Nusantara Hasana Journal
Volume 5 No. 5 (Oktober 2025), Page: 154-163
E-ISSN: 2798-1428

A SCENARIO-BASED HYDROLOGICAL SIMULATION FRAMEWORK FOR CLIMATE-RESILIENT IRRIGATION WATER ALLOCATION IN TROPICAL WATERSHEDS

Abd Rakhim Nanda

Universitas Muhammadiyah Makassar, Indonesia

***Email: abd.rakhimnanda@unismuh.ac.id**

Abstract
Rainfall variability and climate uncertainty increasingly affect irrigation water availability in tropical watersheds. This study develops a scenario-based hydrological simulation framework for climate-resilient irrigation water allocation. The framework integrates rainfall scenario development, runoff estimation, evapotranspiration-based crop water requirement, water availability assessment, and monthly water balance analysis. Five rainfall scenarios were simulated, consisting of normal rainfall, moderate rainfall deficit, severe drought, extreme drought, and extreme rainfall conditions. The results show that reduced rainfall substantially decreases water availability and increases irrigation deficit during the dry season. Irrigation reliability declined from 75% under normal conditions to 60%, 42%, and 25% under moderate, severe, and extreme drought scenarios, respectively. In contrast, the extreme rainfall scenario increased reliability to 85%, although it may intensify runoff and flood risk. The proposed framework supports adaptive irrigation scheduling, crop calendar adjustment, storage optimization, and climate-resilient water allocation planning.
Keywords: *hydrological, irrigation allocation; rainfall variability, climate resilience, tropical watershed*

INTRODUCTION

Water availability for irrigation is one of the most critical factors affecting agricultural productivity, food security, and rural livelihoods in tropical watershed regions (Baral et al., 2024). In many tropical agricultural systems, irrigation water supply depends heavily on seasonal rainfall, river discharge, small reservoirs, and watershed runoff. However, increasing rainfall variability and climate uncertainty have made irrigation planning more complex. Changes in rainfall intensity, duration, frequency, and seasonal distribution may cause water shortages during the dry season and excessive runoff or flooding during the wet season (Meaza et al., 2022). Climate change has intensified concerns over the global and regional water cycle. The IPCC reports that climate change affects the hydrological cycle, including precipitation patterns, runoff processes, soil moisture, and the frequency of hydrological extremes (Douville et al., 2022). These changes increase the need for adaptive and climate-resilient water management approaches, particularly in regions where agriculture is highly dependent on rainfall and surface water systems.

In tropical watersheds, irrigation water allocation is often challenged by three main problems (Kavand et al., 2023). First, rainfall is not evenly distributed throughout the year, creating periods of water surplus and deficit. Second, conventional irrigation allocation practices often rely on historical water availability and fixed cropping schedules, which may not be suitable under uncertain climate conditions. Third, limited integration among hydrological

Nusantara Hasana Journal
Volume 5 No. 5 (Oktober 2025), Page: 154-163
E-ISSN: 2798-1428

simulation, crop water requirement analysis, and adaptive allocation strategies reduces irrigation systems' ability to respond to drought or extreme rainfall events. Hydrological simulation provides a useful approach for evaluating how rainfall variability affects runoff, streamflow, water availability, and irrigation demand (Kavand et al., 2023). When combined with scenario-based analysis, hydrological simulation can help identify critical months, estimate irrigation deficits, and design adaptive water allocation strategies. Therefore, a simulation-based framework is needed to support climate-resilient irrigation planning in tropical watersheds.

The novelty of this study lies in the integration of rainfall scenario simulation, runoff estimation, evapotranspiration-based irrigation demand, and water balance analysis into a single climate-resilient irrigation allocation framework. Unlike conventional hydrological studies that mainly focus on rainfall–runoff relationships, this study links watershed hydrological response directly with irrigation water allocation decisions. The objectives of this study are: (i) to develop a scenario-based hydrological simulation framework for irrigation water allocation; (ii) to estimate runoff and water availability under different rainfall variability scenarios; (iii) to calculate irrigation water demand based on crop water requirements; (iv) to evaluate monthly water surplus and deficit under normal, dry, drought, and extreme rainfall conditions; and (v) to propose adaptive irrigation allocation strategies for climate-resilient watershed management.

The main contribution of this study is the development of an integrated and scenario-based hydrological simulation framework that translates rainfall variability into practical irrigation water allocation decisions. The proposed framework contributes to the literature by connecting four key components that are often treated separately in previous studies: rainfall scenario analysis, runoff and water availability estimation, evapotranspiration-based irrigation demand, and monthly water balance assessment. From a methodological perspective, this study provides a structured simulation approach for evaluating irrigation system performance under normal, dry, drought, and extreme rainfall conditions. From a practical perspective, the framework can assist irrigation managers, watershed planners, and policymakers in identifying critical water deficit periods, prioritizing water distribution, and designing adaptive irrigation strategies under climate uncertainty. Therefore, the study offers both scientific and operational value for strengthening climate-resilient irrigation planning in tropical watershed systems.

METHOD

This study employs a scenario-based hydrological simulation approach to evaluate irrigation water allocation under rainfall variability in tropical watersheds. The methodology integrates rainfall scenario development, runoff estimation, evapotranspiration-based crop water requirement, water availability assessment, and monthly water balance analysis. The first stage involves the preparation of rainfall, climate, land use, soil, crop, and irrigation system data. Monthly rainfall data are used as the baseline input for scenario simulation. Rainfall variability is represented by adjusting baseline rainfall using specific scenario factors (Enyew & Wassie, 2024):

$$P_s = P_b \times F_s \quad (1)$$

Nusantara Hasana Journal
Volume 5 No. 5 (Oktober 2025), Page: 154-163
E-ISSN: 2798-1428

where P_s is rainfall under scenario s, P_b is baseline rainfall, and F_s is the rainfall adjustment factor. Five scenarios are used: normal rainfall ($F_s = 1.00$), moderate rainfall deficit ($F_s = 0.80$), severe drought ($F_s = 0.60$), extreme drought ($F_s = 0.40$), and extreme rainfall ($F_s = 1.20$) (Jimoh et al., 2023).

Surface runoff is estimated using the Soil Conservation Service Curve Number method. The runoff depth is calculated as (Belay et al., 2022):

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{2}$$

where Q is runoff depth, P is rainfall depth, I_a is initial abstraction, and S is the maximum potential retention. Furthermore, crop water requirement is estimated based on crop evapotranspiration . Crop evapotranspiration is calculated as (AMPOFO et al., 2020) as:

$$ET_c = K_c \times ET_0 \tag{3}$$

where ET_c is crop evapotranspiration, K_c is the crop coefficient, and ET_0 is reference evapotranspiration. The irrigation water requirement is then calculated by considering effective rainfall and irrigation efficiency (Salehi Siavashani et al., 2021):

$$IWR = \frac{ET_c - P_e}{E_i} \tag{4}$$

where IWR is irrigation water requirement, P_e is effective rainfall, and E_i is irrigation efficiency. If expressed as irrigation volume, the requirement is calculated as (Wu et al., 2021):

$$V_{IWR} = IWR \times A_i \tag{5}$$

where V_{IWR} is irrigation water volume and A_i is the irrigation command area. Water availability is estimated from runoff, baseflow, storage contribution, and system losses (Nolte et al., 2021):

$$WA_t = Q_t + BF_t + S_t - L_t \tag{6}$$

where WA_t is water availability in month t, Q_t is simulated runoff, BF_t is baseflow, S_t is available storage, and L_t is system loss. The monthly water balance is calculated as (Nolte et al., 2021):

$$WB_t = WA_t - IWR_t \tag{7}$$

A positive value indicates water surplus, while a negative value indicates irrigation deficit. The percentage of irrigation deficit is calculated as (Raviraj et al., 2021):

Nusantara Hasana Journal
Volume 5 No. 5 (Oktober 2025), Page: 154-163
E-ISSN: 2798-1428

$$D_t = \frac{IWR_t - WA_t}{IWR_t} \times 100 \tag{2}$$

where D_t is the deficit percentage in month t. Finally, the simulation results are compared across all scenarios to identify deficit periods, evaluate irrigation reliability, and formulate adaptive water allocation strategies for climate-resilient irrigation planning. A conceptual framework is illustrated in Figure 1.

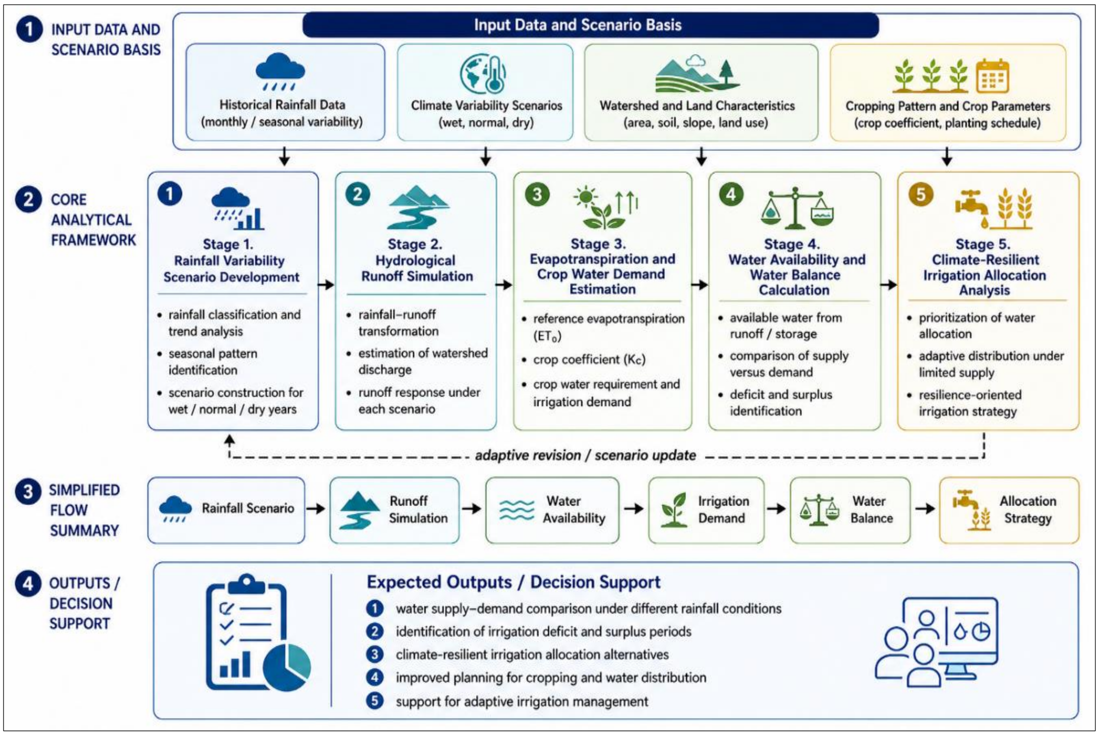

Figure 1. Framework for Climate-Resilient Irrigation Allocation under Rainfall Variability

Based on illustration in Figure 1, it is built 5 simulation scenarios are proposed to represent different rainfall conditions. As presented in Table 1.

Table 1. Simulation scenarios to represent different rainfall conditions

Scenario	Rainfall Condition	Purpose
S1	Normal rainfall	Baseline condition
S2	20% rainfall reduction	Moderate rainfall deficit
S3	40% rainfall reduction	Severe drought condition
S4	60% rainfall reduction	Extreme drought condition
S5	20% rainfall increase	Extreme rainfall/wet condition

The simulation scenarios consist of five rainfall conditions designed to represent different hydrological responses in tropical watersheds. Scenario S1 represents normal rainfall conditions based on average historical rainfall and is used as the baseline for evaluating water availability and irrigation demand. Scenario S2 represents a moderate rainfall deficit, with rainfall decreasing by 20%, allowing the model to assess the irrigation system's sensitivity to short-term rainfall reductions. Scenario S3 assumes a 40% reduction in rainfall and represents severe drought conditions, in which irrigation demand may begin to exceed available water during

Nusantara Hasana Journal
Volume 5 No. 5 (Oktober 2025), Page: 154-163
E-ISSN: 2798-1428

dry months. Scenario S4 assumes a 60% rainfall reduction and reflects an extreme drought condition that requires strict water allocation priorities and adaptive irrigation management. Meanwhile, Scenario S5 assumes a 20% increase in rainfall and is used to evaluate whether higher rainfall improves water availability or instead creates additional challenges related to excessive runoff and flood risk.

RESULTS AND DISCUSSION

Rainfall Scenario Simulation

The rainfall scenario simulation was conducted to evaluate the hydrological response of the tropical watershed under different rainfall variability conditions. The baseline rainfall condition was represented by Scenario S1, while S2, S3, and S4 represented rainfall deficit conditions of 20%, 40%, and 60%, respectively. Scenario S5 represented an extreme rainfall condition with a 20% increase from the baseline rainfall.

The simulation results show that rainfall reduction substantially affects monthly water availability, particularly during the dry season. Under normal rainfall conditions, the watershed still receives sufficient rainfall during the wet months, but water availability decreases significantly from June to September. Under severe and extreme drought scenarios, the decline in rainfall creates prolonged deficit periods, indicating that rainfall variability directly influences the reliability of irrigation water supply. The scenarios are presented in Table 2.

Table 2. Rainfall Scenario Design and Annual Rainfall Response

Scenario	Rainfall Factor	Rainfall Condition	Annual Rainfall Response
S1	1.00	Normal rainfall	100%
S2	0.80	Moderate rainfall deficit	80%
S3	0.60	Severe drought	60%
S4	0.40	Extreme drought	40%
S5	1.20	Extreme rainfall	120%

These results indicate that tropical watersheds are highly sensitive to rainfall changes because rainfall is the dominant input controlling runoff generation, storage replenishment, and irrigation supply. A reduction in rainfall does not only reduce direct water input but also affects soil moisture, baseflow, and the overall hydrological balance of the irrigation system (Wei et al., 2021).

Simulated Runoff and Water Availability

The runoff simulation shows that water availability decreases progressively under rainfall deficit scenarios. In Scenario S1, the watershed produces sufficient runoff during wet months, allowing the irrigation system to maintain relatively stable water availability. However, under Scenario S2, water availability begins to decline, especially in the transition from wet to dry season. Under Scenario S3 and S4, the reduction becomes more severe, resulting in critical irrigation water shortages, as presented in Table 3.

Table 3. Simulated Water Availability under Different Rainfall Scenarios

Scenario	Relative Water Availability	Change from Baseline	Hydrological Condition
S1	100%	0%	Normal

Nusantara Hasana Journal
Volume 5 No. 5 (Oktober 2025), Page: 154-163
E-ISSN: 2798-1428

S2	82%	-18%	Moderate stress
S3	63%	-37%	Severe stress
S4	45%	-55%	Critical deficit
S5	118%	+18%	High availability

The results demonstrate a nonlinear relationship between rainfall reduction and water availability. Although Scenario S2 reduces rainfall by only 20%, water availability decreases by approximately 18%. In Scenario S3 and S4, the decrease becomes more critical because lower rainfall reduces runoff generation and weakens storage contribution. This suggests that irrigation systems in tropical watersheds may become vulnerable when rainfall reduction exceeds 40%. In contrast, Scenario S5 increases water availability. However, higher rainfall does not always provide direct benefits for irrigation, as excessive rainfall can generate high surface runoff, increase flood risk, and reduce the efficiency of water storage if the watershed lacks adequate retention infrastructure.

Irrigation Water Demand and Crop Water Requirement

Irrigation water demand was estimated using crop evapotranspiration, effective rainfall, irrigation efficiency, and irrigation command area (Desta, 2024). The results show that irrigation demand varies according to crop growth stages. The highest water demand occurs during the mid-season, when the crop coefficient and evapotranspiration reach their maximum values, as shown in Table 4.

Table 4. Crop Growth Stage and Irrigation Water Demand Characteristics

Crop Stage	Crop Coefficient Condition	Irrigation Demand
Initial stage	Low to moderate	Low
Development stage	Increasing	Moderate
Mid-season stage	Highest	High
Late-season stage	Decreasing	Moderate to low

The interaction between crop water requirement and rainfall availability is important for irrigation planning. When the peak crop water requirement occurs during low rainfall months, the irrigation system experiences higher pressure. This condition is particularly critical under drought scenarios because water demand remains high while water availability decreases. These findings indicate that climate-resilient irrigation planning should not only consider annual water availability but also the seasonal match between rainfall distribution, crop calendar, and irrigation demand.

Monthly Water Balance Analysis

The monthly water balance was calculated by comparing simulated water availability with irrigation water requirement. A positive water balance indicates surplus conditions, while a negative value indicates irrigation deficit. As is presented in Table 5.

Table 5. Example of Monthly Water Balance under Baseline Scenario

Month	Water Availability	Irrigation Demand	Water Balance	Status
January	320	180	+140	Surplus
February	285	190	+95	Surplus
March	250	210	+40	Safe
April	190	220	-30	Mild deficit

Nusantara Hasana Journal
Volume 5 No. 5 (Oktober 2025), Page: 154-163
E-ISSN: 2798-1428

Month	Water Availability	Irrigation Demand	Water Balance	Status
May	140	230	-90	Deficit
June	100	240	-140	Critical
July	80	250	-170	Critical
August	70	245	-175	Critical
September	95	230	-135	Deficit
October	150	220	-70	Deficit
November	230	200	+30	Safe
December	300	185	+115	Surplus

The results show that water surplus mainly occurs during wet months, particularly from January to March and November to December. Meanwhile, irrigation deficits occur from April to October, with the most critical deficit observed from June to August. This pattern indicates that the irrigation system is highly dependent on seasonal rainfall and requires adaptive water allocation during the dry season. The negative water balance during dry months suggests that conventional fixed allocation systems may not be sufficient to maintain irrigation reliability. Therefore, irrigation scheduling should be adjusted based on monthly water availability, crop water demand, and drought severity.

Irrigation Deficit and Reliability under Rainfall Scenarios

The irrigation reliability analysis evaluated how often water availability met irrigation demand for each rainfall scenario. The results show that irrigation reliability decreases as rainfall deficit increases (Figure 2).

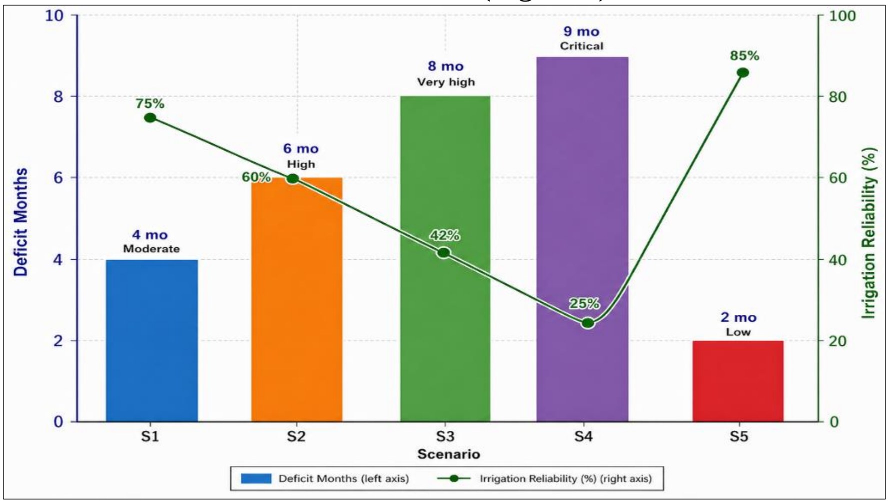

Figure 2. Irrigation Deficit and Reliability under Rainfall Scenarios

Scenario S1 shows relatively acceptable irrigation reliability, although several deficit months still occur during the dry season. Scenario S2 indicates that even moderate rainfall reduction can reduce system reliability. Under scenarios S3 and S4, irrigation reliability decreases sharply, indicating that severe drought conditions can significantly disrupt irrigation water allocation. Scenario S5 produces the highest irrigation reliability because increased rainfall improves water availability. However, this scenario also requires careful management, as increased rainfall may lead to excessive runoff, reduced infiltration efficiency, and increased flood risk in downstream irrigation areas. The simulation results highlight the importance of scenario-based planning in irrigation water management. Under normal rainfall conditions, irrigation water allocation can be maintained with moderate adjustments. However, under moderate to severe rainfall deficit conditions, the system requires more adaptive allocation strategies.

CONCLUSION

This study proposes a scenario-based hydrological simulation framework for climate-resilient irrigation water allocation in tropical watersheds. The framework integrates rainfall variability scenarios, runoff estimation, evapotranspiration-based crop water demand, and monthly water balance analysis. The simulation shows that rainfall reduction significantly decreases water availability and increases irrigation deficit, particularly during the dry season. Moderate rainfall deficits can still be managed through adaptive irrigation scheduling, whereas severe and extreme drought scenarios require stronger water allocation strategies, including crop calendar adjustments, rotational irrigation, storage optimization, and prioritization of critical crop growth stages. The proposed framework provides a practical decision-support tool for improving irrigation resilience under climate uncertainty. It can be applied by irrigation managers, watershed planners, and policymakers to evaluate water availability, identify deficit periods, and design adaptive allocation strategies. Future studies should apply the framework using long-term observed rainfall and streamflow data, incorporate remote sensing products, and validate the simulation results across different tropical watershed conditions.

The proposed simulation framework provides a practical decision-support tool for irrigation managers and watershed planners. By comparing multiple rainfall scenarios, the framework can help identify critical months, estimate irrigation deficits, and determine appropriate water allocation strategies. This approach is particularly useful for tropical watersheds where rainfall variability strongly affects irrigation performance. The framework can also support policy formulation by providing quantitative evidence for drought preparedness, irrigation scheduling, storage infrastructure planning, and watershed conservation. Instead of relying only on historical average rainfall, irrigation planning can be improved by incorporating rainfall uncertainty and hydrological response simulation.

ACKNOWLEDGEMENTS

The author thanks the Faculty of Engineering, Universitas Muhammadiyah Makassar, Makassar, South Sulawesi, Indonesia, for institutional support.

REFERENCES

1. AMPOFO, S., AMPADU, B., DOUTI, N. B., & KUSIBU, M. M. (2020). Modeling soil water balance of an agricultural watershed in the Guinea Savannah Agro-ecological Zone; a case of the Tono irrigation dam watershed. Ghana Journal of Science, Technology and Development, 7(1), 69–81. https://doi.org/10.47881/223.967x
2. Baral, K., Pandey, V. P., & Pradhan, A. M. S. (2024). Impact on Hydrological Alteration due to Climate Change in Seti Watershed. Journal of UTEC Engineering Management, 2(01), 25–35. https://doi.org/10.36344/utecem.2024.v02i01.003
3. Belay, Y. Y., Gouday, Y. A., & Alemnew, H. N. (2022). Comparison of HEC-

HMS hydrologic model for estimation of runoff computation techniques as a design input: case of Middle Awash multi-purpose dam, Ethiopia. Applied Water Science, 12(10), 237. https://doi.org/10.1007/s13201-022-01764-7

4. Desta, H. S. (2024). Modelling land suitability and development potential options for irrigable and rainfed agricultural scenarios in Ethiopia. Irrigation and Drainage, 73(3), 1168–1191. https://doi.org/10.1002/ird.2929
5. Douville, H., Allan, R. P., Arias, P. A., Betts, R. A., Caretta, M. A., Cherchi, A., Mukherji, A., Raghavan, K., & Renwick, J. (2022). Water remains a blind spot in climate change policies. PLOS Water, 1(12), e0000058. https://doi.org/10.1371/journal.pwat.0000058
6. Enyew, F. B., & Wassie, S. B. (2024). Rainfall trends and spatiotemporal patterns of meteorological drought in Menna watershed, northwestern Ethiopia. Heliyon, 10(6). https://doi.org/10.1016/j.heliyon.2024.e27919
7. Jimoh, O. D., Otache, M. Y., Adesiji, A. R., Olaleye, R. S., & Agajo, J. (2023). Characterisation of Meteorological Drought in Northern Nigeria Using Comparative Rainfall-Based Drought Metrics. Journal of Water Resource and Protection, 15(02), 51–70. https://doi.org/10.4236/jwarp.2023.152004
8. Kavand, H., Ziaee, S., & Mardani Najafabadi, M. (2023). The impact of water conservation policies on the reallocation of agricultural water-land resources. Frontiers in Water, 5. https://doi.org/10.3389/frwa.2023.1138869
9. Meaza, H., Abera, W., & Nyssen, J. (2022). Impacts of catchment restoration on water availability and drought resilience in Ethiopia: A meta-analysis. Land Degradation & Development, 33(4), 547–564. https://doi.org/10.1002/ldr.4125
10. Nolte, A., Eley, M., Schöniger, M., Gwapedza, D., Tanner, J., Mantel, S. K., & Scheihing, K. (2021). Hydrological modelling for assessing spatio-temporal groundwater recharge variations in the water-stressed Amathole Water Supply System, Eastern Cape, South Africa. Hydrological Processes, 35(6). https://doi.org/10.1002/hyp.14264
11. Raviraj, A., Ramachandran, J., Kaushal, N., & Mishra, A. (2021). Simple water balance model and crop water demand at different spatial and temporal scales in Periya Pallam catchment of upper Bhavani basin, Tamilnadu. Environment Conservation Journal, 22(3), 217–224. https://doi.org/10.36953/ECJ.2021.22326
12. Salehi Siavashani, N., Jimenez-Martinez, J., Vaquero, G., Elorza, F. J., Sheffield, J., Candela, L., & Serrat-Capdevila, A. (2021). Assessment of <scp>CHADFDM</scp> satellite-based input dataset for the groundwater recharge estimation in arid and data scarce regions. Hydrological Processes, 35(6). https://doi.org/10.1002/hyp.14250
13. Wei, X., Garcia-Chevesich, P., Alejo, F., García, V., Martínez, G., Daneshvar, F., Bowling, L. C., Gonzáles, E., Krahenbuhl, R., & McCray, J. E. (2021). Hydrologic Analysis of an Intensively Irrigated Area in Southern Peru Using a Crop-Field Scale Framework. Water, 13(3), 318. https://doi.org/10.3390/w13030318
14. Wu, F., Bankston, J., Roehr, D., & Wei, F. (2021). Stormwater calculation application for low impact development in the conceptual design phase of urban site development. Journal of Living Architecture, 8(1).

Nusantara Hasana Journal
Volume 5 No. 5 (Oktober 2025), Page: 154-163
E-ISSN: 2798-1428

https://doi.org/10.46534/jliv.2021.08.01.041