



## RAINFALL–RUNOFF SIMULATION FOR SUSTAINABLE IRRIGATION WATER MANAGEMENT IN TROPICAL AGRICULTURAL CATCHMENT

Abd Rakhim Nanda

Universitas Muhammadiyah Makassar, Indonesia

\*Email: [abd.rakhimnanda@unismuh.ac.id](mailto:abd.rakhimnanda@unismuh.ac.id)

### **Abstract**

*Rainfall–runoff processes play a crucial role in determining irrigation water availability in tropical agricultural catchments. This study develops a rainfall–runoff simulation framework for sustainable irrigation water management by integrating rainfall characterization, SCS-CN runoff estimation, runoff coefficient analysis, effective runoff availability, irrigation water demand, water balance, Surplus–Deficit Ratio, and Irrigation Sustainability Index. Monthly rainfall data were used to estimate runoff depth and runoff-derived water availability, while irrigation demand was evaluated based on crop water requirement and effective water availability. The results show that runoff generation is highly seasonal, with high runoff coefficients during wet months and low runoff response during dry months. The ISI results indicate highly sustainable irrigation conditions in January, February, and December; sustainable conditions in March and November; and critical conditions from June to September. The proposed framework supports runoff harvesting, storage optimization, rotational irrigation, crop calendar adjustment, and priority-based water allocation.*

**Keywords:** *rainfall–runoff, runoff coefficient, Irrigation sustainability, water balance, tropical agriculture*

### **INTRODUCTION**

Agricultural water management in tropical regions is increasingly challenged by rainfall variability, seasonal water imbalance, and growing pressure on irrigation systems (Narsimlu et al., 2024). Although tropical catchments generally receive high annual rainfall, the temporal distribution is often uneven, leading to periods of excessive runoff during wet months and water deficit during dry months. This seasonal imbalance creates uncertainty in irrigation scheduling, especially for agricultural areas that depend on surface runoff, small reservoirs, diversion structures, or local catchment storage (Minh et al., 2024).

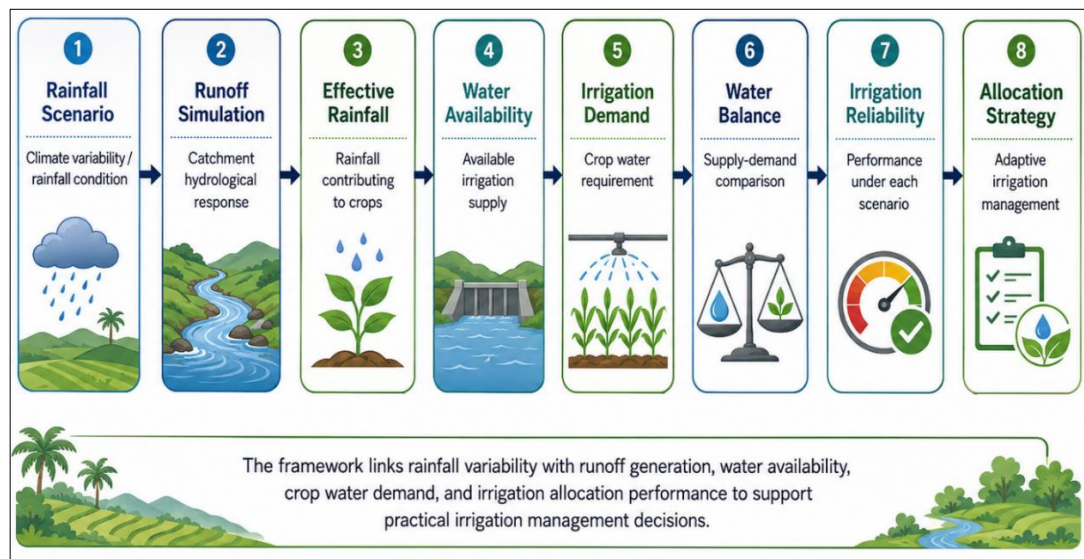
In tropical agricultural catchments, rainfall is the primary hydrological input controlling runoff generation, soil moisture availability, streamflow response, and irrigation supply (Shokri, 2023). However, rainfall depth alone is insufficient to describe water availability, as part of the rainfall is lost through interception, infiltration, evapotranspiration, and soil storage before contributing to direct runoff. Therefore, rainfall–runoff simulation is necessary to transform rainfall information into hydrologically meaningful indicators such as runoff depth, water availability, and irrigation supply reliability (Muhammad et al., 2023). The SCS Curve Number method, for example, estimates precipitation excess as a function of rainfall, initial abstraction, soil-cover condition, land use, and catchment retention capacity,

making it widely applicable for event-based runoff estimation in agricultural and mixed land-use catchments.

Sustainable irrigation management also requires the estimation of crop water demand (Surfia Dioh, 2022). FAO guidelines define reference evapotranspiration, crop evapotranspiration, crop coefficients, and soil-water balance as key components in computing crop water requirements and irrigation needs (Gharsiram et al., 2023). FAO's CROPWAT framework similarly calculates crop and irrigation water requirements based on soil, climate, and crop data, and supports irrigation scheduling and scheme water-supply analysis across different cropping patterns. These concepts are important because irrigation planning should not only consider available water but also crop-specific water demand and the timing of rainfall contribution (Naeem & Jahan, 2023).

Previous irrigation studies have often examined rainfall characteristics, runoff generation, or crop water requirement estimation as separate analytical components (Abushandi & Al Ajmi, 2022). However, limited attention has been given to integrating these components into a practical, scenario-based framework that links hydrological simulation with irrigation reliability assessment. This limitation is important because irrigation managers require not only hydrological outputs, such as runoff depth or water balance (Khaydar et al., 2021), but also operational indicators, including deficit months, maximum deficit severity, and reliability percentage, to support water allocation decisions under variable rainfall conditions.

This study contributes to the literature and practice of irrigation water management in several important ways. First, it provides an integrated hydrological–irrigation assessment framework that connects rainfall variability, runoff generation, crop water demand, and water balance evaluation within a single analytical structure. Second, it translates rainfall–runoff simulation outputs into operational irrigation indicators, including deficit months, maximum deficit severity, and irrigation reliability, which are directly useful for irrigation planning and decision-making. Third, it introduces a scenario-based evaluation approach that enables comparison of irrigation system performance under normal, deficit, extreme-deficit, and wet rainfall conditions. Finally, the proposed framework supports climate-resilient irrigation allocation by identifying critical periods of water scarcity and providing a basis for adaptive strategies, such as rotational irrigation, storage optimization, crop calendar adjustment, and priority-based water distribution in tropical agricultural catchments. A conceptual framework is illustrated in Figure 1.



**Figure 1. Framework for Tropical Agricultural Catchments**

Therefore, this study aims to develop a rainfall–runoff simulation framework for sustainable irrigation water management in tropical agricultural catchments. The specific objectives are: (i) to simulate runoff response under different rainfall variability scenarios; (ii) to estimate irrigation water demand using crop evapotranspiration and effective rainfall principles; (iii) to evaluate monthly water balance and irrigation reliability; and (iv) to propose climate-resilient irrigation allocation strategies based on scenario performance. The novelty of this study lies in its integration of rainfall–runoff simulation, crop water demand estimation, monthly water balance analysis, and irrigation reliability assessment into a scenario-based decision-support framework for sustainable irrigation planning in tropical agricultural catchments.

## METHOD

This study applies a rainfall–runoff simulation approach to evaluate sustainable irrigation water management in tropical agricultural catchments. The method comprises six main stages: rainfall characterization, catchment parameter identification, runoff simulation, runoff coefficient analysis, irrigation water demand estimation, and irrigation sustainability assessment. The framework differs from a scenario-based allocation model because it emphasizes monthly rainfall–runoff transformation and the extent to which effective runoff can satisfy irrigation water demand.

Monthly rainfall data are the primary input for hydrological simulation. Annual rainfall is calculated as :

$$P_{annual} = \sum_{t=1}^{12} P_t \quad (1)$$

where  $P_{annual}$  is annual rainfall and  $P_t$  is rainfall depth in month  $t$ . Surface runoff is estimated using the Soil Conservation Service Curve Number method (Girons Lopez et al., 2021). Furthermore, the runoff depth is calculated as (Hernandez Gamboa, 2023):

$$Q_t = \frac{(P_t - I_a)^2}{P_t - I_a + S} \quad (2)$$

where  $Q_t$  is runoff depth in month  $t$ ,  $P_t$  is rainfall depth,  $I_a$  is initial abstraction, and  $S$  is maximum potential retention. If  $P_t \leq I_a$ , then  $Q_t = 0$ . The retention parameter is calculated as:

$$S = \frac{25400}{CN} - 254 \quad (3)$$

where  $CN$  is the Curve Number representing land use, soil type, and runoff potential (Poblete et al., 2020). Initial abstraction is estimated as:

$$I_a = 0.2S \quad (4)$$

Runoff depth is then converted into runoff volume using the catchment area (Naz et al., 2020):

$$I_a = 0.2S \quad (5)$$

$$VQ_t = Q_t \times A \times 10 \quad (6)$$

where  $VQ_t$  is runoff volume in month  $t$ ,  $Q_t$  is runoff depth in mm, and  $A$  is catchment area in hectares. The multiplier 10 is used because 1 mm rainfall over 1 hectare is equivalent to 10 m<sup>3</sup> of water.

To evaluate the catchment response to rainfall, the runoff coefficient is calculated as:

$$C_t = \frac{Q_t}{P_t} \quad (7)$$

where  $C_t$  is the monthly runoff coefficient. A higher value of  $C_t$  indicates that a larger proportion of rainfall is converted into runoff, while a lower value indicates greater losses through infiltration, storage, or evapotranspiration (Zhang et al., 2023).

Effective runoff availability is calculated by considering storage or conveyance efficiency:

$$ERA_t = VQ_t \times \eta_s \quad (8)$$

where  $ERA_t$  is effective runoff availability and  $\eta_s$  is the storage or conveyance efficiency. Crop evapotranspiration is calculated as:

$$ET_c = K_c \times ET_0 \quad (9)$$

where  $ET_c$  is crop evapotranspiration,  $K_c$  is the crop coefficient, and  $ET_0$  is reference evapotranspiration (Sabah et al., 2023). Irrigation water requirement is calculated as:

$$IWR_t = \frac{ET_{c,t} - P_{e,t}}{E_i} \quad (10)$$

where  $IWR_t$  is irrigation water requirement,  $ET_{c,t}$  is crop evapotranspiration,  $P_{e,t}$  is effective rainfall, and  $E_i$  is irrigation efficiency (Silvestro et al., 2021). If expressed as volume, irrigation water demand is calculated as:

$$VIWR_t = IWR_t \times A_i \times 10 \tag{11}$$

where  $VIWR_t$  is irrigation water requirement volume and  $A_i$  is irrigation command area in hectares. The monthly water balance is calculated as:

$$WB_t = ERA_t - VIWR_t \tag{12}$$

where  $WB_t$  is monthly water balance. A positive value indicates surplus water, while a negative value indicates irrigation deficit.

## RESULTS AND DISCUSSION

### Rainfall Characteristics and Seasonal Distribution

The rainfall analysis shows a strong seasonal pattern in the tropical agricultural catchment. High rainfall occurs during the wet months, particularly from January to March and November to December, while lower rainfall is observed from June to September. This seasonal distribution strongly influences runoff generation and irrigation water availability. Wet-season rainfall provides opportunities for runoff harvesting and water storage, whereas dry-season rainfall is insufficient to sustain irrigation demand without supplemental storage or improved water allocation. The result is presented in Table 1.

**Table 1. Monthly Rainfall Characteristics**

Month	Rainfall	Rainfall Condition
January	320	Very wet
February	280	Wet
March	240	Wet
April	180	Moderate
May	120	Transition
June	80	Dry
July	60	Very dry
August	50	Very dry
September	70	Dry
October	130	Transition
November	210	Wet
December	300	Very wet

The results indicate that irrigation planning in tropical agricultural catchments should not rely only on annual rainfall totals. Although annual rainfall may appear sufficient, the seasonal mismatch between water availability and irrigation demand can create dry-season water stress. Therefore, monthly rainfall distribution is a more relevant basis for sustainable irrigation management.

### Rainfall–Runoff Simulation Results

The rainfall–runoff simulation shows that runoff generation increases during high rainfall months and decreases sharply during dry months. The highest runoff occurs in January, February, and December, while the lowest occurs in July and August. This confirms that rainfall is the dominant input controlling surface runoff, but runoff response is also affected by catchment retention and initial abstraction. The result is presented in Table 2.

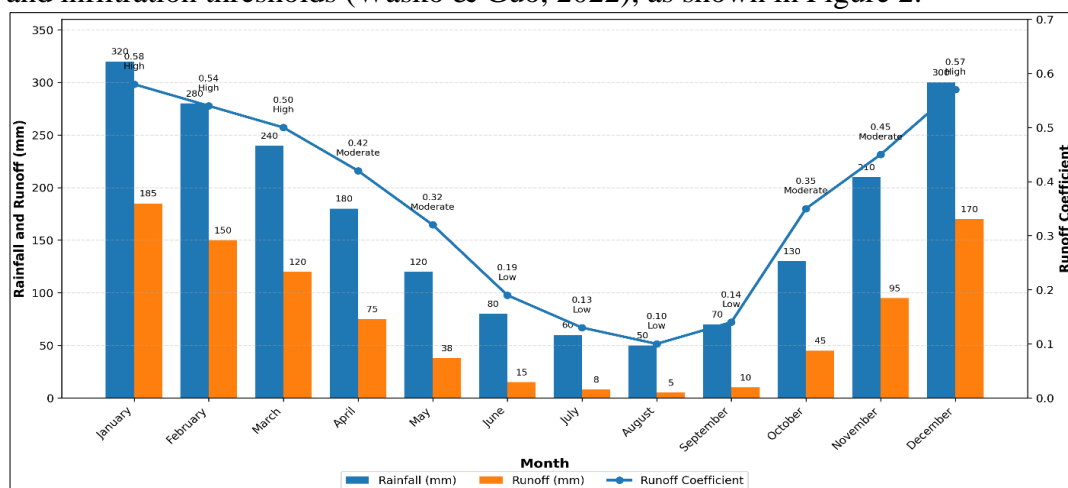
**Table 2. Monthly Rainfall–Runoff Simulation Results**

Month	Rainfall	Runoff	Runoff Volume	Hydrological Status
January	320	185	High	Wet-season surplus
February	280	150	High	Wet-season surplus
March	240	120	Moderate	Safe
April	180	75	Moderate	Transition
May	120	38	Low	Early deficit
June	80	15	Very low	Deficit
July	60	8	Very low	Critical
August	50	5	Very low	Critical
September	70	10	Very low	Deficit
October	130	45	Low	Recovery
November	210	95	Moderate	Safe
December	300	170	High	Surplus

The results demonstrate that runoff response is not fully proportional to rainfall. During wet months, rainfall exceeds the initial abstraction and retention capacity, leading to higher runoff. During dry months, rainfall may be largely absorbed by soil and catchment storage processes, resulting in very low runoff availability. This seasonal runoff pattern has direct implications for irrigation planning, especially in catchments where dry-season water supply depends on stored wet-season runoff.

**Runoff Coefficient and Catchment Response**

The runoff coefficient analysis provides insight into how efficiently rainfall is transformed into surface runoff. High runoff coefficients are observed during wet months, while low coefficients occur during dry months. This indicates that the catchment produces more usable surface water when rainfall exceeds the storage and infiltration thresholds (Wasko & Guo, 2022), as shown in Figure 2.



**Figure 2. Monthly Rainfall–Runoff Response and Catchment Behavior**

The runoff coefficient ranges from 0.10 to 0.58, indicating substantial seasonal variation in catchment response. High runoff response during January, February, March, and December suggests strong potential for runoff harvesting. In

contrast, the low runoff coefficients during June to September indicate that rainfall during these months contributes little to surface water availability. These findings emphasize the importance of wet-season storage to support irrigation during dry months.

**Effective Runoff Availability for Irrigation**

Effective runoff availability is the portion of simulated runoff that can be used for irrigation after accounting for storage or conveyance efficiency. This component is important because not all generated runoff can be directly utilized. Some water may be lost through seepage, evaporation, uncontrolled drainage, or conveyance inefficiency.

The water balance results show that surplus occurs mainly during January, February, March, November, and December. Deficit conditions occur from April to October, with the most critical deficits observed from June to September. The result is presented in Table 3.

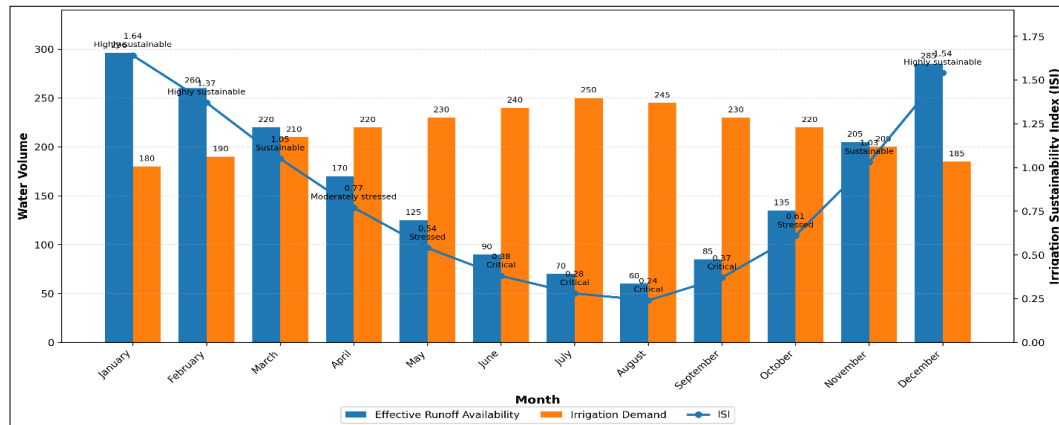
**Table 3. Effective Runoff Availability and Irrigation Demand**

Month	Effective Runoff Availability	Irrigation Demand	Water Balance	Status
January	296	180	+116	Surplus
February	260	190	+70	Surplus
March	220	210	+10	Safe
April	170	220	-50	Mild deficit
May	125	230	-105	Deficit
June	90	240	-150	Critical
July	70	250	-180	Critical
August	60	245	-185	Critical
September	85	230	-145	Critical
October	135	220	-85	Deficit
November	205	200	+5	Safe
December	285	185	+100	Surplus

Based on the results in Table 3, this pattern indicates that irrigation sustainability is not determined solely by total annual runoff but by the timing of effective runoff availability relative to crop water demand.

**Irrigation Sustainability Index (ISI)**

The Irrigation Sustainability Index was calculated to assess the extent to which effective runoff availability meets irrigation water demand. Higher ISI values indicate better irrigation sustainability, while lower values indicate stress or critical water shortage, as shown in Figure 3.



**Figure 3. Monthly Effective Runoff Availability, Irrigation Demand, and ISI**

The ISI results show that irrigation is highly sustainable during January, February, and December. Sustainable conditions are observed in March and November, while April is moderately stressed. May and October are classified as stressed, whereas June to September are categorized as critical. These findings indicate that the main irrigation challenge occurs during the dry season, when effective runoff availability is far below irrigation demand.

**Surplus–Deficit Ratio and Management Implications**

The surplus–deficit ratio provides a relative measure of water surplus or shortage compared with irrigation demand. Positive values indicate surplus conditions, while negative values indicate deficit conditions. The result is presented in Table 4.

**Table 4. Surplus–Deficit Ratio and Management Priority**

Month	SDR	Condition	Management Priority
January	+0.64	Surplus	Runoff harvesting
February	+0.37	Surplus	Storage optimization
March	+0.05	Near balanced	Maintain allocation
April	-0.23	Mild deficit	Flexible scheduling
May	-0.46	Deficit	Rotational irrigation
June	-0.63	Critical deficit	Priority allocation
July	-0.72	Critical deficit	Crop calendar adjustment
August	-0.76	Critical deficit	Emergency water control
September	-0.63	Critical deficit	Supplemental irrigation
October	-0.39	Deficit	Irrigation efficiency improvement
November	+0.03	Near balanced	Recovery allocation
December	+0.54	Surplus	Water storage preparation

The SDR analysis confirms that the catchment has strong surplus potential during wet months but severe water stress during dry months. Therefore, sustainable irrigation management should emphasize seasonal redistribution of water. Excess runoff during wet months should be captured and stored to support irrigation during critical dry months. This can be achieved through farm ponds, small reservoirs, canal storage, recharge structures, and improved conveyance systems.

**Sustainable Irrigation Water Management Strategy**

Based on the rainfall–runoff simulation, runoff coefficient, ISI, and SDR results, several management strategies can be formulated. The result is presented in Table 5.

**Table 5. Recommended Sustainable Irrigation Management Strategies**

Hydrological Condition	Main Problem	Recommended Strategy
High runoff coefficient	Excess wet-season runoff	Runoff harvesting and storage
Moderate runoff response	Transition-season uncertainty	Flexible irrigation scheduling
Low runoff coefficient	Limited surface water generation	Supplemental storage use
Stressed ISI	Demand exceeds effective runoff	Rotational irrigation
Critical ISI	Severe dry-season deficit	Crop calendar adjustment
Negative SDR	Unsustainable water balance	Priority-based allocation
High conveyance loss	Inefficient distribution	Canal lining and gate control
Seasonal mismatch	Water surplus and demand occur at different times	Synchronization of planting calendar

These strategies show that sustainable irrigation management must be based on catchment hydrological behavior rather than fixed irrigation schedules alone. The proposed framework enables irrigation managers to determine when to harvest runoff, when to reduce irrigation, and when to adjust crop calendars to match water availability.

**CONCLUSION**

This study developed a rainfall–runoff simulation framework for sustainable irrigation water management in tropical agricultural catchments. The framework integrates rainfall characterization, SCS-CN runoff estimation, runoff coefficient analysis, effective runoff availability, irrigation water requirements, water balance, surplus–deficit ratio, and the Irrigation Sustainability Index. The results show that runoff generation is highly seasonal, with high runoff response during wet months and low runoff availability during dry months.

The runoff coefficient analysis indicates that wet months provide strong potential for runoff harvesting, while dry months generate limited usable surface water. The water balance and Irrigation Sustainability Index show that irrigation conditions are highly sustainable during wet months, sustainable or near-balanced during transition months, and critical during the dry season. These findings demonstrate that sustainable irrigation management in tropical agricultural catchments requires seasonal water redistribution, storage optimization, rotational irrigation, crop calendar adjustment, and improved conveyance efficiency.

The proposed framework provides a practical decision-support tool for irrigation managers, watershed planners, and policymakers. It can help identify high runoff-harvesting periods, critical deficit months, and suitable management interventions. Future studies should apply the framework using long-term observed

rainfall, discharge, land use, soil, and crop data, and should validate the simulation results across different tropical agricultural catchments to improve model robustness and transferability..

## ACKNOWLEDGEMENTS

The author thanks the Universitas Muhammadiyah Makassar, Makassar, South Sulawesi, Indonesia, for valuable support.

## REFERENCES

1. Abushandi, E., & Al Ajmi, M. (2022). Assessment of Hydrological Extremes for Arid Catchments: A Case Study in Wadi Al Jizzi, North-West Oman. *Sustainability (Switzerland)*, *14*(21). <https://doi.org/10.3390/su142114028>
2. Gharsiram, Solanki, R. M., Suchitra, Kumawat, L., & Jaryal, R. D. (2023). Assessment of Crop-Water Requirement of Alfalfa Using FAO-CROPWAT Model-8.0. *International Journal of Environment and Climate Change*, *13*(10), 3896–3905. <https://doi.org/10.9734/ijecc/2023/v13i103063>
3. Girons Lopez, M., Crochemore, L., & Pechlivanidis, I. G. (2021). Benchmarking an operational hydrological model for providing seasonal forecasts in Sweden. *Hydrology and Earth System Sciences*, *25*(3), 1189–1209. <https://doi.org/10.5194/hess-25-1189-2021>
4. Hernandez Gamboa, R. (2023). La economía política como disciplina de la organización biopolítica en la modernidad. *Intersticios Sociales*, *25*, 31–67. <https://doi.org/10.55555/is.25.490>
5. Khaydar, D., Chen, X., Huang, Y., Ilkhom, M., Liu, T., Friday, O., Farkhod, A., Khusen, G., & Gulkaiyr, O. (2021). Investigation of crop evapotranspiration and irrigation water requirement in the lower Amu Darya River Basin, Central Asia. *Journal of Arid Land*, *13*(1), 23–39. <https://doi.org/10.1007/s40333-021-0054-9>
6. Minh, H. V. T., Kumar, P., Meraj, G., Van Thinh, L., Downes, N. K., Van Ty, T., Nam, N. D. G., Zhang, F., Liu, B., Hung, L. T., Van Duy, D., Ly, T. T. T., Luat, N. Q., Avtar, R., & Almazroui, M. (2024). Climate-driven runoff variability in semi-mountainous reservoirs of the Vietnamese Mekong Delta: Insights for sustainable water management. *Irrigation and Drainage*, *73*(4), 1633–1653. <https://doi.org/10.1002/ird.2968>
7. Muhammad, S. H., Abo, A. A., & Azeez, Y. W. (2023). Estimation of Flood Hydrograph for Aquaban Catchment Area Using Two Models. *Zanco Journal of Pure and Applied Sciences*, *35*(6), 59–66. <https://doi.org/10.21271/ZJPAS.35.6.6>
8. Naeem, M. B., & Jahan, S. (2023). Unveiling the Thirst: Revealing the Water Requirements of Gujrat's Thriving Crops using CROPWAT 8.0. *Journal of Plant and Environment*, *5*(2), 123–134. <https://doi.org/10.33687/jpe.005.02.4983>
9. Narsimlu, B., Prasad, J. V. N. S., Reddy, A. A., Chary, G. R., Gopinath, K. A., Sridhar, K. B., Balyan, J. K., Kothari, A. K., & Singh, V. K. (2024). Catchment Storage Command Relationship for Sustainable Rainfed Agriculture in the Semi-Arid Regions of Rajasthan, India. *Sustainability*



- (Switzerland) , 16(10). <https://doi.org/10.3390/su16103996>
10. Naz, R., Ashraf, A., Van der Tol, C., & Aziz, F. (2020). Modeling hydrological response to land use/cover change: case study of Chirah Watershed (Soan River), Pakistan. *Arabian Journal of Geosciences*, 13(22), 1220. <https://doi.org/10.1007/s12517-020-06177-x>
  11. Poblete, D., Arevalo, J., Nicolis, O., & Figueroa, F. (2020). Optimization of Hydrologic Response Units (HRUs) Using Gridded Meteorological Data and Spatially Varying Parameters. *Water*, 12(12), 3558. <https://doi.org/10.3390/w12123558>
  12. Sabah, N., Al-Mukhtar, M., & Shemal, K. (2023). Future Water Requirements and Crop Productivity at Al-Najaf Governorate Under Different Climate Change Scenarios (2020–2080). *Engineering and Technology Journal*, 41(5), 1–11. <https://doi.org/10.30684/etj.2023.137102.1335>
  13. Shokri, A. (2023). Development of a New Event-Based Rainfall-Runoff Equation Based on Average Rainfall Intensity During an Event. *Environmental Modeling and Assessment*, 28(4), 651–664. <https://doi.org/10.1007/s10666-023-09876-3>
  14. Silvestro, P. C., Casa, R., Hanuš, J., Koetz, B., Rascher, U., Schuettemeyer, D., Siegmann, B., Skokovic, D., Sobrino, J., & Tudoroiu, M. (2021). Synergistic Use of Multispectral Data and Crop Growth Modelling for Spatial and Temporal Evapotranspiration Estimations. *Remote Sensing*, 13(11), 2138. <https://doi.org/10.3390/rs13112138>
  15. Surfia Dioh, F. (2022). Assessment of Water Requirement of Ten Selected Crops Cultivated in Cestos River Basin Greenville, Liberia Using the Cropwat 8.0 Software. *International Journal of Engineering Applied Sciences and Technology*, 7(4), 15–30. <https://doi.org/10.33564/ijeast.2022.v07i04.003>
  16. Wasko, C., & Guo, D. (2022). Understanding event runoff coefficient variability across Australia using the hydroEvents R package. *Hydrological Processes*, 36(4). <https://doi.org/10.1002/hyp.14563>
  17. Zhang, L., Xu, Q., Wang, K., Chen, G., Luo, Z., Li, X., & Guo, B. (2023). Event-scaled hydrological response of a headwater catchment in Hong Kong. *Frontiers in Environmental Science*, 11. <https://doi.org/10.3389/fenvs.2023.1218239>