtration

Experimental N	TSS in Hilly Runoff Water (mg/L)	TSS in Product Water FWOC (mg/L)	TSS in Product Water FWC	Water flow (Qm^3/hour	Overall Energy Consumption kWh/m3
1.0	2	0.832	0.8	1.1	0.504
2.0	1.9	0.78065	0.855	1.2	0.549
3.0	1.8	0.927	0.9	1.1	0.504
4.0	1.9	1.07635	1.045	1.3	0.595
5.0	1.6	0.80	0.8	1.2	0.549
6.0	1.7	0.78795	0.765	1.3	0.595
7.0	1.5	0.76625	0.825	1.1	0.504
8.0	2	0.945	0.9	1.2	0.549
9.0	1.9	1.0374	0.988	1.1	0.504
10.	1.8	0.7344	0.72	1.3	0.595
11	1.9	0.798	0.76	1.2	0.549
12	1.6	0.7976	0.88	1.3	0.595
13	1.7	0.884	0.85	1.2	0.549
14	1.5	0.618	0.6	1.3	0.595
15	1.9	0.798	0.76	1.1	0.504
16	1.6	0.824	0.8	1.2	0.549
17	1.7	0.73542	0.714	1.1	0.504
18	1.5	0.64575	0.615	1.3	0.595
19	2	0.824	0.8	1.2	0.549
20	1.9	0.8778	0.836	1.1	0.504
21.	1.8	0.88128	0.864	1.3	0.595
22.	1.9	0.71086	0.893	1.2	0.549
23	1.9	0.7904	0.76	1.3	0.595
24	1.6	0.8064	0.768	1.1	0.504
25	1.7	0.71094	0.697	1.2	0.549
26	1.5	0.9135	0.87	1.1	0.504
27	1.9	0.85785	0.817	1.3	0.595
28	1.6	0.924	0.88	1.2	0.549
29	1.8	0.8316	0.792	1.3	0.595
30	1.7	0.91902	0.901	1.2	0.549
Result	A(TSS) =1.76	A(TSS) = 0.89	A(TSS) = 0.84	Average(Q) =1.20 m3/hr	Average Energy = 0.55kWh/m^3

Reference to Row 31 of Table 4 indicates that the average TSS concentration in the feed water was 1.76 mg/L. The TSS concentration in the product water was measured at 0.84 mg/L when the coagulant dosing rate in the feed water was 8.0 mg/L, compared with 0.89 mg/L when no coagulant was added. The experimental results therefore demonstrate that, in both cases, the difference in product water quality measured in terms of TSS concentration is negligible. Using Equation (2.0), the TSS separation efficiency was calculated as 53% without coagulant dosing and 52% with coagulant dosing. Furthermore, the renewable energy consumption associated with producing clean water from instream flow was found to be 0.55 kWh m^{-3}. These findings clearly indicate that coagulant dosing has no significant influence on the quality of the product water, therefore, coagulant dosing into the feed water is not require to produce required clean water in accordance with the WHO guideline limit of 1.0 mg L^{-1}[38]

4.2.1 Research Finding and Answer to the research question no 2.0

The research outcome listed in Table 4.0 can be presented **by** Equation (7), (8), and (9):

Coagulant dosing rate = 0		**Eq (7).**	To produce clean water from hilly runoff, coagulant dosing is not required.
P_{RE}	**= 0.55 kWh/m3**	**Eq (8)**	P_{RE} is power from renewable energy
CO_2eq	**≈ 0**	**Eq.(9)**	Carbon Emission is zero for using renewable Energy

Based on Equation (7), the production of clean water from Sarawak's hilly runoff requires no chemical coagulants, resulting in a dosing rate of zero. These results are consistent with previous studies [3, 4, 32]. Shahidul et al. (2023) further reported that coagulant dosing into hilly runoff has no significant effect on clean water production, with their findings validated using paired t-tests at a 95% confidence level. Reference to the Equation (8), The estimated energy consumption for this process is approximately 0.55 kWh m^{-3}, which aligns closely with values reported in the literature (0.55–0.70 kWh m^{-3}) [4, 32, 35, 37]. These findings demonstrates that carbon emission (CO_2eq) to produce clean water from hilly runoff by instream water flow energy is zero (0). Thus, research question 2.0 has been effectively addressed.

4.3 Impact of Producing Clean Water from Hilly Runoff Without Chemical Dosing and by Harnessing the Inherent Energy of Instream Flow

This study assessed the economic and environmental impacts of coagulant dosing and the utilisation of instream potential energy in filtrating hilly runoff water. As of 2024, Sarawak's total water demand for domestic and industrial use is estimated at 2,060 MLD [5]. Experimental results presented in Section 4.2 confirm that clean water can be produced from hilly runoff without the need for chemical coagulants and fossil fuel-based energy. This is primarily due to the naturally low turbidity of the source water and the utilisation of its gravitational potential energy. By contrast, Sarawak's continued reliance on conventional water treatment technologies, which are heavily dependent on chemical base coagulant dosing and electricity derived from fossil fuels, imposes substantial economic and environmental burdens, and these include high operational costs,

The coagulant dosing and using of fossil fuel-based energy in the water treatment process generates polluted sludge and green house gases which are the risk factors to ecosystems and public health.

Collectively, these findings highlight the urgent need for a sustainable transition in Sarawak's water treatment practices.

Producing clean water from hilly runoff without chemical inputs, while harnessing the inherent energy of instream flows, offers multiple environmental advantages. Based on the results presented in Section 4.2 and expressed in Equations (10) and (11), meeting Sarawak's water demand of 2,060 MLD requires neither coagulant addition nor fossil fuel-derived electricity. This implies that both sludge discharge and carbon emissions can be effectively eliminated, as shown below:

P(Sludge Discharge) ≈ 0 Eq.(10)

P(CO_2eq) ≈ 0 Eq(11)

Equations (10) and (11) further illustrate that harnessing the gravitational potential energy of in-stream hilly runoff offers a viable pathway for clean water production with negligible environmental impact. By contrast, under current practice, the production of 2,060 MLD of treated water in Sarawak [5] relies predominantly on coagulant dosing technologies, which generate significant volumes of chemically contaminated sludge. To evaluate the relative merits of these approaches, a comparative analysis of conventional treatment methods and hilly runoff–based clean water production has been conducted, as presented in Table 5.0. The table provides an integrated environmental and economic assessment for producing 2,060 MLD of treated water, highlighting the advantages of hilly runoff utilisation over conventional treatment systems.

Table 5.0: Economic and Environmental Benefit in Using Hilly Runoff for Clean Water Production

Parameter	Conventional Chemical–Fossil Fuel Treatment	Hilly Runoff–Based Clean Water Production
Sludge generation	≈ 60,600 kg/day [39], [40]	0.0 kg/day
Coagulant cost at dosing rate 10 mg/L at 50% efficiency	Annual recurring cost (10 mg/L dosing; RM 3.00/kg) [39], [41], [42].	0.0 (no chemical dosing required)
Carbon emissions at energy consumption .55 kWh with emission rate 0.3 kg/m^3 of water	≈ 793.1 tonnes CO_2eq/day [39], [43],	0.0 (natural potential energy harnessed)
Public health cost due to CO_2 emissions @ $100/ton of emission	≈ USD 21.7 million/year (≈ RM 97.65 million) [39], [43]	0.0
Sludge management cost @$150/ton of sludge	≈ USD 2,060/year (at USD 100/tonne) [40], [44]	0.0
Overall environmental impact	High: sludge discharge, chemical pollution, CO_2 emissions	Negligible: no sludge, no chemicals, no emissions
Overall economic impact	Substantial recurring expenditure	Near zero recurring cost

Table 5.0 demonstrates that water filtration powered by green technology delivers substantial economic and environmental benefits to society. The results are presented as a comparative analysis between clean water production from hilly runoff and conventional chemical–fossil-fuel-based treatment systems. Traditional systems require continuous coagulant dosing, resulting in the generation of approximately 60,600 kg of sludge per day [39,43], alongside recurring chemical procurement costs [39,43] and significant carbon emissions of nearly 793.1 tonnes CO_2eq per day. These emissions are associated with an estimated annual public health burden of USD 21.7 million (≈ RM 97.65 million), in addition to sludge management costs. By contrast, hilly runoff–based clean water production eliminates the need for chemical inputs, fossil fuel consumption, sludge generation, and carbon emissions. This approach therefore offers not only long-term economic savings but also enhanced environmental resilience, directly addressing research question three.

5.0 Scenario Analysis of research findings

This study assessed the potential of hilly runoff in Sarawak as a sustainable source of both clean water and renewable energy. A total of 157 project sites were identified, with an estimated micro-hydro energy potential of 16,240 kW and a state-wide capacity of approximately 4.3 MW. Sarawak receives an average annual rainfall of 3.5 m, and with 37% of its land categorised as hilly terrain, an estimated 184.186 billion m^3 of runoff is generated each year [3,37]. If only 1% of the hilly areas situated between 10 and 100 m elevation were harnessed, up to 8,000 MLD of water could potentially be harvested. Assuming an effective head of 100 m and a system efficiency of 75%, the technically available renewable energy would be sufficient to support decentralised water purification and rural electrification initiatives. Such integration would contribute significantly to sustainable regional development by addressing water security, enhancing energy access, and reducing reliance on fossil-fuel-based systems

Experimental results confirmed that clean water production from hilly runoff does not require chemical coagulants. Feed water with an average TSS concentration of 1.76 mg/L produced treated water containing 0.89 mg/L without coagulants and 0.84 mg/L with coagulants, showing no measurable advantage of chemical dosing. The corresponding TSS removal efficiencies were 53% and 52% respectively, with an energy consumption of 0.55 kWh m^{-3}, consistent with reported values (0.55–0.70 kWh m^{-3}). Importantly, the product water remained within WHO guideline limits, confirming the viability of chemical-free treatment [45].

Comparative analysis demonstrated that meeting Sarawak's demand of 2,060 MLD using conventional methods would require continuous chemical dosing, generating approximately 60,600 kg of sludge daily and 793.1 tonnes of CO_2eq emissions, with an estimated annual public health cost of USD 21.7 million. In contrast, hilly runoff-based treatment eliminates sludge, chemical inputs, and carbon emissions, thereby reducing both environmental pollution and operational costs to near zero. In conclusion, hilly runoff offers a viable low-carbon pathway to secure water supply, generate renewable energy, and enhance economic sustainability in Sarawak. Overcoming policy and technical barriers will be essential to unlock its full potential for inclusive and sustainable development. Comparative environmental impact: Conventional treatment generates ≈60,600 kg of sludge per day and ≈793.1 tonnes of CO_2eq emissions, incurring a public health cost of ~USD 21.7 million annually. Hilly runoff-based treatment eliminates sludge, chemicals, and carbon emissions entirely. Economic sustainability: Conventional systems impose recurring costs from chemicals, sludge management, and energy, while hilly runoff treatment operates at near-zero recurring cost, offering long-term savings.

Implications

These findings offer significant implications for various stakeholders. It could be a reference for researchers for further study to explore and optimize chemical-free water treatment systems adapted to hilly terrains. Policy makers are encouraged to develop regulatory frameworks that support decentralized, renewable-powered treatment infrastructures. For economic and environmental planners, the data presents a strong case for investing in low-impact technologies that yield both financial savings and environmental protection. Integrating clean energy and non-chemical processes into water management strategies can also enhance climate resilience and public health outcomes.

RECOMMENDATION

It is strongly recommended that Sarawak requires to prioritise the adoption of sustainable water treatment solutions by piloting renewable-powered, chemical-free systems in strategically selected hilly regions. The success of such initiatives will depend on comprehensive policy support, including targeted incentives, the establishment of collaborative research partnerships, and the mobilisation of appropriate funding mechanisms. These measures will not only facilitate the scaling-up of innovative technologies but also ensure a cost-effective and environmentally responsible transformation of the state's water management practices

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