# ANALYSIS OF GROUNDWATER UTILIZATION EFFECTIVENESS AS AN IRRIGATION WATER SOURCE TO SUPPORT AGRICULTURAL PRODUCTIVITY

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**Abstract**
Groundwater plays a crucial role in supporting agricultural productivity, particularly in areas with limited access to surface water irrigation systems. This study aims to analyze the effectiveness of groundwater utilization as an irrigation water source by evaluating crop water requirements, irrigation efficiency, pumping performance, water productivity, operating costs, and resource sustainability. The research employed a quantitative descriptive and evaluative approach using hypothetical simulation data for a 2-hectare maize cultivation area over a 110-day growing season. Three irrigation management scenarios were compared, representing baseline conditions (S0), improved management (S1), and optimized management (S2). The simulation results indicated a net irrigation water requirement of 6,400 m³ per growing season. Improving irrigation efficiency from 65% under S0 to 80% under S2 reduced groundwater abstraction from 10,000 m³ to 8,000 m³, representing a potential water withdrawal reduction of 20%. Under the assumed scenarios, maize productivity increased from 5.20 to 5.60 tons/ha, while irrigation water productivity improved from 1.040 to 1.400 kg/m³. Pumping energy consumption decreased from 5,000 to 3,680 kWh, and total operation and maintenance costs declined from IDR 9,000,000 to IDR 7,320,000, representing potential cost savings of 18.67%. These findings suggest that integrated irrigation management could improve water use efficiency and operational performance while maintaining crop water adequacy. However, because the results were derived entirely from hypothetical assumptions, the estimated productivity improvements and groundwater sustainability benefits require validation through field measurements and long-term aquifer monitoring.
**Keywords:** Groundwater Irrigation; Agricultural Productivity; Irrigation Efficiency; Water Productivity; Sustainable Water Management.

## INTRODUCTION

Water is one of the essential natural resources that plays a fundamental role in supporting human life, economic growth, and agricultural productivity. Adequate water availability is a critical factor in ensuring successful crop cultivation, particularly in regions that are highly dependent on irrigation systems. In agricultural activities, water supports plant physiological processes, maintains soil moisture, facilitates nutrient absorption, and sustains optimal growing conditions. Limited water supply may disrupt plant growth, reduce crop yields, and increase the risk of crop failure. The United Nations Educational, Scientific and Cultural Organization (UNESCO, 2024) reported that the agricultural sector accounts for approximately 70% of total global freshwater withdrawals, emphasizing the importance of agricultural water management in maintaining food security and water resource sustainability. These conditions indicate that improving agricultural productivity requires efficient, measurable, and sustainability-oriented irrigation management.

Irrigation systems play a strategic role in supplying water according to crop requirements, particularly during periods when rainfall is insufficient to meet agricultural water demands. Irrigation water sources generally include rivers, reservoirs, lakes, small water storage facilities, and groundwater extracted through wells and pumping systems. The selection of irrigation water sources is influenced by hydrological conditions, land characteristics, crop water requirements, infrastructure availability, and farmers' capacity to manage water distribution. In regions with limited surface irrigation networks, groundwater can serve as an alternative source that plays an important role in maintaining agricultural activities. UNESCO (2022) explained that groundwater is an essential resource for irrigated agriculture and contributes approximately one-quarter of the total water withdrawn for irrigation globally. Therefore, groundwater utilization offers considerable opportunities to improve the reliability of agricultural water supply, particularly in areas experiencing limited surface water availability.

Groundwater has different characteristics from surface water resources because it is stored in underground aquifer formations, and its availability is influenced by geological conditions, infiltration, groundwater recharge, and extraction intensity. Groundwater utilization for irrigation provides flexibility in scheduling water extraction and distribution according to crop requirements. Under certain conditions, irrigation wells enable farmers to obtain water supplies without depending entirely on surface irrigation distribution schedules. UNESCO (2022) reported that approximately 70% of global groundwater withdrawals are used for agricultural activities and that groundwater supplies approximately 38% of the world's land equipped for irrigation. These substantial contributions demonstrate the importance of groundwater in

agricultural production systems. However, increasing groundwater utilization must be accompanied by management practices that maintain a balance among resource availability, crop water requirements, and aquifer capacity to sustain water supplies over the long term.

The primary challenges associated with groundwater utilization for irrigation are not limited to water resource availability but also concern the effectiveness of its use in supporting agricultural productivity. Extracting large quantities of groundwater does not necessarily result in optimal agricultural production when water distribution, irrigation scheduling, and crop requirements are not properly considered. Excessive water application may increase pumping costs, intensify conveyance losses, and place additional pressure on groundwater reserves. Conversely, applying less water than required by crops may lead to soil moisture deficits and reduced plant growth and yields. Lin Lawell (2016) explained that agricultural groundwater management is influenced by irrigation efficiency, policies, institutions, and resource user behavior. The study also indicated that improvements in irrigation technology efficiency do not always lead to reductions in groundwater extraction unless accompanied by comprehensive water use management. Therefore, the effectiveness of groundwater utilization should be evaluated by examining the relationships among water consumption, crop requirements, operating costs, and agricultural yields.

The effectiveness of groundwater utilization as an irrigation source can be assessed using several technical indicators that reflect the system's ability to meet agricultural water demands. These indicators include well discharge capacity, continuity of water supply, conveyance efficiency, compatibility between supplied water volumes and crop requirements, and agricultural productivity relative to the amount of water used. Measuring these indicators is necessary to determine whether groundwater resources can support crop cultivation efficiently and economically. Guo et al. (2023), through a meta-analysis of subsurface irrigation systems, explained that irrigation application methods can influence crop yields, water productivity, and irrigation water productivity. These findings emphasize the importance of considering water distribution and application methods when evaluating irrigation system effectiveness. Accordingly, groundwater utilization assessment should not focus exclusively on the capacity of irrigation wells to supply water but should also examine the extent to which extracted groundwater is productively used by crops.

In addition to technical considerations, the sustainability of groundwater utilization is an important concern because extraction exceeding aquifer recharge capacity may cause groundwater level declines and reductions in available water reserves. Declining groundwater levels can increase pumping energy requirements, raise operating costs, and reduce the reliability of future water supplies. Tracy et al. (2019) explained that excessive groundwater exploitation in several agricultural regions can lead to aquifer depletion, threatening the long-term sustainability of agricultural productivity. Their research emphasized the importance of maintaining a balance between groundwater extraction and recharge through improved irrigation efficiency, water use management, and protection of groundwater recharge areas. These conditions demonstrate that groundwater utilization effectiveness cannot be measured solely by short-term water supply performance but must also consider the resource's capacity to support agricultural needs sustainably.

The sustainability of groundwater utilization is also closely associated with climate change, rainfall variability, and increasing agricultural water requirements. Changes in rainfall patterns may influence surface water availability and groundwater recharge processes, while rising temperatures may increase crop water requirements through evapotranspiration. Under these conditions, groundwater is frequently utilized as a supplementary resource to maintain agricultural production. However, excessive dependence on groundwater pumping may place considerable pressure on aquifer systems if increasing water demands are not accompanied by adequate resource management. Mohan et al. (2022), through a global assessment of groundwater stress and the sustainability of food production, demonstrated that excessive groundwater utilization can increase pressure on aquifers and threaten sustainable agricultural production. Their study also highlighted the importance of improving irrigation efficiency and water productivity to reduce pressure on groundwater resources. Therefore, the development of groundwater-based irrigation systems must simultaneously consider hydrological characteristics and agricultural water demands.

In the context of agricultural development in Indonesia, groundwater utilization can serve as an alternative for supplying irrigation water to agricultural areas that are not connected to technical irrigation networks or that experience water shortages during the dry season. Successful implementation is strongly influenced by aquifer conditions, groundwater table depth, soil characteristics, crop water requirements, and pumping infrastructure availability. Furthermore, energy costs, equipment maintenance capacity, and water distribution arrangements are important considerations in developing groundwater irrigation systems. The implementation of pumping technologies without adequate water demand planning may result in inefficient water and energy consumption. Consequently, groundwater irrigation development requires technical evaluations that integrate water source characteristics, infrastructure capacity, and crop requirements. Such an approach is essential to ensure that groundwater utilization not only expands access to irrigation water but also generates measurable benefits for agricultural productivity and resource efficiency.

Assessing groundwater utilization effectiveness also requires consideration of the economic and operational characteristics of irrigation systems. Pumping systems require energy, labor, equipment maintenance, and operating expenditures that may influence agricultural profitability. High pumping costs may reduce the economic benefits associated with increased crop production, particularly among small-scale farmers with limited financial resources. Haryanto et al. (2018) investigated the utilization of shallow groundwater for rice irrigation using liquefied petroleum gas (LPG)-powered pumps in South Lampung, Indonesia. Their study evaluated the technical and economic performance of pumping systems

based on groundwater depth, discharge capacity, operating duration, fuel consumption, and irrigation costs. Meanwhile, Wahyudi et al. (2019) analyzed the relationship between groundwater irrigation network operation and maintenance costs and agricultural production under alternative pump operating schedules. Both studies highlighted the importance of aligning pumping operations with irrigation requirements and the economic feasibility of agricultural activities.

Previous studies have contributed significantly to the development of groundwater utilization practices for supporting agricultural productivity. Aqil et al. (2002) investigated groundwater irrigation in dryland agricultural systems and demonstrated that crop scheduling and pump operation could influence irrigation water requirements and costs. Haryanto et al. (2018) evaluated shallow groundwater utilization through pumping technologies in rice cultivation, while Wahyudi et al. (2019) examined the optimization of operation and maintenance costs in groundwater irrigation networks. At a broader scale, Mohan et al. (2022) analyzed the pressure associated with groundwater utilization on the sustainability of food production, whereas Guo et al. (2023) investigated the effects of irrigation methods on crop productivity and water use efficiency. Collectively, these studies demonstrated that groundwater management is closely associated with irrigation system technical performance, operating expenditures, agricultural productivity, and water resource sustainability.

Although numerous studies have examined groundwater utilization for irrigation, evaluating its effectiveness still requires an approach that integrates water availability, pumping performance, crop water adequacy, operating costs, and agricultural productivity. Studies focusing separately on pumping efficiency or economic feasibility may not provide a comprehensive understanding of irrigation system effectiveness when they do not consider the relationship between water resource conditions and crop production outcomes. Furthermore, improving agricultural productivity through groundwater extraction requires attention to declining groundwater levels and aquifer sustainability. Therefore, an integrated evaluation framework is needed to connect technical and economic indicators with agricultural production results using data collected from consistent locations and observation periods. This approach is consistent with the perspective of the Food and Agriculture Organization (FAO, 2020), which emphasized the importance of improving water productivity and sustainable water resource management in addressing agricultural water scarcity.

Based on the preceding discussion, the research gap addressed in this study is the need for an integrated evaluation of groundwater utilization effectiveness as an irrigation water source by connecting water supply capacity, crop water requirements, operational efficiency, water productivity, and groundwater resource sustainability. The proposed novelty lies in developing an evaluation framework that combines indicators of well discharge and pumping continuity, water consumption volumes, crop water requirements, operating costs, and agricultural production outcomes within a unified analytical approach. Through this framework, groundwater utilization effectiveness can be assessed not only according to the system's ability to supply water but also based on the productivity benefits generated from resource utilization. The study also aims to identify operating conditions that may cause excessive or suboptimal water consumption, enabling the formulation of more efficient management alternatives. However, the proposed novelty should be further substantiated through detailed comparisons with previous studies and applications of the analytical framework to measurable research objects.

Based on the aforementioned background, this study aims to analyze the effectiveness of groundwater utilization as an irrigation water source in supporting agricultural productivity. The analysis focuses on identifying groundwater availability characteristics, evaluating well discharge capacity and pumping system performance, estimating crop water requirements, and assessing the compatibility between delivered water volumes and irrigation demands. Furthermore, the study aims to evaluate water use efficiency, irrigation system operating costs, and agricultural productivity to determine the extent to which groundwater utilization provides technical and economic benefits. The findings are expected to contribute to the development of more integrated groundwater irrigation evaluation methods and provide a basis for formulating effective, economical, and sustainable water resource management recommendations. Accordingly, this study is expected to support improvements in agricultural productivity while maintaining groundwater availability for long-term agricultural needs.

## RESEARCH METHODOLOGY

### 3.1. Research Design and Approach

This study was designed using a quantitative approach with descriptive and evaluative methods to analyze the effectiveness of groundwater utilization as an irrigation water source in supporting agricultural productivity. The quantitative approach was employed to obtain measurable insights into the relationships among groundwater availability, pumping system capacity, crop water requirements, water distribution efficiency, and agricultural production outcomes. The descriptive method was applied to identify groundwater source conditions, irrigation system characteristics, and water utilization patterns on agricultural land, while the evaluative method was used to assess the adequacy of available water supplies in meeting actual crop requirements. The study also incorporated comparative analysis to examine different irrigation system operating conditions based on technical and economic indicators. This approach aimed to establish an evaluation framework capable of comprehensively assessing groundwater utilization effectiveness while considering agricultural productivity and water resource sustainability.

### 3.2. Research Object and Scope

The research focused on groundwater-based irrigation systems used on agricultural land, where wells and pumping

equipment served as the primary sources of irrigation water. The scope of the study included groundwater source characteristics, well discharge capacity and continuity, pump operating conditions, crop water requirements, irrigation water distribution, and the relationship between groundwater utilization and agricultural productivity. Observations were designed to be conducted on agricultural land where groundwater was used as either the primary or supplementary irrigation source during the cultivation period. The units of analysis included well systems, distribution networks, agricultural plots, and cultivated crop types. Site characteristics considered in the evaluation included agricultural land area, soil type, groundwater table depth, topographical conditions, cropping patterns, and the availability of alternative water sources. The study was limited to evaluating the effectiveness of groundwater utilization for irrigation purposes and did not include detailed engineering design for new well construction. This limitation allowed the analysis to focus on the relationships among water supply performance, resource utilization, and agricultural production outcomes.

### 3.3. Types and Sources of Data

The research data consisted of primary and secondary data related to groundwater source characteristics, irrigation requirements, and agricultural production activities. Primary data were planned to be collected through measurements of well discharge, observations of groundwater table depth, records of pump operating duration, measurements of delivered irrigation water volumes, and assessments of irrigation distribution network conditions. Primary data also included information on irrigated land area, irrigation schedules, crop types, crop growth stages, and harvest yields during the observation period. Secondary data were obtained from climatological information, rainfall records, air temperature, relative humidity, wind speed, solar radiation, soil characteristics, agricultural documents, and technical references concerning crop water requirements and irrigation management. Operating cost information was collected from records of energy consumption, fuel utilization, pump maintenance, and labor requirements. All data were categorized according to consistent observation periods and analytical units to support the evaluation of relationships between groundwater utilization and agricultural productivity.

### 3.4. Data Collection Techniques

Data collection was designed to involve field observations, hydrological measurements, irrigation system operational records, documentation of agricultural activities, and structured interviews with users or managers of pumping systems. Discharge measurements were conducted at pump outlets or distribution channels using appropriate flow measurement instruments, while groundwater table depth was observed through measurements at the wells selected for investigation. Groundwater levels were recorded before and during pumping operations and, where observation conditions permitted, during the recovery period after pumping ceased. Pump operating times were recorded based on the duration of each irrigation activity to determine the total pumping period throughout the cultivation season. The volume of water utilized was determined from measured discharge rates and operating durations, while accounting for possible discharge variations during pumping. Agricultural data collection included recording cultivated land area, crop types, planting dates, irrigation schedules, and the quantities of agricultural products harvested at the end of the growing season. Additionally, documentation and interviews were used to obtain information regarding operational challenges, changes in water availability, and irrigation management practices adopted by farmers.

### 3.5. Analysis of Groundwater Availability and Potential

Groundwater availability was analyzed by evaluating the capacity of groundwater sources to provide the discharge required to meet irrigation demands throughout the observation period. The primary parameters included pumping discharge, groundwater table depth, groundwater level drawdown during pumping, and water level recovery after groundwater extraction ceased. Discharge measurements were used to characterize water supply capacity, while groundwater level changes provided preliminary indicators of aquifer responses to pumping activities. Periodic observations were conducted to identify variations in groundwater source conditions associated with pumping duration and hydrological conditions. Where sufficient hydrogeological information and pumping test data were available, the analysis could be extended to estimate aquifer characteristics and sustainable water supply potential. However, well discharge measured during a single observation period was not automatically considered equivalent to the long-term sustainable groundwater abstraction capacity. Therefore, groundwater availability assessments considered data limitations, recharge conditions, groundwater level fluctuations, and water supply continuity during irrigation operations.

### 3.6. Analysis of Crop Irrigation Water Requirements

Crop irrigation water requirements were analyzed by estimating the amount of water needed throughout the growing season based on climatic conditions, crop characteristics, and water availability within the agricultural soil. Crop water requirements were determined using a crop evapotranspiration approach that considered reference evapotranspiration and crop coefficients corresponding to different growth stages. Reference evapotranspiration could be estimated using the FAO Penman–Monteith method when adequate climatological data were available, while crop coefficients were adjusted according to crop type and developmental stage. In addition to evapotranspiration requirements, the analysis considered effective rainfall contributions, changes in root-zone soil water storage, and other requirements relevant to the cultivation system. Net irrigation requirements were determined based on the water deficit that needed to be supplied through irrigation.

These requirements were subsequently used to estimate the volume of groundwater that needed to be delivered, taking into account water losses during conveyance and application. The analytical results were used to evaluate water supply adequacy and identify potential over-irrigation or insufficient irrigation during the cultivation period.

### 3.7. Analysis of Pumping System Performance and Water Distribution

Pumping system performance was evaluated to determine the ability of pumping equipment to supply water according to the irrigation requirements of agricultural land. The assessed parameters included pump discharge capacity, operating duration, total pumped water volume, energy or fuel consumption, and flow continuity during irrigation activities. The evaluation also considered pump technical conditions, groundwater extraction depth, distribution network length, and the characteristics of irrigation channels or pipelines. Water distribution performance was assessed by comparing the volume of water discharged from the pumping system with the volume reaching agricultural fields or designated irrigation application points. Differences between these quantities were used to identify potential water losses during conveyance. Furthermore, distribution uniformity could be evaluated when measurements were available from multiple locations across agricultural plots. The results were used to determine whether pumping operations were appropriately aligned with irrigation requirements and whether improvements to the distribution system could reduce water losses and unnecessary energy consumption.

### 3.8. Analysis of Groundwater Utilization Effectiveness

Groundwater utilization effectiveness was evaluated based on the relationship among available water supply, crop irrigation requirements, the amount of water used, and the ability of the system to distribute water to agricultural fields. The evaluation involved comparing delivered irrigation water volumes with estimated irrigation requirements over corresponding observation periods. Water supply adequacy was assessed to determine whether the irrigation system could satisfy crop requirements without generating unnecessary excess water application. Additionally, irrigation conveyance and application efficiencies were considered to establish the proportion of water effectively utilized in agricultural fields. The analysis accounted for rainfall conditions, crop growth stages, soil characteristics, and pump operating patterns. The evaluation results were subsequently used to identify relatively efficient operating conditions, suboptimal utilization patterns, and situations requiring adjustments to irrigation schedules. Groundwater utilization effectiveness was not assessed solely based on the magnitude of available discharge or water volume but also on the ability of the irrigation system to supply water according to crop demands while maintaining controlled resource consumption.

### 3.9. Analysis of Agricultural Productivity and Water Productivity

Agricultural productivity was analyzed to evaluate the relationship between groundwater utilization and crop production outcomes on the agricultural land included in the study. Land productivity was assessed based on harvested crop quantities per unit of cultivated area, while water productivity was evaluated by comparing agricultural production with the amount of water used during a single growing season. Crop yields were measured using consistent mass units appropriate to the agricultural commodities investigated. Water productivity could be assessed based on either the volume of irrigation water applied or total crop water consumption, with the selected indicator explicitly specified to avoid inconsistencies in interpretation. Comparisons were conducted among operating conditions characterized by comparable crop types, growing seasons, and cultivated land areas. The analysis also acknowledged that agricultural yields are influenced by soil fertility, fertilizer application, seed quality, pest management, and weather conditions. Consequently, the relationship between irrigation water volume and agricultural productivity was interpreted cautiously to avoid attributing changes in crop yields exclusively to groundwater utilization.

### 3.10. Economic Efficiency Analysis of Groundwater Utilization

Economic efficiency was analyzed to evaluate the costs associated with groundwater supply and the benefits of water utilization for agricultural production. The cost components included electricity or fuel consumption, pump maintenance, equipment component replacement, labor, and other operating expenses directly related to groundwater irrigation. Total irrigation costs were estimated based on resource consumption throughout a single cultivation period and subsequently compared with cultivated land area, pumped water volume, and agricultural production outcomes. The analysis also considered the cost of water supply per unit volume to assess pumping system operating efficiency. Where crop selling prices and other agricultural production costs were available, the evaluation could be extended to determine the contribution of irrigation costs to farm revenue and profitability. Comparisons among different pumping schedules were conducted to identify alternatives capable of reducing operating expenses without creating irrigation water shortages. Thus, groundwater utilization effectiveness was evaluated by considering the balance among crop water requirements, energy consumption, operating costs, and agricultural productivity benefits.

### 3.11. Evaluation of Groundwater Utilization Sustainability

Groundwater utilization sustainability was evaluated by considering the capacity of groundwater sources to support irrigation requirements throughout the utilization period without causing uncontrolled extraction pressure. The primary parameters included groundwater level changes, pumping discharge continuity, well operating duration, and potential

variations in groundwater source conditions between wet and dry periods. Observational data were used to identify indications of groundwater level decline that could affect pumping energy requirements and water supply reliability. The evaluation also considered groundwater recharge conditions, aquifer characteristics, and potential groundwater utilization by other sectors surrounding the study location. Observations conducted during a single growing season were treated as a preliminary assessment, whereas conclusions regarding long-term groundwater abstraction sustainability would require hydrological and hydrogeological data collected over longer periods. The evaluation results were intended to support recommendations for controlling pumping duration, adjusting irrigation schedules, regulating groundwater abstraction volumes, and conducting periodic groundwater level monitoring. This approach aimed to maintain a balance between agricultural production requirements and groundwater resource protection.

### 3.12. Data Processing and Interpretation Techniques

Data obtained from measurements and field observations were processed using descriptive and comparative statistical analysis techniques. Initial data processing involved examining data completeness, verifying measurement unit consistency, and categorizing observations according to monitoring periods, water sources, agricultural plots, and crop types. Discharge measurements, pumping duration records, and water volume data were used to characterize water supply performance, while climatological and crop information was employed to estimate irrigation requirements. The analytical results were subsequently compared to evaluate water supply adequacy, distribution performance, energy consumption, and operating costs. Agricultural productivity data were analyzed based on crop yields per unit of cultivated area and agricultural production relative to the volume of water utilized. Comparisons among operating conditions considered consistency in observation periods, crop types, and land characteristics. Where the quantity and quality of available data were sufficient, the analysis could be extended using correlation or regression techniques to investigate relationships between groundwater utilization indicators and agricultural productivity while accounting for statistical assumptions and potential confounding factors. The processed results were presented through tables, graphs, and comparative descriptions to facilitate interpretation. Research conclusions were formulated by integrating technical, economic, productivity, and sustainability indicators to ensure that groundwater irrigation management recommendations were supported by measurable and scientifically defensible evaluations.

## RESULTS AND DISCUSSION

### 4.1. Characteristics of Agricultural Land and Groundwater Sources

The research object in this simulation was an agricultural area covering 2 hectares that utilized groundwater extracted from a drilled well as its primary irrigation water source. Maize was selected as the agricultural commodity in the simulation model, with a cultivation period of 110 days. The selection of maize was intended to provide an example of crop water requirement evaluation throughout a growing season using crop evapotranspiration and effective rainfall approaches. The irrigation system employed an electrically powered pump connected to a distribution network supplying water to agricultural plots. These characteristics provided the basis for examining the relationships among water supply capacity, irrigation water application, and crop productivity.

**Table 1.** Characteristics of the research object in the simulation model

| Parameter | Assumed Value |
|---|---|
| Agricultural commodity | Maize |
| Agricultural land area | 2.00 ha |
| Cultivation period | 110 days |
| Water source | Groundwater drilled well |
| Well depth | 30 m |
| Initial static groundwater depth | 7.0 m |
| Reference pump discharge | 10 $m^3$/hour |
| Pump power system | Electricity |
| Water distribution system | Pipelines and field distribution |
| Primary irrigation source | Groundwater |

Source: Research simulation assumptions, 2026.

Based on the characteristics presented in Table 1, groundwater availability was evaluated through operational pump discharge and groundwater level changes under different extraction conditions. The assumed pump discharge of 10 $m^3$/hour represented the water supply capacity under a particular operating condition; however, this value alone could not establish the ability of the aquifer to provide water sustainably. Determining a safe groundwater abstraction capacity requires well testing, groundwater level monitoring, hydrogeological information, and data concerning groundwater recharge and surrounding groundwater utilization.

Groundwater plays an important role in irrigation water supply, particularly in regions experiencing limited surface water availability. UNESCO (2022) reported that agriculture is the primary user of groundwater worldwide and that excessive extraction may threaten groundwater sustainability, food production, and groundwater-dependent ecosystems.

Consequently, irrigation well management must consider agricultural water requirements alongside groundwater source responses to pumping activities.

### 4.2. Analysis of Crop Irrigation Water Requirements

Crop irrigation water requirements were analyzed by considering crop evapotranspiration and the contribution of effective rainfall throughout the cultivation period. In the simulation model, maize crop evapotranspiration was assumed to be 430 mm over 110 days, while effective rainfall available for crop utilization was estimated at 110 mm. By excluding changes in root-zone soil water storage and capillary contributions from groundwater, the net irrigation requirement was determined from the difference between crop evapotranspiration demand and effective rainfall.

This approach followed the irrigation water requirement assessment principles described by the Food and Agriculture Organization (FAO), which indicate that crop water requirements not satisfied by effective rainfall must be supplied through irrigation. In actual field investigations, crop evapotranspiration should be calculated using appropriate climatic data and crop coefficients corresponding to the different stages of crop development.

**Table 2.** Simulated maize irrigation water requirements during one growing season

| Component | Value |
|---|---|
| Agricultural land area | 20,000 m² |
| Crop evapotranspiration | 430 mm |
| Effective rainfall | 110 mm |
| Net irrigation requirement | 320 mm |
| Net irrigation water volume | 6,400 m³ |
| Average daily net irrigation requirement | 58.18 m³/day |

Source: Calculations based on simulation assumptions, 2026.

The results indicated that the net irrigation water requirement during one growing season was approximately 6,400 m³. This value represented the amount of water required by the crops after accounting for effective rainfall. However, the volume of groundwater that needed to be extracted from the well could be greater because water losses might occur during conveyance and irrigation application.

These findings emphasized the importance of distinguishing between the volume of water extracted from groundwater sources and the volume effectively available within the crop root zone. Extracting greater quantities of groundwater does not necessarily indicate better irrigation performance when part of the water is lost during distribution or applied beyond crop requirements.

### 4.3. Evaluation of Pumping System Performance and Water Distribution

Pumping system performance was evaluated by comparing three operational scenarios representing improvements in irrigation efficiency and pumping schedules. The first scenario (S0) represented the baseline condition with an overall conveyance and application efficiency of 65%. The second scenario (S1) represented improved irrigation management, increasing efficiency to 76%, while the third scenario (S2) represented a more optimized operating condition with an assumed efficiency of 80%. These efficiency levels were hypothetical assumptions developed for comparative analysis and were not derived from actual irrigation system testing.

**Table 3.** Comparison of groundwater irrigation system operating performance

| Parameter | S0 | S1 | S2 |
|---|---|---|---|
| Pump discharge (m³/hour) | 10 | 10 | 10 |
| Total pumping duration (hours/season) | 1,000 | 850 | 800 |
| Pumped water volume (m³) | 10,000 | 8,500 | 8,000 |
| Conveyance and application efficiency | 65% | 76% | 80% |
| Effective water reaching the root zone (m³) | 6,500 | 6,460 | 6,400 |
| Net irrigation requirement (m³) | 6,400 | 6,400 | 6,400 |
| Water adequacy ratio | 1.016 | 1.009 | 1.000 |

Source: Hypothetical scenario calculations, 2026. The water adequacy ratio represents the effective water volume divided by the net irrigation requirement.

The simulation results indicated that the baseline scenario (S0) required groundwater extraction of 10,000 m³ to

deliver 6,500 m³ of effective water to the crop root zone. After implementing improved management practices under Scenario S1, the pumped volume decreased to 8,500 m³, while the effective irrigation water supply remained above the net irrigation requirement. Under Scenario S2, groundwater extraction was further reduced to 8,000 m³, producing an effective water volume of 6,400 m³, equivalent to the assumed net irrigation requirement.

Compared with Scenario S0, Scenario S1 resulted in a 15% reduction in groundwater abstraction, while Scenario S2 achieved a 20% reduction. These changes illustrated the potential for reducing groundwater pumping through improved water distribution and pumping schedule management. However, reductions in pumped water volumes do not necessarily correspond directly to groundwater savings at the aquifer scale because some irrigation losses may return to groundwater recharge or contribute to recoverable water flows. Therefore, evaluating broader hydrological benefits requires a comprehensive assessment of the local water balance.

### 4.4. Analysis of Groundwater Utilization Effectiveness

Groundwater utilization effectiveness was analyzed based on the relationship between extracted water volumes, crop irrigation requirements, and the ability of the distribution system to deliver water effectively to agricultural land. Under the baseline condition (S0), the pumped water volume provided a slightly greater effective water supply than the net irrigation requirement. Nevertheless, the conveyance and application efficiency of 65% indicated that a substantial proportion of the extracted water did not become effective irrigation water within the crop root zone.

Improvements in irrigation efficiency under Scenarios S1 and S2 provided opportunities to reduce groundwater extraction without compromising the assumed adequacy of crop water supply. Adjustments to irrigation schedules, discharge control, distribution network inspections, and improved irrigation application methods were identified as potential measures for achieving these conditions. Irrigation effectiveness was also influenced by the timing of water application because crop water requirements vary according to growth stages and climatic conditions.

**Table 4.** Indicators of groundwater utilization effectiveness

| Indicator | S0 | S1 | S2 |
|---|---|---|---|
| Irrigation efficiency | 65% | 76% | 80% |
| Groundwater abstraction (m³) | 10,000 | 8,500 | 8,000 |
| Reduction in abstraction relative to S0 | 0% | 15% | 20% |
| Effective irrigation water volume (m³) | 6,500 | 6,460 | 6,400 |
| Irrigation water adequacy | 101.56% | 100.94% | 100.00% |
| Average pumping duration (hours/day) | 9.09 | 7.73 | 7.27 |

Source: Hypothetical scenario calculation results, 2026.

The results presented in Table 4 indicated that Scenario S2 achieved the lowest groundwater abstraction volume and the highest irrigation efficiency. These findings suggested that improving groundwater utilization effectiveness does not necessarily require increasing water supply capacity. Under certain conditions, improvements in distribution systems and irrigation scheduling may provide a more efficient alternative than increasing groundwater extraction rates.

However, the 100% irrigation water adequacy achieved under Scenario S2 only represented the fulfillment of total seasonal water requirements within the simulation model. This condition did not guarantee that crops would consistently receive sufficient water during every growth stage. Therefore, actual irrigation performance evaluations must incorporate crop water requirement calculations for individual growth stages, soil moisture monitoring, and assessments of water supply adequacy during peak demand periods.

### 4.5. Analysis of Agricultural Productivity and Water Productivity

Agricultural productivity was analyzed based on maize production during a single growing season, while irrigation water productivity was evaluated by comparing harvested yields with the volume of groundwater extracted. In this simulation, crop yields were assumed to increase progressively as a result of improved water distribution accuracy and irrigation management. However, the assumed yield values were established as hypothetical scenario parameters rather than outputs from crop growth models or empirical evidence demonstrating that irrigation improvements directly increased agricultural production.

**Table 5.** Simulation of maize productivity and irrigation water productivity

| Parameter | S0 | S1 | S2 |
|---|---|---|---|
| Agricultural land area (ha) | 2.00 | 2.00 | 2.00 |
| Total crop yield (tons) | 10.40 | 11.00 | 11.20 |
| Land productivity | 5.20 | 5.50 | 5.60 |

| | | | |
|---|---|---|---|
| (tons/ha) | | | |
| Pumped water volume ($m^3$) | 10,000 | 8,500 | 8,000 |
| Irrigation water productivity ($kg/m^3$) | 1.040 | 1.294 | 1.400 |
| Change in crop yield relative to S0 | 0% | +5.77% | +7.69% |

Source: Hypothetical simulation data, 2026. Water productivity was calculated using the volume of groundwater extracted rather than actual crop evapotranspiration.

The results indicated that agricultural land productivity increased from 5.20 tons/ha under Scenario S0 to 5.50 tons/ha under Scenario S1 and 5.60 tons/ha under Scenario S2. Simultaneously, the volume of groundwater extracted decreased across the scenarios. Consequently, irrigation water productivity increased from 1.040 $kg/m^3$ under the baseline condition to 1.400 $kg/m^3$ under Scenario S2, representing an improvement of approximately 34.62%.

These illustrative findings demonstrated that irrigation water productivity could potentially be improved through a combination of reducing ineffective water use and increasing agricultural production. FAO distinguishes water productivity indicators according to the boundaries of water consumption, including irrigation water withdrawals and water actually consumed through evapotranspiration. Therefore, the water productivity indicator expressed in $kg/m^3$ in this study specifically referred to irrigation water productivity based on the volume of groundwater extracted.

From an agronomic perspective, changes in crop yields cannot be explained solely by variations in irrigation water volumes. Seed quality, fertilizer application, soil physical and chemical properties, pest and disease pressure, and climatic variability also influence crop growth and agricultural production. Accordingly, validating the relationship between irrigation effectiveness and crop productivity requires measurable agricultural data and analytical approaches that adequately account for these influencing factors.

### 4.6. Analysis of Energy Efficiency and Pumping Operating Costs

Groundwater pumping requires energy, with consumption influenced by the volume of water pumped, total dynamic head, pump efficiency, and distribution network characteristics. In the simulation model, specific energy consumption was assumed to be 0.50 $kWh/m^3$ under Scenario S0, 0.48 $kWh/m^3$ under Scenario S1, and 0.46 $kWh/m^3$ under Scenario S2. The reduction in specific energy consumption represented an additional assumption concerning improvements in pumping system efficiency rather than an automatic consequence of shorter pumping durations.

Electricity costs were calculated using an assumed tariff of IDR 1,500/kWh across all scenarios. Maintenance costs varied according to the assumed equipment servicing and maintenance requirements associated with each operational condition.

**Table 6.** Simulated groundwater pumping energy consumption and operating costs

| Parameter | S0 | S1 | S2 |
|---|---|---|---|
| Pumped water volume ($m^3$) | 10,000 | 8,500 | 8,000 |
| Specific energy consumption ($kWh/m^3$) | 0.50 | 0.48 | 0.46 |
| Electricity consumption (kWh) | 5,000 | 4,080 | 3,680 |
| Electricity cost (IDR million) | 7.50 | 6.12 | 5.52 |
| Maintenance cost (IDR million) | 1.50 | 1.60 | 1.80 |
| Total operating cost (IDR million) | 9.00 | 7.72 | 7.32 |
| Operating cost per $m^3$ pumped (IDR) | 900.00 | 908.24 | 915.00 |
| Total cost savings relative to S0 | 0% | 14.22% | 18.67% |

Source: Hypothetical simulation calculations, 2026. Electricity tariffs and maintenance costs do not represent actual project prices.

The simulation results indicated that total operation and maintenance costs under Scenario S0 amounted to IDR 9,000,000 per growing season. These costs decreased to IDR 7,720,000 under Scenario S1 and IDR 7,320,000 under Scenario S2. Consequently, implementing Scenario S2 resulted in an estimated saving of IDR 1,680,000, equivalent to approximately 18.67% compared with the baseline condition.

Although Scenario S2 exhibited the lowest total operating cost, its average cost per cubic meter of pumped water was slightly higher than that of Scenario S0. This occurred because maintenance costs were assumed to increase while the volume of extracted groundwater decreased. These findings emphasized the importance of distinguishing between total operating cost efficiency and unit cost efficiency. Reductions in total expenditure may occur because less water is pumped, even when certain cost components increase.

Furthermore, improvements in pumping system efficiency may reduce electricity demand, but the economic feasibility of equipment upgrades cannot be established solely from operating costs. A more comprehensive economic evaluation would require information regarding initial investment costs, equipment service life, component replacement requirements, and the economic benefits associated with agricultural production.

### 4.7. Evaluation of Groundwater Level Responses to Pumping

Groundwater level responses were evaluated to illustrate changes in groundwater depth during pump operation. In this simulation, the initial static groundwater level was assumed to be 7.0 meters below ground surface. During pumping operations, groundwater levels declined by different amounts according to the assumed operational scenarios. It is important to emphasize that the relationships between pumping duration and groundwater drawdown were established as hypothetical scenario assumptions rather than derived from actual aquifer pumping tests.

**Table 7.** Simulated groundwater level responses during pumping

| Parameter | S0 | S1 | S2 |
|---|---|---|---|
| Initial static groundwater depth (m) | 7.0 | 7.0 | 7.0 |
| Illustrative dynamic groundwater depth (m) | 8.2 | 8.0 | 7.8 |
| Groundwater drawdown (m) | 1.2 | 1.0 | 0.8 |
| Pumping duration (hours/season) | 1,000 | 850 | 800 |

Source: Assumed well responses in hypothetical simulation scenarios, 2026. Groundwater depths were measured from ground surface to the water level.

The results presented in Table 7 showed that Scenario S0 represented groundwater drawdown of 1.2 meters, whereas Scenarios S1 and S2 exhibited assumed drawdowns of 1.0 meter and 0.8 meter, respectively. These differences illustrated the possibility that changes in groundwater extraction patterns could influence groundwater level responses. However, drawdown under the same pumping discharge is also influenced by continuous pumping duration, aquifer hydraulic properties, well construction characteristics, and groundwater recovery periods.

UNESCO (2022) emphasized that intensive groundwater extraction over extended periods may cause aquifer depletion and threaten long-term water supply sustainability. Therefore, the reductions in pumped groundwater volume shown in this simulation should be interpreted as potentially reducing abstraction pressure rather than proving that groundwater utilization satisfies sustainable withdrawal limits.

Assessing the long-term sustainability of groundwater utilization in actual research requires groundwater level monitoring over multiple seasons, pumping and recovery test results, groundwater recharge information, and observations of the influence of nearby wells. These assessments are necessary to ensure that recommendations concerning pumping operations consider not only crop irrigation requirements but also the capacity of the aquifer system to provide water sustainably.

### 4.8. Integrated Analysis of Groundwater Irrigation Effectiveness and Agricultural Productivity

An integrated evaluation was conducted by comparing technical, productivity, and economic indicators across the three groundwater utilization scenarios. This comparison aimed to identify operational conditions that provided an appropriate balance among irrigation water adequacy, water use efficiency, reduced energy consumption, and agricultural production.

**Table 8.** Summary of groundwater utilization effectiveness

| Indicator | S0 | S1 | S2 |
|---|---|---|---|
| Groundwater abstraction volume ($m^3$) | 10,000 | 8,500 | 8,000 |
| Irrigation efficiency | 65% | 76% | 80% |
| Crop water requirement adequacy | 101.56% | 100.94% | 100.00% |
| Agricultural land productivity (tons/ha) | 5.20 | 5.50 | 5.60 |

| | | | |
|---|---|---|---|
| Irrigation water productivity (kg/m³) | 1.040 | 1.294 | 1.400 |
| Pumping energy consumption (kWh) | 5,000 | 4,080 | 3,680 |
| Operating costs (IDR million) | 9.00 | 7.72 | 7.32 |

Source: Summary of hypothetical simulation data, 2026.

The results presented in Table 8 indicated that Scenario S2 represented the operational condition with the lowest groundwater abstraction volume, the highest irrigation efficiency, and the lowest operating costs. Under this scenario, the net irrigation water requirement was fully satisfied within the simulation model, while irrigation water productivity reached 1.400 kg/m³. Compared with the baseline condition (S0), groundwater consumption decreased by 20%, while operating costs were reduced by approximately 18.67%.

In terms of agricultural productivity, Scenario S2 was also assumed to produce a higher maize yield than the other two scenarios. However, this result cannot be interpreted as empirical evidence that improvements in irrigation efficiency directly increased agricultural production because crop yield values were predetermined as part of the hypothetical simulation. Testing this relationship would require actual crop yield data collected under different irrigation conditions while accounting for other relevant agronomic variables.

Conceptually, these findings demonstrated the benefits of using integrated indicators to evaluate groundwater irrigation performance. The selection of irrigation operating conditions should not be based solely on the ability of a pumping system to provide high discharge rates but should also consider crop water requirements, irrigation water productivity, pumping costs, and groundwater resource sustainability.

### 4.9. Strategies for Improving Groundwater Utilization Effectiveness

Based on the hypothetical simulation results, improvements in groundwater utilization effectiveness could be achieved through irrigation scheduling based on actual crop water requirements. Operating pumping systems according to the water requirements of individual crop growth stages has the potential to reduce unnecessary irrigation applications. Irrigation managers may utilize effective rainfall data, crop evapotranspiration estimates, and soil moisture conditions to determine appropriate irrigation timing and duration.

Improving water distribution systems represents another potential strategy for increasing the proportion of extracted groundwater that can be effectively utilized by crops. Such improvements may include inspecting pipeline leakage, repairing connections, regulating water flow, and maintaining distribution networks. Where agricultural land conditions permit, irrigation methods that provide more controlled water application may be considered based on soil characteristics, crop types, farmers' operational capacity, and implementation costs.

From an energy management perspective, pumping operations should be adjusted according to equipment capacity and system characteristics to ensure efficient energy utilization. Regular pump maintenance, motor performance inspections, and the reduction of pressure losses within distribution networks could contribute to improved operating efficiency. The adoption of energy-efficient pumping technologies should also be accompanied by evaluations of investment costs and potential economic benefits throughout the equipment service life.

Regarding sustainability, groundwater utilization requires periodic monitoring of well discharge and groundwater levels. Measurements conducted before and after pumping, along with records of groundwater level variations across observation periods, can provide preliminary indications of changing groundwater conditions. If continuous groundwater level declines are observed, pumping strategies should be reassessed by considering hydrogeological investigation results and the potential availability of alternative irrigation water sources.

### 4.10. Research Limitations and Implications for Further Development

This study has several limitations because all numerical data were developed using hypothetical simulations. Well characteristics, discharge capacity, groundwater levels, irrigation water requirements, electricity consumption, and agricultural production values were not obtained through direct field measurements. Therefore, the reported numerical results cannot be used to characterize the actual performance of groundwater irrigation systems at specific locations.

Furthermore, changes in crop productivity were not derived from crop growth models or field experiments that accounted for climatic conditions, soil characteristics, fertilizer application, and agricultural management practices. The groundwater sustainability evaluation was also limited to illustrative groundwater level responses without a comprehensive aquifer water balance assessment. Meanwhile, the economic analysis did not include well construction investment costs, equipment depreciation, or major component replacement expenses.

Future research should incorporate actual measurements of well discharge, groundwater levels, irrigation water volumes, energy consumption, and agricultural production over multiple growing seasons. These data could be used to evaluate the relationships between irrigation efficiency and agricultural productivity more accurately. Consequently, the resulting recommendations could be supported by stronger technical, economic, and environmental evidence to promote sustainable groundwater resource management.

## CONCLUSIONS

Based on the analysis of the effectiveness of groundwater utilization as an irrigation water source in supporting agricultural productivity, it can be concluded that groundwater management that considers crop water requirements, distribution efficiency, pumping performance, and operating costs has the potential to improve water resource utilization efficiency. The hypothetical simulation results for a 2-hectare maize cultivation area with a growing period of 110 days indicated that the net irrigation water requirement reached 6,400 m³ per growing season. A comparison of three management scenarios demonstrated that increasing irrigation efficiency from 65% under the baseline condition (S0) to 80% under the optimized management scenario (S2) could reduce groundwater abstraction from 10,000 m³ to 8,000 m³. This represented a potential 20% reduction in groundwater extraction while maintaining the fulfillment of net crop irrigation requirements under the model assumptions. These findings suggested that improving water distribution efficiency and optimizing pumping schedules could provide a more effective management approach than increasing groundwater extraction capacity without considering actual crop water requirements.

Regarding agricultural productivity, the simulation indicated an increase in maize yield from 5.20 tons/ha under the baseline condition to 5.60 tons/ha under Scenario S2, representing an improvement of 7.69%. Consistent with this change, irrigation water productivity increased from 1.040 kg/m³ to 1.400 kg/m³, equivalent to an improvement of 34.62%. From an economic perspective, implementing Scenario S2 reduced pumping energy consumption from 5,000 kWh to 3,680 kWh per growing season, while total operation and maintenance costs decreased from IDR 9,000,000 to IDR 7,320,000. This reduction represented potential cost savings of 18.67% compared with the baseline condition. These simulation results illustrated that improvements in irrigation system efficiency could simultaneously generate technical and economic benefits. However, the increased agricultural yields in these scenarios were based on hypothetical assumptions and cannot be interpreted as direct consequences of improved irrigation efficiency without field investigations accounting for soil characteristics, climatic conditions, fertilization practices, and cultivation techniques.

Overall, this study demonstrated that the effectiveness of groundwater utilization for irrigation should be evaluated through an integrated approach incorporating water availability, crop water requirements, water productivity, energy efficiency, operating costs, and resource sustainability. Strategies for improving groundwater utilization effectiveness could include adjusting pumping schedules according to crop growth stages, improving water distribution networks, minimizing water losses, and periodically monitoring well discharge and groundwater levels. Reducing groundwater abstraction volumes may potentially alleviate extraction pressure on groundwater resources; however, such reductions cannot be considered evidence of aquifer sustainability without comprehensive assessments of hydrogeological conditions, groundwater recharge, and long-term groundwater level fluctuations. Therefore, the simulation results may serve as a preliminary framework for evaluating groundwater irrigation systems, while the practical implementation of the proposed recommendations requires verification through field measurements, observations of crop productivity, and assessments of aquifer conditions over multiple growing seasons. Through this integrated approach, groundwater utilization is expected to support improvements in agricultural productivity while promoting efficient, economically viable, and sustainable water resource management.

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