

Engineering Design of a Hybrid Groundwater Treatment System in Suka Damai Village, Muara Badak Subdistrict, Kutai Kartanegara Regency

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ABSTRAK

Air tanah merupakan sumber utama air bersih bagi masyarakat Desa Suka Damai, Kecamatan Muara Badak, Kabupaten Kutai Kartanegara. Namun, hasil analisis laboratorium menunjukkan bahwa air tanah dari sumur gali dangkal dan sumur bor mengalami kontaminasi mikrobiologis dan fisiko-kimia yang signifikan, melebihi baku mutu Peraturan Menteri Kesehatan Nomor 2 Tahun 2023. Penelitian ini bertujuan merancang sistem pengolahan air tanah hybrid berbasis bukti empiris untuk menghasilkan air minum layak konsumsi. Pengambilan sampel dilakukan pada dua lokasi strategis—sumur bor dan sumur gali—dan dianalisis di Laboratorium Lingkungan DLHK Kutai Kartanegara. Hasil menunjukkan bahwa air mentah mengandung Total Coliform hingga 6.488 MPN/100 mL, *E. coli* sebesar 259 MPN/100 mL, TDS 704 mg/L (melebihi baku mutu <300 mg/L), kekeruhan 47,6 NTU, serta bau tidak sedap. Berdasarkan temuan tersebut, direkomendasikan sistem hybrid tiga tahap: (1) aerasi menggunakan menara aerasi, (2) filtrasi multistage (pasir zeolit, media mangan, karbon aktif), dan (3) disinfeksi UV—dengan sengaja menghindari penggunaan klorin guna mencegah pembentukan disinfeksi by-products (DBPs) karsinogenik seperti trihalometana (THM). Keberlanjutan sistem dijamin melalui model tata kelola berbasis Badan Usaha Milik Desa (BUMDes) dan willingness to pay (WTP) masyarakat sebesar Rp50.000–Rp150.000 per bulan. Penelitian ini menunjukkan bahwa air tanah yang terkontaminasi dapat ditransformasikan menjadi sumber air minum yang aman dan berkelanjutan melalui pendekatan teknologi yang terintegrasi, sosial, dan energi terbarukan. Kata kunci: air tanah; BUMDes; ketahanan air; pengolahan air; WTP

ABSTRACT

Groundwater serves as the primary source of clean water for residents of Suka Damai Village, Muara Badak Subdistrict, Kutai Kartanegara Regency. However, laboratory analyses reveal severe microbiological and physicochemical contamination in both shallow dug wells and deep boreholes, exceeding the standards set by the Indonesian Ministry of Health Regulation No. 2 of 2023. This study aims to design a hybrid groundwater treatment system based on empirical laboratory data to produce safe drinking water. Water samples were collected from two strategic locations—a deep borehole and a shallow dug well—and analyzed at the Environmental Laboratory of DLHK Kutai Kartanegara. Results showed that raw water exhibits total coliform levels up to 6,488 MPN/100 mL, *E. coli* at 259 MPN/100 mL, total dissolved solids (TDS) of 704 mg/L (exceeding the 300 mg/L standard), turbidity of 47.6 NTU, and offensive odor. Based on these findings, a three-stage hybrid system is recommended: (1) aeration using an aeration tower, (2) multistage filtration (zeolite sand, manganese media, granular activated carbon), and (3) ultraviolet (UV) disinfection—deliberately avoiding chlorine to prevent the formation of carcinogenic disinfection by-products (DBPs), such as trihalomethanes (THMs). System sustainability is ensured through a governance model managed by the Village-Owned Enterprise (BUMDes) and supported by household willingness to pay (WTP) of IDR 50,000–150,000 per month. This research demonstrates that contaminated groundwater can be transformed into safe drinking water through an integrated approach combining appropriate technology, social engagement, and renewable energy.

Keywords: BUMDes; groundwater; water security; water treatment; willingness to pay

INTRODUCTION

Access to safe and potable drinking water remains a fundamental human right that is still unfulfilled in many rural areas of Indonesia, particularly in hilly, dryland regions such as Suka Damai Village, Muara Badak Subdistrict, Kutai Kartanegara Regency, East Kalimantan. In this community, residents rely entirely on groundwater—both from shallow dug wells (<15 m) and deep boreholes (>15 m)—as their primary source of clean water [1]. However, field reports and preliminary surveys indicate systematic complaints regarding foul odor, brownish discoloration, high turbidity, and health impacts such as diarrhea and skin irritation—clear indicators of biological and chemical contamination [2], [3].

Laboratory analyses of groundwater samples from Suka Damai Village confirm serious violations of national drinking water quality standards. Shallow dug wells show total coliform concentrations of 6,488 MPN/100 mL and *E. coli* at 259 MPN/100 mL—far exceeding the zero threshold stipulated in Ministerial Regulation of Health No. 2/2023 [4]. This condition indicates unmanaged domestic wastewater infiltration, particularly given the very close proximity between wells and household sanitation systems [5]. Meanwhile, boreholes—although visually clearer—still contain TDS levels of 704 mg/L and total coliform of 488.4 MPN/100 mL, showing that well depth alone does not guarantee safe water quality [6].

Conventional approaches such as basic sand filtration or boiling are insufficient to address this complexity of contaminants. Sand filtration may reduce turbidity but fails to eliminate pathogenic microorganisms or odor-causing organic compounds [7]. Boiling, while effective against microbes, does not reduce TDS or dissolved metals and may even worsen taste due to increased mineral concentration [8]. Therefore, a hybrid treatment system is required—one that simultaneously addresses physical, chemical, and microbiological aspects through evidence-based scientific design.

This study fills this gap through the integration of three innovative pillars: first, a hybrid treatment technology comprising aeration, multistage filtration, and UV disinfection—specifically tailored to the contaminant profile of tropical groundwater rich in organic matter and pathogens; second, the utilization of a 500-watt Solar Photovoltaic Power Plant (PLTS) to ensure energy independence in remote areas; third, a BUMDes-based governance model supported by community willingness to pay (WTP), thereby

ensuring long-term operational sustainability [9], [10]. This holistic approach not only addresses technical challenges but also strengthens local capacity through village institution empowerment, in accordance with the principles of community-based water governance [11]. Thus, this research not only yields a technical solution but also offers a replicable model applicable to hundreds of similar villages across Indonesia.

2. METHODOLOGY

This research adopts a multidisciplinary approach combining technical, environmental, and socio-economic aspects to design a sustainable groundwater treatment system in Suka Damai Village. The methodology is structured in stages to ensure data validity, technical feasibility, and operational sustainability.

2.1. Water Sampling Method

Water sampling was conducted on November 30, 2023, at two representative locations: (1) a deep borehole (>15 m; coordinates E: 117°15'55.8", S: 00°14'41.3") and (2) a shallow dug well (<15 m; near residential area). Site selection was based on depth variation, water usage patterns, and community complaints regarding water quality.

Grab sampling was performed in accordance with Indonesian National Standard SNI 6989.57:2008, using 5 liters of water per site collected in sterilized HDPE bottles pre-rinsed three times with sample water.

Samples were immediately stored in a cooler box with dry ice and delivered to the UPTD Environmental Laboratory of DLHK Kutai Kartanegara on December 1, 2023. This procedure ensures sample integrity in accordance with chain-of-custody principles for surface water quality analysis, as recommended by Standard Methods for the Examination of Water and Wastewater [12].

2.2. Laboratory Analysis

Water quality was analyzed for 22 key parameters encompassing physical (temperature, TDS, TSS, color, EC, turbidity, odor), chemical (pH, BOD₅, COD, salinity, Fe, Mn, heavy metals), and microbiological (*E. coli* and total coliform) aspects. All analyses were conducted at the ISO/IEC 17025-accredited DLHK Kutai Kartanegara Laboratory using methods aligned with national (SNI) and international (Standard Methods) standards. Accredited parameters—such as TDS, turbidity, pH, BOD₅, and microbiology—were prioritized in technical interpretation due to their direct implications for pretreatment design. Analytical results were

compared against the standards of Ministerial Regulation of Health No. 2/2023 as a reference for raw water suitability for drinking water treatment [4]. Additionally, laboratory data were cross-referenced with technical standards for aeration and filtration units—for example, turbidity <5 NTU for filtration efficiency and Fe/Mn <0.3 mg/L to prevent media fouling—ensuring that technical recommendations are grounded in valid and engineering-relevant empirical evidence [13], [14].

2.3. Social Analysis (Willingness to Pay/WTP)

The socio-economic aspect was evaluated through a field survey of 30 household heads selected via purposive sampling, with primary criteria: (1) active users of local water sources, (2) permanent residents of Suka Damai Village for over two years, and (3) participants in the Water Supply System (WSS) program. The survey instrument included structured questionnaires and in-depth interviews to assess Willingness to Pay (WTP), water quality perception, distribution preferences (piped vs. bottled), and trust in managing institutions. Data were analyzed descriptively to identify payment willingness ranges and drivers of financial sustainability. Findings were linked to the institutional role of the Village-Owned Enterprise (BUMDes) Mekar Sejati, which has managed WSS since 2018 with support from village funds and PT Pertamina Hulu Sanga Sanga's CSR program [6]. This approach aligns with the community-based water governance framework, which emphasizes local participation and participatory financing mechanisms [11], thereby addressing non-technical sustainability questions often overlooked in community-scale water system design.

2.4. Treatment System Design

Based on the synthesis of laboratory data and social findings, a three-stage hybrid treatment system was designed, specifically adapted to the unique characteristics of groundwater at the study site. The design follows the multi-barrier approach principle in water treatment, which emphasizes the need for layered barriers to handle contaminant complexity [15]. The first stage involves an aeration tower to oxidize ferrous iron (Fe^{2+}) and manganous ion (Mn^{2+}) into insoluble forms (Fe^{3+} and MnO_2), while simultaneously stripping volatile compounds such as hydrogen sulfide (H_2S) responsible for foul odor [13]. The second stage is multistage filtration, consisting of: (i) zeolite sand to remove suspended particles and adsorb ammonium, (ii) manganese zeolite as a catalytic oxidant for dissolved metals, and (iii) activated carbon to adsorb organic compounds, color, and odor [16], [17]. The third stage is UV disinfection (254 nm, 40 mJ/cm² dose) for

pathogen inactivation without forming carcinogenic disinfection by-products (DBPs)—a major risk when using chlorine on organically rich water [9], [10]. The entire system is designed to operate on a 500-watt solar photovoltaic system (PLTS) to ensure energy autonomy [18]. Detailed Engineering Design (DED) and Budget Estimate (RAB) were developed for a capacity of 1,200 liters/hour, assuming 1 hour of daily operation, aligned with community drinking water needs [6].

RESULTS AND DISCUSSION

3.1. Groundwater Quality from Deep Borehole

Laboratory analysis of groundwater from the deep borehole (>15 m) in Suka Damai Village reveals water quality that is visually clear yet chemically and microbiologically unsafe for consumption. Analytical results are presented in Table 1.

Table 1. In Situ Characteristics of Deep Borehole Groundwater in Suka Damai Village

No	Parameter	Unit	Lab Result	Standard (PP 22/2021)
A. Physical				
1	Temperature	°C	29.5	Deviation $\leq 3^\circ\text{C}$ from air temp
2	Total Dissolved Solids (TDS)	mg/L	704	< 300
3	Color	TCU	7.24	< 10
4	Odor	—	Offensive	Odorless
5	Turbidity	NTU	0.85	< 3
B. Chemical				
6	pH	—	7.59	6.5–8.5
7	BOD ₅	mg/L	3.94	< 3
8	COD	mg/L	9.65	< 25
9	Salinity	%	0.57	—
C. Microbiological				
10	E. coli	CFU/100 mL	3	Not detected
11	Total Coliform	MPN/100 mL	488.4	0

Source: Final Report, Universitas Kutai Kartanegara, DLHK Laboratory Report 2023

Interpretation of the data in Table 1 reveals that although turbidity and pH are within regulatory limits, three critical violations render this water unfit for consumption. First, the total dissolved solids (TDS) level of 704 mg/L—more than double the 300 mg/L limit—reflects high mineral dissolution from local geology, likely influenced by hydrogeochemical processes in Kalimantan's sedimentary basins [19]. Second, the persistent offensive odor, despite visual clarity, suggests the presence of volatile organic compounds such as hydrogen sulfide (H_2S) or

oxidized humic acids—substances not captured by standard parameters but significantly affecting consumer acceptance [20]. Third, and most concerning, is the presence of total coliform at 488.4 MPN/100 mL and *E. coli* at 3 CFU/100 mL—conclusive evidence of fecal infiltration into the deep aquifer, possibly due to borehole casing failure or surface contamination during sampling [5].

These findings have clear technical implications: the treatment system must reduce TDS, eliminate odor, and ensure microbiological sterilization. However, since TDS remains below the 1,000 mg/L threshold, expensive and energy-intensive reverse osmosis (RO) technology is unnecessary. Instead, a hybrid approach based on aeration and multistage filtration proves more technically and economically suitable for this context [21].

Aeration addresses odor and precipitates metals, while multistage filtration can reduce BOD and COD to safe levels, enabling effective and efficient UV disinfection in the final stage.

3.2. Groundwater Quality from Shallow Dug Well

Results for the shallow dug well (<15 m) reveal far more severe contamination than the borehole, as shown in **Table 2**.

Table 2. In Situ Characteristics of Groundwater from Shallow Dug Well in Suka Damai Village

No	Parameter	Unit	Lab Result	Standard (PP 22/2021)
A. Physical				
1	Temperature	°C	20.8	Deviation $\leq 3^{\circ}\text{C}$ from air temp
2	TDS	mg/L	68.1	< 300
3	Turbidity	NTU	47.6	< 3
4	Color	TCU	57.5	< 10
5	Odor	—	Offensive	Odorless
B. Chemical				
6	pH	—	7.64	6.5–8.5
7	BOD ₅	mg/L	3.16	< 3
8	COD	mg/L	11.9	< 25
9	Salinity	%	0.01	—
C. Microbiological				
10	<i>E. coli</i>	CFU/100 mL	259	Not detected
11	Total Coliform	MPN/100 mL	6,488	0

Source: DLHK Laboratory Report, 2023

Interpretation of Table 2 underscores the extreme contamination of shallow groundwater. The high turbidity (47.6 NTU) and brown color (57.5 TCU) indicate substantial suspended solids and organic colloids—typical of shallow aquifers

in tropical regions where organic-rich topsoil leaches humic substances into groundwater [22]. Most alarming, however, is the extreme fecal contamination: *E. coli* at 259 CFU/100 mL and total coliform at 6,488 MPN/100 mL directly indicate proximity to unsealed domestic sanitation systems—a common issue in rural Indonesia where sanitation coverage remains suboptimal [5], [23]. This condition places well users at high risk of diarrheal diseases, cholera, and leptospirosis [24].

The technical implication is the need for robust pretreatment prior to disinfection. Aeration alone cannot address high turbidity and color; multistage filtration with layered media—zeolite sand for coarse particles, manganese zeolite for metals, and activated carbon for organics—is essential to ensure that UV feedwater has turbidity <5 NTU and is free from organic compounds that could shield pathogens from UV radiation [17], [25].

Without adequate pretreatment, UV disinfection will fail to achieve optimal pathogen inactivation, leaving significant health risks.

3.3. Social Analysis Willingness to Pay and Role of BUMDes

A survey of 30 households revealed that 78% are willing to pay IDR 50,000–150,000 per month for safe drinking water. This WTP level is sufficient to cover the estimated monthly operational cost of IDR 1,766,725 for a community-scale system [6]. This finding confirms that the community not only values access to safe drinking water but also possesses the economic capacity to contribute—a crucial foundation for system sustainability.

The Village-Owned Enterprise (BUMDes) Mekar Sejati has demonstrated its capacity as a WSS manager since 2018, supported by village funds (APBDes) and PT Pertamina Hulu Sanga Sanga's CSR program [6]. However, the current piped distribution system suffers from pipe corrosion and algal growth—indicating post-treatment recontamination [26]. This highlights that sustainability depends not only on treatment technology but also on hygienic distribution.

Therefore, the bottled (refillable gallon) distribution model—easier to sterilize and control—becomes the more strategic choice, aligning with BUMDes's existing bottled water depot operations [6], [10].

3.4. Recommended Hybrid Treatment System

Based on the above findings, a three-stage system is proposed. The aeration tower oxidizes ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) and manganous ion (Mn^{2+}) to manganese dioxide (MnO_2) for precipitation, while simultaneously stripping hydrogen sulfide (H_2S) and other

volatile organic compounds responsible for odor [13], [14].

Multistage filtration follows, beginning with zeolite sand to remove suspended solids and adsorb ammonium, then manganese zeolite to catalyze residual iron and manganese oxidation [20], followed by granular activated carbon (GAC) to adsorb color, odor, and organic contaminants [15], and finally a 0.5 μm cartridge filter to protect the UV unit from fouling.

UV disinfection at a dose of 40 mJ/cm^2 achieves over 99.9% inactivation of *E. coli* and coliforms without chemical residuals [17]. Critically, UV avoids carcinogenic disinfection by-products (DBPs) such as trihalomethanes (THMs), a major risk given the elevated COD (3.16–9.65 mg/L) in raw water [9], [10].

The system is designed for a capacity of 1,200 L/day, with energy options including grid (PLN) at an operational cost of approximately IDR 5,938/day, solar (500 W PV) with zero long-term cost, or generator at approximately IDR 22,304/day. The total capital cost ranges from IDR 71.3 to 76.8 million [6].

3.5. Sustainable Distribution via BUMDes

To prevent recontamination, bottled water (refillable gallons) is recommended over piped networks. This model allows routine sterilization of containers, reduces biofilm and algal growth, generates revenue for BUMDes, and aligns with existing community practices [6], [15].

CONCLUSION

This study confirms that raw groundwater in Suka Damai Village is unsafe for direct consumption due to severe microbiological and physicochemical contamination. The shallow dug well is critically contaminated (*E. coli*: 259 CFU/100 mL; turbidity: 47.6 NTU), while the deep borehole exceeds TDS and microbial limits. A three-stage hybrid system—(1) aeration, (2) multistage filtration, (3) UV disinfection—effectively addresses all contaminants while avoiding carcinogenic by-products. The integration of solar energy enhances cost-efficiency and resilience.

Long-term sustainability is ensured through BUMDes governance and strong community willingness to pay (IDR 50,000–150,000/month). The bottled water distribution model minimizes recontamination risk and supports local economic development.

This research demonstrates that even highly contaminated groundwater can be transformed into safe drinking water through appropriate, community-centered engineering

solutions, offering a replicable model for remote regions

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