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Analysis of the Potential of a Subsurface Dam as a Groundwater Storage System in the Tukad Ketes Alluvial Deposits, Bunutan Village, Karangasem, Bali

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Abstract

Bunutan Village, Abang District, Karangasem Regency, East Bali, experiences water shortages during the dry season due to rocky geology, low rainfall, limited groundwater discharge, and increasing domestic, irrigation, and tourism demand. Pumping from coastal alluvial deposits may also increase the risk of seawater intrusion because the freshwater layer is relatively thin. This study assesses the potential of a subsurface dam as a groundwater conservation and storage system in the alluvial deposits of Tukad Ketes. A descriptive-quantitative case study method was applied through geological, hydrogeological, and hydrological analyses, supported by an estimation of groundwater storage capacity. Results indicate that the Tukad Ketes valley contains 30–35 m thick alluvial deposits composed of sand, gravel, cobbles, and boulders, which can function as an underground reservoir. Alluvial permeability ranges from 10^{-2} to 10^{-4} cm/s, while volcanic breccia bedrock acts as a natural impermeable boundary. With a reservoir length of 1,000 m, an effective width of 700 m, a cutoff wall depth of 40 m, and an effective porosity of 10%, the theoretical storage capacity reaches approximately 2.8 million m^3. Therefore, a subsurface dam at Tukad Ketes is feasible for further development as a solution for groundwater conservation and raw water supply.

Keywords: *Subsurface dam; groundwater; alluvial deposit; water conservation; Bunutan Karangasem*

INTRODUCTION

Eastern Bali, particularly Abang Subdistrict in Karangasem Regency, frequently experiences clean water crises-especially during the dry season-due to a combination of unfavorable geographical, geological, and climatic factors. One of the driest areas in Bali is Bunutan Village, Amed Subdistrict, Karangasem Regency, East Bali. This has led to severe water shortages for local residents during the dry season-for household use, irrigation, and tourism.

Why is Eastern Bali a water-scarce region? This is primarily due to geological and geographical factors (rocky soil conditions). The Abang area and its surroundings are dominated by dry hills and rocky soil structures that are unable to retain groundwater effectively. This region of East Bali receives lower rainfall compared to Central or West Bali. During the dry season, natural springs often diminish or even dry up completely.

Hydrologically, water availability in subdistricts such as Abang, Kubu, and eastern Karangasem is relatively low (low flow rates), making it insufficient to meet residents' needs, especially during the dry season. This reliance on water sources means that most people in this area still depend on natural springs located far away; some even have to travel up to 2 km to collect seepage water.

According to I. Masayuki (2024), groundwater accounts for 30% of global freshwater reserves, and in arid and semi-arid regions, it can make up more than 80% of total water availability [1]. Groundwater is often described as high-quality, easily accessible, and generally less affected by short-term climate and hydrological changes. Underground dams are facilities that increase groundwater capacity by constructing watertight walls within an aquifer, effectively raising the groundwater table and also preventing seawater intrusion in coastal areas [2]. The history of underground dams can be traced back more than 2,000 years, but it was not until the early 1980s that the first dams were builtusing modern civil engineering techniques. Since then, underground dams have been found in countries such as Japan, Brazil, India, South Korea, Mexico, Bolivia, the U.S., and throughout Europe [3]. According to a study by Ahmet Apaydın (2024), the successful implementation of underground dams is greatly influenced by suitable geological conditions, aquifer characteristics, the thickness of alluvial deposits, and groundwater flow patterns. Therefore, geological and hydrogeological studies are crucial steps that must be conducted before the construction of an underground dam begins [4].

The use of underground dams is not a new concept. According to Andreas N. Angelakis (2024) [5], water dam technology has evolved since ancient civilizations and has continued to be refined into the modern era. With advances in civil engineering, underground reservoirs have increasingly been implemented as a solution for water resource conservation, particularly in areas with limited surface water and shallow aquifers [6]. This development indicates that underground reservoirs are becoming an increasingly important form of water infrastructure in addressing the challenges of climate change and rising water demand [7].

Although water is scarce, the stretch from Amed Beach to the beautiful Bunutan Beach has become a bustling tourist area because the beaches are clean and ideal for marine tourism. Until now, raw water for restaurants, inns, and resort hotels has been obtained by pumping from the coastal alluvial layer. Because the freshwater aquifer is shallow (approximately 2 meters above the brackish water layer), continuous pumping will lead to seawater intrusion, and this phenomenon has begun to occur in the Amed area (approximately 4 km west of Bunutan village). The construction of an underground dam in the village of Bunutan may address the aforementioned needs, in accordance with regional and local geological conditions, geomorphological conditions, climatic conditions, and local rainfall patterns [8]. The characteristics of seasonal rivers (intermittent streams) and thick, deep alluvial deposits present both opportunities and challenges for securing a sufficient supply of raw water.

This research is necessary because dams are generally located above ground (surface dams), whereas this study examines the potential for implementing subsurface dams as an alternative for groundwater conservation and storage, as they are well-suited to the characteristics of Bunutan Village. Therefore, a thorough understanding of the concept of subsurface dams is necessary, along with a strong commitment from various stakeholders to make this a reality.

METHOD

The research method is descriptive-quantitative, based on a case study, through an analysis of geological, hydrogeological, and hydrological conditions; characteristics of the alluvial aquifer; and an estimation of groundwater storage capacity. Data analysis includes:

1. Analysis of regional and local geological maps, topographic data and the Digital Elevation Model (DEM), rainfall data, land-use data, well and spring data, and satellite imagery to

understand the initial conditions of the study area, determine the main investigation zones, and assess the suitability of the local geology as a site for a subsurface dam. Hydrological analysis of rainfall values, runoff discharge, groundwater recharge, and the water balance, aimed at estimating the potential for groundwater recharge in dry alluvial layers and determining the capacity of the underground reservoir.

2. Analysis of the potential for a subsurface dam, including an evaluation of geological conditions, aquifer thickness, the presence of impermeable layers, groundwater storage potential, and the optimal location for the cutoff wall. Groundwater modeling was performed using the Seep/W and Modflows software.
3. Simulations of existing conditions and conditions after the construction of the subsurface dam were conducted (Figure 1).

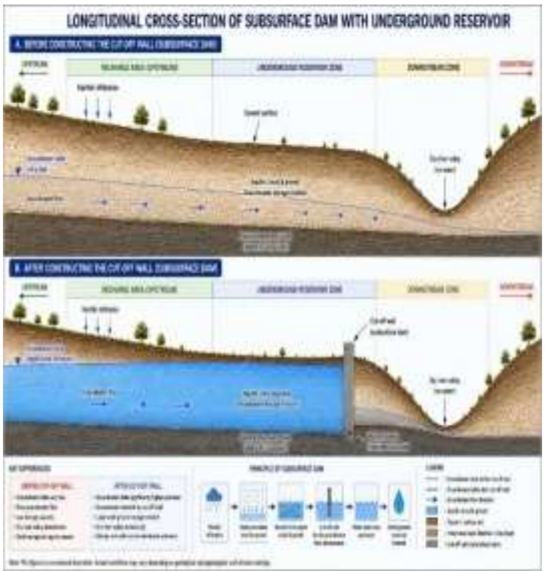


Figure 1. Concept of *a subsurface dam* in the thick alluvial layer at Bunutan, Karangasem, Bali

Study Location and Regional Geological Conditions

The study area for this subsurface dam is located in the eastern part of Bali, which is known for its hilly landscape and natural valleys. Further information regarding local land use planning and geography can be accessed through the Bali Regional and Spatial Planning Information System. Administratively, the Tukad Kades Valley and Bunutan Village are part of Abang Subdistrict, Karangasem Regency, Bali Province (Figure 2) [9].

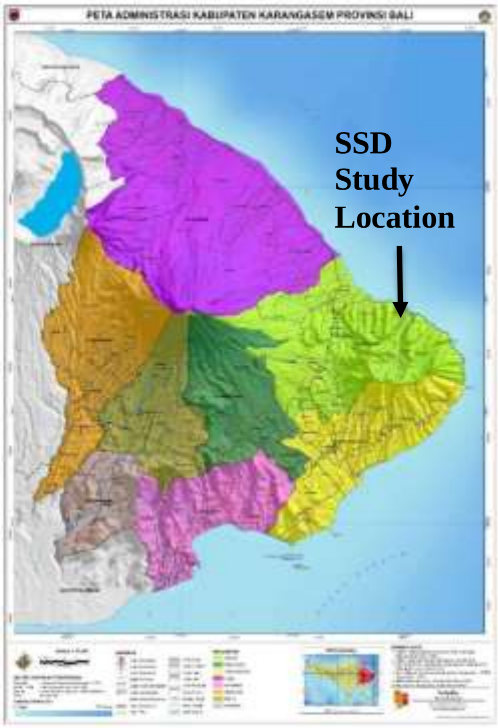


Figure 2. Study location of *the subsurface dam in* Bunutan Village, Karangasem, Bali

RESULTS AND DISCUSSION

Local Geology of the Subsurface Dam (SSD) Site

The Bunutan Valley is situated between two hills extending from south to north, with slopes inclining toward the valley at approximately 30º; the valley's width ranges from 200 to 500 m. The valley's shape closely resembles the letter "U," with a relatively flat valley floor. Morphogenetically, the valley is believed to have formed as a result of a landslide caused by a fault in this area (Figure 3).

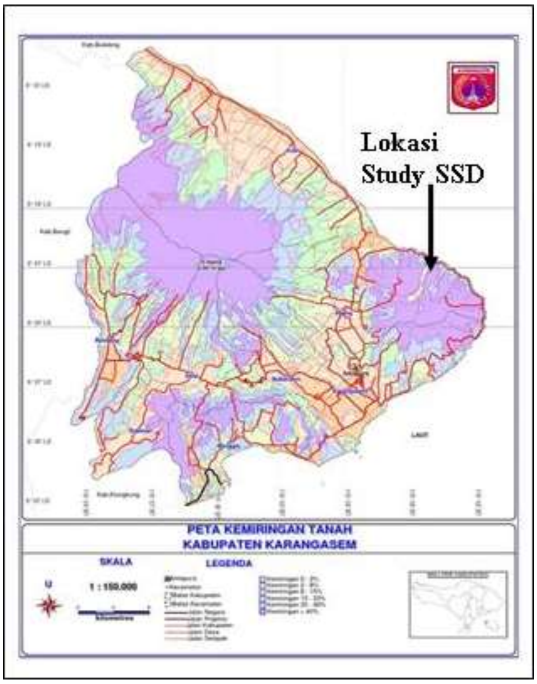
The bedrock in this valley consists of volcanic breccia interbedded with andesitic lava. Meanwhile, the central part of the valley is filled with fluvial deposits and slope debris (talus). The rocks found in this area are breccias with interbedded andesitic lava as the bedrock. River deposits have been deposited on top of the bedrock in the central part of the valley, and slope debris deposits are found along the valley edges. It is estimated that some of the river deposits here originate from slope debris. The rock types are described as follows:

a. The breccia rock layer consists of several cycles, each of which is bounded by an erosion surface. The breccia is dark gray, hard, and compact, with andesitic fragments up to 1.5 m in diameter. Lava intrusions are found in several locations with thicknesses ranging from 1.0 to 3.0 meters; they are dark gray, crystalline, hard, and compact, and consist of andesite. Above the breccia with andesite lava intrusions lies a covering unit consisting of talus and river deposits.
b. The talus deposits consist of slope debris from the hills on the left and right sides of the valley; this debris may consist of andesite boulders (breccia fragments) or breccia boulders with a maximum size of 2.00 m and a thickness ranging from 2 to 10 m.
c. The river deposits consist of boulders with a maximum fragment size of 2 m, comprising fragments of andesite, basalt, or breccia. These river deposits have not been transported very far from their source; thus, they represent talus deposits accumulated at the valley floor, where the Tukad Ketes channel also runs. The thickness of these river deposits ranges from 30 to 35 meters.

Groundwater Conditions in the Tukad Ketes River Valley

According to local residents, prior to 1942 (before the Japanese occupation), the Tukad Ketes channel always carried water throughout the day for a distance of approximately 2.5 km downstream from the current spring, before disappearing underground near the downstream location of the planned underground dam axis. The length of the Bunutan Valley, stretching from its spring in Bangle Village to the northern shoreline, is approximately 4 km. The underground dam axis is planned 2 km downstream from the spring. Currently, during the rainy season, the spring's flow rate can reach approximately 50 liters per second, and the water flows through the river valley for about 100 meters from the spring before disappearing underground and reemerging near the coast. During prolonged rainy seasons, the Tukad Ketes riverbed is always filled with water; in fact, the flow is strong enough to carry away rock fragments ranging in size from pebbles to boulders. This occurs primarily in the upper reaches of the valley, where the river hydraulic gradient is quite steep at 30 m/500 m. This is in stark contrast to the dry season, when the Tukad Ketes channel carries water only near the spring, after which it disappears beneath the riverbed and reemerges only about ± 30 m from the shoreline.

Figure 3. Slope Gradient Map of the Study Site for the Subsurface Dam in Bunutan Village, Karangasem, Bali



Therefore, although the river valley appears dry with a surface that looks like a rocky plain, it is suspected that water still flows along the boundary between the alluvial deposits and the underlying bedrock[10]. This assumption is based on local conditions, where a spring exists in the upper reaches of the river, but just a few meters downstream, the water flow disappears directly beneath the ground surface. Another indication is the presence of a geological landslide structure, which thickens the alluvial deposits in the river valley and can function as a natural underground groundwater reservoir. The water in these very coarse-grained alluvial deposits can be directly tapped to meet the water needs of the local population, especially during the dry season. If the underground reservoir is constructed, it could help meet the raw water demand in this area, particularly to anticipate the rapid growth of tourism in this location[11].

Given the conditions and nature of the water described above, this reinforces the assumption that water from the source beneath the alluvial surface continues to flow at all times along the bottom of the Tukad Ketes valley and is not expected to seep in other directions. Thus, with the presence of a cutoff beneath the riverbed, it is hoped that the water flowing day and night toward the sea can be retained and accumulated, while the land surface where the SSD is located can still be used for crop cultivation.

Hydrometeorology and Hydrogeology of the Tukad Ketes River

Hydrometeorology

Abang Subdistrict, including the Bunutan Village area and the Tukad Ketes watershed, has a dry to moderate climate because it is located in a rain shadow area. Average annual rainfall ranges from 1,473 mm to 1,676 mm. The peak rainfall and the highest number of rainy days typically occur from January through April and at the end of the year.
The Karangasem region experiences fairly fluctuating rainfall patterns across its various areas. Based on climatological data, the basic details for this region include:

- Annual Rainfall: The average ranges from 1,473 mm/year to 1,676 mm/year
- Rainfall Categories: Rainfall in eastern subdistricts such as Abang tends to be low to moderate compared to the mountain slopes.
- Wet Months: The highest rainfall generally occurs in January, February, and December, reaching over 300 mm in a single month.
- Daily Rainfall Duration: Under extreme weather conditions, rainfall in this region can exceed 140 mm/day within a 24-hour period.

T. Zheng, et al. (2023), reported that hydraulic conductivity is a key parameter controlling groundwater flow and the transport of dissolved substances, and that anisotropy in hydraulic conductivity is common in aquifers.[12] Previous studies have investigated the effectiveness of subsurface barriers in mitigating seawater intrusion (SWI) and related environmental issues[13]. However, the quantitative impact of hydraulic conductivity anisotropy on the performance of subsurface barriers has not yet been explored. This study goes beyond previous research by examining, for the first time, the effect of subsurface barriers on SWI prevention in an anisotropic environment. Furthermore, this study optimizes the design of subsurface barriers in anisotropic coastal aquifers through numerical simulations that account for environmental impacts[14].

An analysis of the environmental potential and risks of the Tukad Ketes River Valley and the Bunutan region requires hydrometeorological disaster mitigation as well as comprehensive water resource management:

- **Risk of Erosion and Landslides**: During the rainy season with heavy rainfall (over 50 mm/day), the steep slopes of the river valley have the potential to trigger erosion. The soil characteristics in parts of this region, which readily absorb water, also make it prone to the accumulation of rainwater, causing the river's alluvial deposits to become saturated.
- **Seasonal Drought**: During the dry season, due to the sandy soil type and high rate of infiltration, surface water dries up quickly. The Tukad Ketes River is generally intermittent (flowing only during rainfall).
- **Rainwater Harvesting**: Given that annual rainfall remains in the thousands of millimeters, water storage infrastructure—such as rainwater harvesting systems or the construction

of retention ponds—is highly recommended to support the domestic and agricultural water needs of local residents.

Hydrogeology of Reservoir Rocks

Generally, reservoir rock refers to rock used as a water storage medium within the spaces between its grains[15]. In the Sunagi Tukad Ketes valley area of Bunutan village, the rock that can be used as reservoir rock consists of alluvial deposits-a mixture of clay, silt, sand, gravel, cobbles, and chunks of igneous rock or breccia-which is loose and friable.

Solutions to address the water crisis are summarized into two strategies: water resource management and the development of new water sources. In Iran, due to its geographical and climatic conditions, water resource management is a top priority. One method for controlling and storing water during the rainy season for use during the dry season is the construction of underground reservoirs[16].

The most significant challenge in the development and construction of underground reservoirs is the complexity of identifying suitable sites for them. The study area faces critical water conditions due to the temporal and spatial mismatch in rainfall distribution, uncontrolled groundwater extraction, declining groundwater levels, and the interference between saltwater and freshwater. Therefore, the construction of an underground dam could be a practical solution to prevent groundwater level decline, land-use changes, and a gradual increase in groundwater salinity (J. Chezgi, 2021) [17].

Based on the results of on-site water permeability tests on these rocks, permeability coefficients ranging from10^{-2}to10^{-4}cm/s were obtained. This is understandable given that the composition of these rocks generally consists of silt to fine sand. Therefore, based on the conditions described above, we can estimate that these alluvial deposits can be utilized as reservoir rocks for water storage. The rock serving as the bedrock is dense breccia with a permeability coefficient of 10^{-6}cm/s.

Aquifer System and Its Physical Characteristics

Based on the results of a fairly in-depth hydrogeological analysis, the aquifer system in the study area can ultimately be interpreted as follows:

- The groundwater basin system in the study area is located in the center of the valley, stretching from the spring outlet in Kampung Air Masam-which is slightly wider than the river channel-to the northern coastline over a distance of approximately 4 km, or about 24 km from the coast; it widens downstream, ranging from 200 to 500 meters.
- This groundwater basin system is interpreted as a groundwater basin shaped like a bowl open toward the north/coast, consisting of two aquifer layers: an unconfined aquifer and a *semi-* confined aquifer, which are not separated by an impermeable layer.

Based on the nature of the materials, it can be categorized into two types:

1) **Fine alluvial deposits**, resulting from slope erosion (talus), with a thickness ranging from 2 to 10 meters and permeability ranging from$^{10^{-3}}$to$^{10^{-4}}$cm/s.
2) **Coarse alluvial deposits**, consisting of boulders with fragments of andesite, basalt, and breccia that are weathered, with a maximum size of 2 meters; thickness of 25–30 meters; permeability ranging in the order of 10^{-2}–10^{-3}cm/s; classified as highly permeable.
3) **Volcanic breccia** with andesite lava inclusions serves as the bedrock and laterally bounds the aquifer system; due to its hard and compact nature, its permeability is$^{10^{-4}}$–$^{10^{-5}}$cm/sec or even lower, and it is found at depths of 37–41.5 meters below ground level.

Estimates of *Inflow* and Out*flow*

Observations were conducted over a one-year period (September 1999–July 2000) at the inflow and outflow locations of the groundwater reservoir as a system in the study area, in preparation for a groundwater balance evaluation.

Inflow from the groundwater basin/ 's underground reservoir is as follows:
1. Infiltration/percolation caused by rainfall, penetrating the permeable overlying soil layer. Hydrological studies estimate the potential annual inflow to be approximately 16–18% of the annual rainfall.
2. Spring flow upstream of the aquifer, which generally occurs due to rainwater seepage from aquifers of different formations in the upstream area. Measurement data from February 2000 represents conditions during the rainy season at the location

Official data from Karangasem document the presence of various spring sites in Bunutan Village, such as Kayehan and Pekarangan, which residents use for bathing and drinking water. The hilly area of Banjar Bangle even features a phenomenon of five springs whose flows descend toward the Tukad Ketes River basin and then disappear beneath the riverbed of the Tukad Ketes River, as documented in the DPUPR Geospatial Information System. Below are several spring sources, including one named Masam Spring, which has the potential to flow into the Tukad Ketes River Valley (Table 1).

Table 1. Spring locations at the upstream site of the Bunutan Valley

Spring	Location / Village	Cause of Formation Spring	Flow Rate (M) Rain [l/minute]
1	East / Cangwang Village	Topographic Opening	15
2	Air Asem-1*	Fault	25
3	Air Asem-2*		10
4	Bangle-1*	Fault	50
5	Bangle-2*	Fault	25
6	West of Edolang	Topographic Outcrop	15
7	West of Bantul	Topographic Opening	20
8	West of Bantul	Topographic Opening	25

**There are two water sources each at Air Asem and Bangle*

Design Concept Analysis of the Subsurface Dam, Bunutan, East Bali

An analysis of the potential water storage capacity of *the subsurface dam* on the Tukad Ketes River in Bunutan is shown in Table 2.

Calculation of Aquifer or Reservoir

Rock Volume

Total volume of alluvial deposits:

$$V_s = L \times B \times \mathrm{H} \quad (1)$$

Where:
- L = Length of the SSD span $= 1000$ m
- B = Length of *the reservoir* $= 700$ m
- H = *Cutoff* depth = 40 m

Therefore, the reservoir rock volume is:

$V_S = 1000 \times 700 \times 40 = 28{,}000{,}000$ m³

$V_S = 28{,}000{,}000$ m³

Effective stored water volume :

$$V_{\mathrm{W}} = V_S \text{ x } 0{,}10 \quad (2)$$

$V_{\mathrm{W}} = 28{,}000{,}000$ m³ x $0.10 = 2{,}800{,}000$ m

$V_{\mathrm{w}} = 2{,}800{,}000$

or the theoretical water storage capacity is 2.8 million m³ of water

Why is the effective porosity only 10%, even though in *gravelly sand* the total porosity can actually be 20–35%? However, the effective porosity can decrease when[18]:
- there is a silt/clay fraction,
- poor grain size distribution,
- the material is very dense,
- some pores are filled with a fine matrix,
- natural cementation occurs.

A value of 10% is considered conservative, safe for *preliminary design*, and is often used in initial groundwater conservation studies.

Table 2. *Basic Design* Data for *the* Tukad Ketes River *Subsurface Dam*, Bunutan, East Bali

Parameter	Value
Aquifer Type	*Gravelly sand*
Cutoff wall depth	40 m
Dam span length	700 m
Length of the alluvial valley	1,000 m
Cutoff wall material	Plastically reinforced concrete secant piles
Effective porosity	10% = 0.10

Subsurface dam performance analysis

The water storage potential remains very high; even when a conservative low porosity value of 10% is used, the dam will have a water storage capacity of 2.8 million m³, which is still considered substantial for a subsurface dam. For reference, see Table 3.

Table 3. Overview of the Utilization of the 2.8 million m³ Water Storage Volume in the Design of the Alluvial SSD on the Tukad Ketes River, Bunutan, Bali

Utilization	Potential
Domestic raw water	Highly feasible
Irrigation	Feasible
Groundwater recharge	Very good
Drought resilience	High

Feasibility of developing a subsurface dam in Bunutan, Bali

Based on geological, geotechnical, hydrological, and hydrometeorological data, as well as an analysis of the water storage potential in the alluvial deposits of the Tukad Ketes River, and referring to the analysis and calculations of the water to be stored in the underground reservoir, it is evident that the construction of an SSD to store or retain water beneath the alluvial layer of the river valley is feasible and safe to implement, due to its efficiency in water conservation, geological suitability, structural stability, low environmental impact, sustainable water conservation, no land acquisition required, environmental friendliness, and potential for alignment with the Sustainable Development Goals (SDGs)[19] .

This is especially true when comparing this Subsurface Dam (SSD) to the construction of a Conventional Surface Dam (CSD), as a CSD would require land acquisition, is prone to disasters due to Bali's high seismic risk, requires significant Operation and Maintenance (O&M) funds, and entails substantial periodic maintenance costs.

CONCLUSION

1. The Tukad Ketes area has alluvial deposits with significant potential as a shallow aquifer, primarily composed of a thick layer of gravelly sand capable of storing and discharging relatively large volumes of groundwater.
2. The geological and geomorphological conditions in the Bunutan Village area support the development of a subsurface dam, as evidenced by the presence of an alluvial valley, a relatively impermeable bedrock layer, and a subsurface flow system that allows for groundwater accumulation.
3. The alluvial material at the study site exhibits good permeability, making it an effective " " for groundwater storage. These conditions support infiltration, groundwater recharge, and an increase in water reserves during the dry season.
4. The construction of a subsurface dam on the Tukad Ketas River in Abang Subdistrict, Karang Asem, East Bali, has the potential to serve as an effective and sustainable water resource conservation solution in this region, particularly to address seasonal droughts, provide raw water, meet domestic needs, supply water for tourism (hotels and restaurants), and support the agricultural sector in water-scarce areas.
5. Based on estimates of groundwater storage capacity in the alluvial aquifer, the subsurface dam at the study site has significant water storage potential (2.8 million m³), making it feasible for further development through detailed hydrogeological investigations, field testing, and numerical groundwater modeling.

Recommendations

Prior to the construction of *the subsurface dam* at Tukad Ketes, further technical and hydrogeological investigations are required to ensure the safety, effectiveness, and sustainability of the subsurface water storage system. These additional investigations aim to obtain more detailed field data so that the construction design can be optimized and the risk of failure can be minimized.

Geophysical investigations are conducted to understand subsurface conditions in greater detail, particularly regarding the thickness of alluvial deposits, the depth of bedrock, the distribution of aquifers, and groundwater flow paths. Objectives: Determine the geometry of the alluvial aquifer; identify the depth of the *impermeable* layer*;* determine the thickness of the sand and gravel layers; identify potential fracture zones or leaks; and determine the optimal position of *the cutoff wall for the subsurface dam*. Recommended Method: 2D/3D Electrical Resistivity Survey, as this method is most commonly used for subsurface dams and is sufficiently capable of mapping layers of sand, gravel, clay, bedrock, and water-saturated zones.

Development of a Water Distribution System: In addition to groundwater storage, a distribution system must be planned so that water can be optimally utilized by the community, with the goal of ensuring efficient water delivery, reducing water loss, and supporting domestic and agricultural needs.

Components of the Distribution System include production wells built in the upstream area of the subsurface dam to extract the stored groundwater. *The* storage *reservoir* serves to stabilize distribution, provide temporary storage, and regulate pressure. The distribution pipeline network is designed based on the water needs of the community—including hotels, tourist resorts, and *cafes* that require significant amounts of water—as well as *the landscape* and topography of the area, flow pressure, and distribution distance.

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