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Water Balance Analysis for Irrigation Water Allocation in the Idano Eho Watershed, Nias Island, Indonesia

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ABSTRACT

This study evaluates water balance conditions to support irrigation water allocation planning in 27 irrigation areas within the Idano Eho Watershed, Nias Island, Indonesia. Water availability was estimated using dependable discharge derived from the F.J. Mock method based on semi-monthly rainfall data for 2015–2024, while evapotranspiration was calculated using the Modified Penman method based on climatological data for 2020–2024. Water demand was assessed according to irrigation requirements and compared against Q80 dependable discharge as the planning basis under dry-year reliability. The results show marked temporal variability in water availability, with higher discharge generally occurring in April–May and October–November, whereas irrigation demand increases from October and peaks during November-I and March-I. Although the watershed is generally characterized by surplus conditions, seven irrigation areas experience deficits during critical periods, namely Tuindrao, Faohe, Hilimbulawa, Guliho, Laza Gau, Sefa, and Olo-Olo. These findings indicate that irrigation allocation problems are concentrated in specific periods rather than occurring yearround. The study provides a technical basis for priority-based water distribution, irrigation scheduling, and adaptive cropping adjustments in datalimited watershed conditions.

Keywords: *Water allocation, Watershed, Dependable discharge, Irrigation, Water balance*

1. Introduction

Providing sufficient and equitable water for agricultural needs, particularly irrigation, is a major challenge in water resource management. In many regions, agricultural productivity remains highly dependent on the availability of irrigation water, while pressure on water resources continues to increase due to limited supply, increasing food demand, and demands for efficient water use [1, 2]. In this context, watershed-based irrigation water management is becoming increasingly important to ensure the sustainability of agricultural production and minimize the risk of water shortages [3, 4].

In many regions, including Nias Island, the agricultural sector relies heavily on irrigation systems that utilize water from river basins. The Idano Eho Watershed is a critical area requiring efficient water management. Unpredictable changes in rainfall patterns, climate variability, and dependence on limited water resources make water balance analysis in this watershed crucial to ensuring appropriate irrigation water allocation. Various studies have shown that climate change and hydroclimate variability can increase irrigation water needs, alter water demand patterns, and increase pressure on water resources at both regional and watershed scales [3-6].

Water balance analysis is an effective method for assessing water availability and demand in a region. By integrating rainfall, evapotranspiration, dependable discharge, and other hydrological factors, water balance analysis can provide a clear picture of the comparison between water availability and water demand in the Idano Eho watershed, which relies heavily on irrigation to support the agricultural sector. This approach can also help plan more efficient water allocation, reduce potential water shortages, and maintain the sustainability of water use for agricultural needs [7-10]. Therefore, this study aims to conduct a comprehensive water balance analysis in the Idano Eho watershed, particularly for irrigation water allocation, so that it can serve as a basis for designing a more efficient irrigation system and ensuring more equitable water distribution according to agricultural needs and ecosystem sustainability. The novelty of this study does not lie in the introduction of a new hydrological method, but in the application of a planning-oriented water balance framework across 27 irrigation areas at a semi-monthly time scale to support allocation prioritization in a data-limited watershed setting.

2. Method

2.1. Research Location

This research was conducted in the Idano Eho Watershed, which is part of the Nias River Basin. Administratively, the Idano Eho Watershed is located in South Nias Regency, known for its vast natural resource potential, but also for its vulnerability to climate change and erratic rainfall patterns. With an area of 275.35 km², this watershed plays a crucial role in water resource management in the region. The Idano Eho Watershed encompasses 27 irrigation areas spread across various regions, and consists of 20 sub-watersheds, each with distinct hydrological characteristics. A thorough understanding of the physical and hydrological conditions of this region is crucial for more effective and sustainable water management planning. For ease of understanding, Figure 1 shows a map of the Idano Eho Watershed as a whole, along with its existing irrigation areas.

2.2 Regional Rainfall

Accurate hydrological analysis relies heavily on accurate and representative rainfall data for the area under study. One method used to calculate regional rainfall is the Thiessen Polygon method, which allows for the calculation of rainfall distribution by considering the geographic location of each rainfall station. In this study, two rainfall stations were used to collect data: the South Nias Regional Disaster Management Agency Station and the Hilimaenamolo ARR Station. The data collected consisted of rainfall recorded every two weeks over a 10-year period, from 2015 to 2024. This data provides an overview of rainfall patterns in the Idano Eho watershed, which are then used in hydrological models to plan irrigation water requirements [11, 12]. Although this method is appropriate for planning-level assessment, the limited number of stations may not fully capture the spatial variability of rainfall within the watershed. Consequently, some degree of uncertainty remains in representing local hydrological response, especially in sub-watersheds with heterogeneous characteristics.

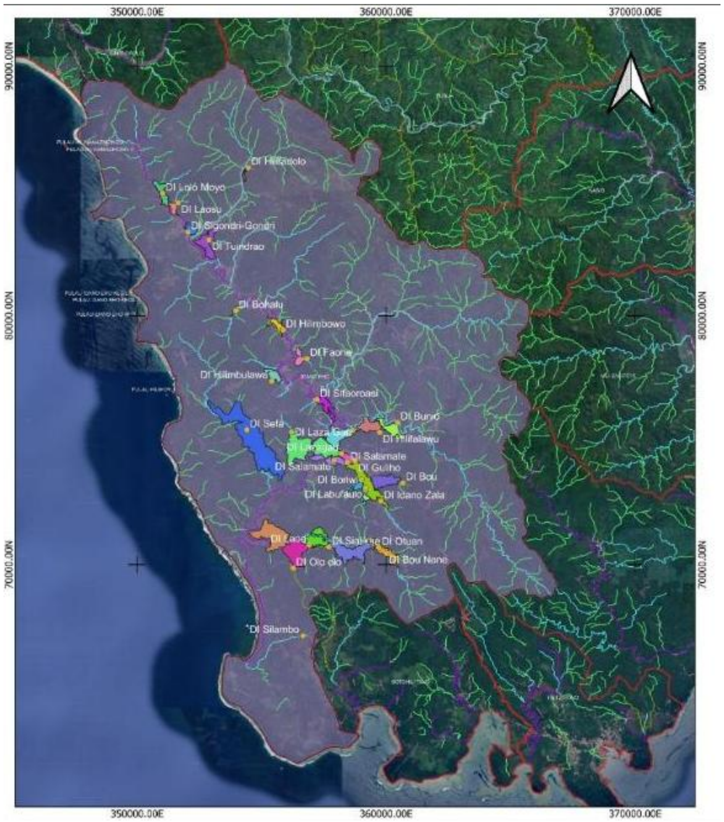

Figure 1. Map of Watershed and Irrigation Areas in the Idano Eho Watershed

2.3 Evapotranspiration

Evapotranspiration is the process of water evaporation from the soil surface and transpiration through plants, which significantly influences the hydrological cycle in this area. Calculating evapotranspiration is crucial for determining water balance, particularly in the context of irrigation and water management in agricultural areas. To calculate evapotranspiration, this study used the Penman Method, which combines the effects of air temperature, humidity, wind speed, and sunshine duration. The climatological data used in this study were taken from the Binaka Meteorological Station in Gunung Sitoli City, which recorded various relevant meteorological parameters from 2020 to 2024. By relying on this data, evapotranspiration analysis will provide more accurate information regarding potential water loss from the soil surface and plants, which forms the basis for calculating irrigation needs [13, 14].

2.4 Dependable Discharge

A dependable discharge is a water discharge that can be relied upon at a certain level of reliability, which is very useful in irrigation system planning and water resource management in general. In this study, the dependable discharge is calculated using the F.J. Mock method to obtain an overview of the available discharge in a certain period. Q80 was selected as the planning dependable discharge because it represents a conservative estimate of water availability under dry-condition reliability, which is commonly used in irrigation planning. The use of Q80 provides a more robust basis for allocation analysis, particularly in identifying critical periods when water demand may exceed dependable supply. In this context, calculating the dependable discharge is very crucial so that water resources can be managed more wisely and efficiently [15].

2.5 Water Balance

The water balance is a crucial tool in water resource planning and management, as it measures the extent to which water availability meets existing needs. In this study, a water balance calculation was conducted to assess whether water availability is sufficient to meet irrigation needs in the Idano Eho watershed. The water balance was constructed by considering key elements such as water availability, water demand, and the water surplus or deficit that occurs within the system. This calculation is crucial for determining whether the existing irrigation system is functioning optimally or requires further improvement and development [16].

2.6 Irrigation Water Requirement

Irrigation water requirements are a determining factor in planning and managing water supply for agriculture. Calculations of irrigation water requirements can be based on cropping plans or through a more detailed approach that takes into account land area, crop type, crop age, crop coefficient, effective rainfall, groundwater contribution, and water losses due to percolation, seepage, and evaporation. Thus, effective water management relies not only on irrigation but also on maximizing the use of rainfall and other water sources [14, 16].

2.7 Uncertainty and Limitations

The present analysis should be interpreted within the scope of a planning-level hydrological assessment. First, dependable discharge was estimated from historical rainfall records and therefore reflects past hydroclimatic conditions rather than future climate scenarios. Second, evapotranspiration was derived from the nearest available climatological station, which may not fully represent microclimatic variability across the entire watershed. Third, the adopted methods involve simplifying assumptions regarding watershed response, rainfall distribution, and irrigation demand representation. Nevertheless, the approach remains useful for identifying temporal allocation stress and supporting preliminary irrigation management decisions in data-limited settings.

3. Result and Discussion

3.1 Water Availability

Analysis of water availability in the Idano Eho Watershed was conducted by estimating the dependable discharge using the F.J. Mock method based on 15-day (semi-monthly) rainfall data. Calculations were conducted at each observation point during the 2015–2024 observation period. Input data used in this analysis included 15-day rainfall, the number of rainy days per 15 days, and evapotranspiration calculated using the Modified Penman method. The F.J. Mock method was applied to each observation area representing water intake points in the Idano Eho Watershed. The calculated discharges were then sorted from largest to smallest and analyzed for their probability of occurrence using the Weibull probability formula. Based on this analysis, discharges with probabilities of 35%, 50%, and 80% were designated as dependable discharges for wet, normal, and dry conditions, respectively. The results of the dependable discharge calculations in the Idano Eho Watershed are presented in Figure 2.

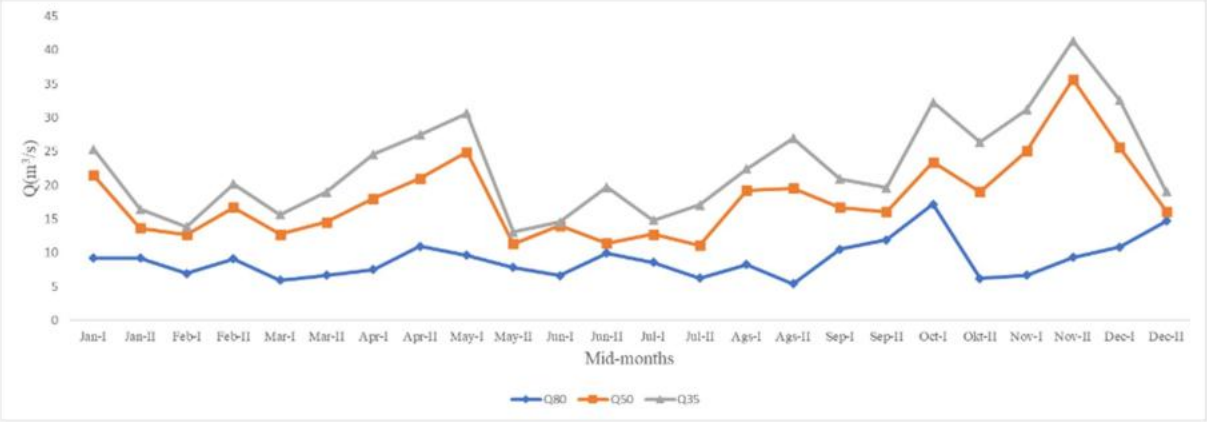

Figure 2. The dependable discharge Idano Eho Watershed.

The Idano Eho Watershed's dependable discharge graph shows varying discharge fluctuations throughout the semi-monthly periods of the year. The Q35 value is consistently higher than the Q50 and Q80 values, while Q80 is the lowest dependable discharge and is most relevant for irrigation planning because it reflects more reliable water availability. Temporarily, discharge tends to increase from March, peaking in April II–May I, then declining sharply in May II and remaining relatively low until July. Afterward, discharge increases again in August–September and reaches a second peak in October–November, particularly in November II.

This pattern indicates that water availability in the Idano Eho Watershed is uneven throughout the year, with periods of relative surplus occurring in April–May and October–November, while mid-year periods tend to show lower discharge. From a planning perspective, this unevenness is more important than annual aggregate availability because irrigation allocation decisions are made during specific operational periods. In particular, the lower Q80 values during several early planting periods indicate reduced supply reliability under dry-condition planning, which may create stress when irrigation demand increases simultaneously across multiple service areas.

3.2 Irrigation Water Requirement

Irrigation water requirement is a crucial component of water balance analysis because it reflects the amount of water required to meet crop needs during each growing season within the irrigation service area. Therefore, periodic irrigation water demand analysis is necessary to illustrate the dynamics of water demand throughout the year and identify periods with high and low water demand. The results of irrigation water demand calculations presented in each semi-monthly period for each irrigation area in the Idano Eho watershed subsequently serve as an important basis for evaluating the balance between water demand and the availability of dependable discharge, thus enabling it to be used in developing more effective and sustainable irrigation water allocation strategies.

Figure 3 shows that irrigation water demand in the irrigated areas of the Idano Eho Watershed fluctuates significantly throughout the year. Water demand begins to increase in October, reaches a peak in November, then fluctuates and increases again until it peaks in March. After this period, water demand decreases gradually from March II to May, then drops sharply from June to September. Observed demand patterns indicate that irrigation water requirement is significantly influenced by the planting calendar and crop growth stages, not just by annual water demand. This finding implies that allocation challenges are partly operational, as periods of high demand concentration can create local shortages even when the watershed is generally characterized by surplus conditions throughout the year.

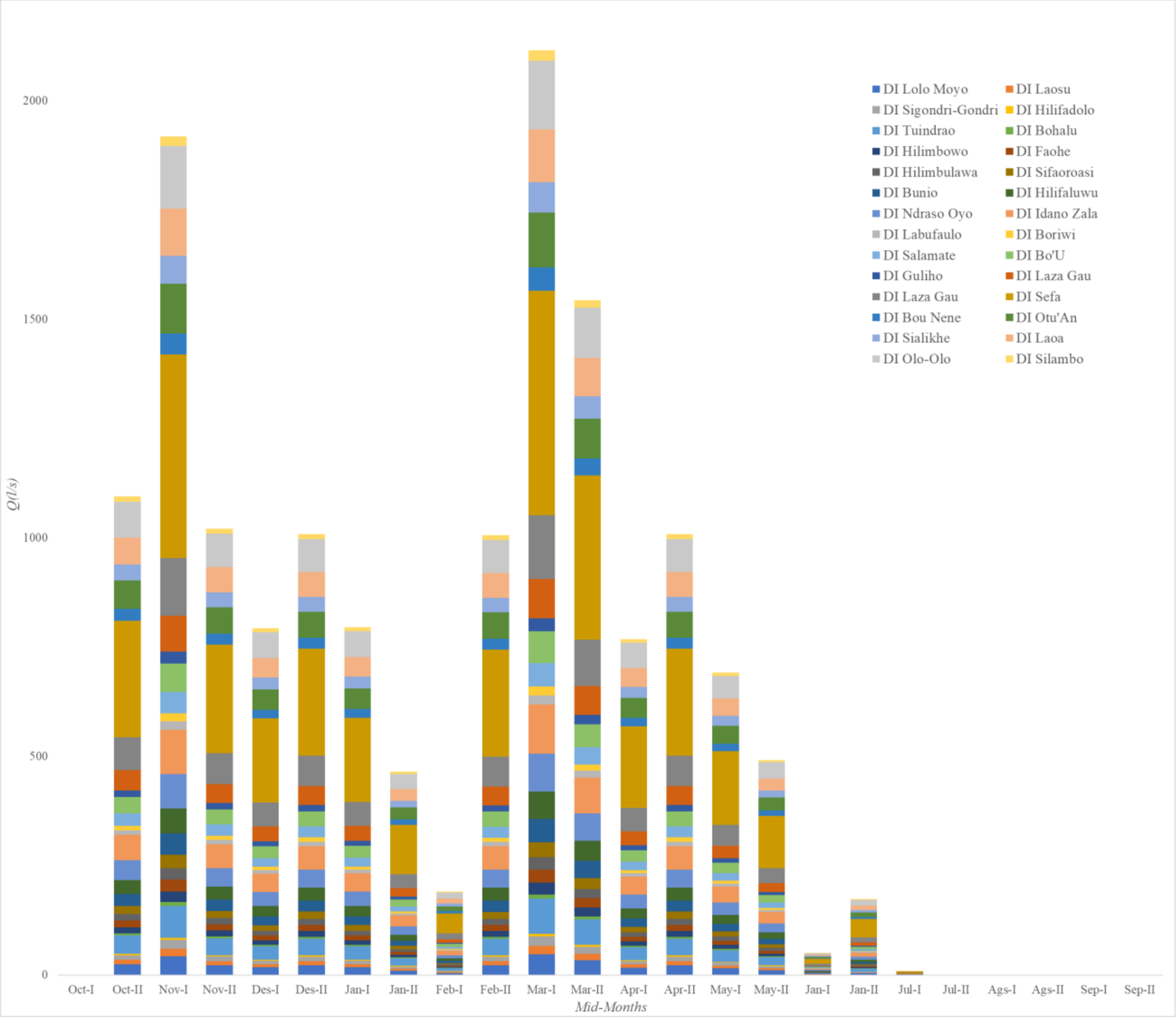

Figure 3. Irrigation water requirement in Idaho Eho Watershed.

3.3 Water Balance

At each irrigation water intake location, an analysis of water availability and water demand was conducted, then the two components were compared to determine the water balance condition. The graph compiled shows the comparison between the available and required water discharge in each irrigation area. If the available discharge is greater than the required discharge, the water balance condition is declared a surplus. Conversely, if the required discharge is greater than the available discharge, the water balance condition is declared a deficit. Based on the results of the analysis of 27 irrigation areas in the Idano Eho watershed, there are 7 irrigation areas that experience water deficits in certain periods, namely the Tuindrao Irrigation Area, Faohe Irrigation Area, Hilimbulawa Irrigation Area, Guliho Irrigation Area, Laza Gau Irrigation Area, Sefa Irrigation Area, and Olo-Olo Irrigation Area. Figure 4 presents the relationship between water availability and water demand in each of these irrigation areas.

This figure shows a comparison between water availability and water demand in seven irrigation areas experiencing deficits over a specific period. In general, the pattern across all sub-figures indicates that the water balance is still dominated by a surplus, characterized by a greater availability than demand for most semi-monthly periods. However, in certain periods, the opposite occurs, with demand increasing sharply or availability decreasing, resulting in a water deficit. Deficit periods generally appear at the beginning of the planting season, particularly around October–November, and reappear around February–April in some irrigation areas.

Based on the graphical pattern, Figures 4(a), (b), (e), and especially (g) show a more pronounced deficit because the demand curve is above the availability curve several times. Figures 4(c), (d), and (f) also experience deficits, but only for a shorter duration and over a more limited period. Among all the graphs, Figure 4(g) shows the most critical condition because the difference between demand and availability appears to be the largest and persists for more than one period. After entering the middle to the end of the observation period, the demand flow generally decreased, while the available flow remained relatively stable or increased again, so that the water balance returned to a surplus. Although the overall watershed condition remains predominantly surplus, deficit conditions are concentrated in specific irrigation areas and periods. This indicates that the main allocation problem in the Idano Eho Watershed is not permanent annual water scarcity, but a temporal mismatch between dependable discharge and irrigation demand. In practical terms, this means that irrigation management should focus on critical periods of local imbalance rather than assuming uniform adequacy across the system.

From an infrastructure management perspective, the results imply that irrigation operation in the Idano Eho Watershed should not rely on uniform water distribution assumptions throughout the year. Instead, management attention should be directed toward critical periods in which irrigation demand peaks coincide with lower dependable discharge. During such periods, priority-based allocation, rotational water delivery, and cropping schedule adjustment are likely to be more effective than static distribution rules.

At the regional planning level, the findings provide a basis for identifying deficit-prone service areas and prioritizing intervention measures. Short-term responses may include operational scheduling adjustments and demand management, whereas medium-term measures may involve improving conveyance efficiency or rehabilitating irrigation infrastructure in the most vulnerable areas. Thus, the study contributes not only to hydrological diagnosis, but also to technical decision support for watershed-based irrigation planning.

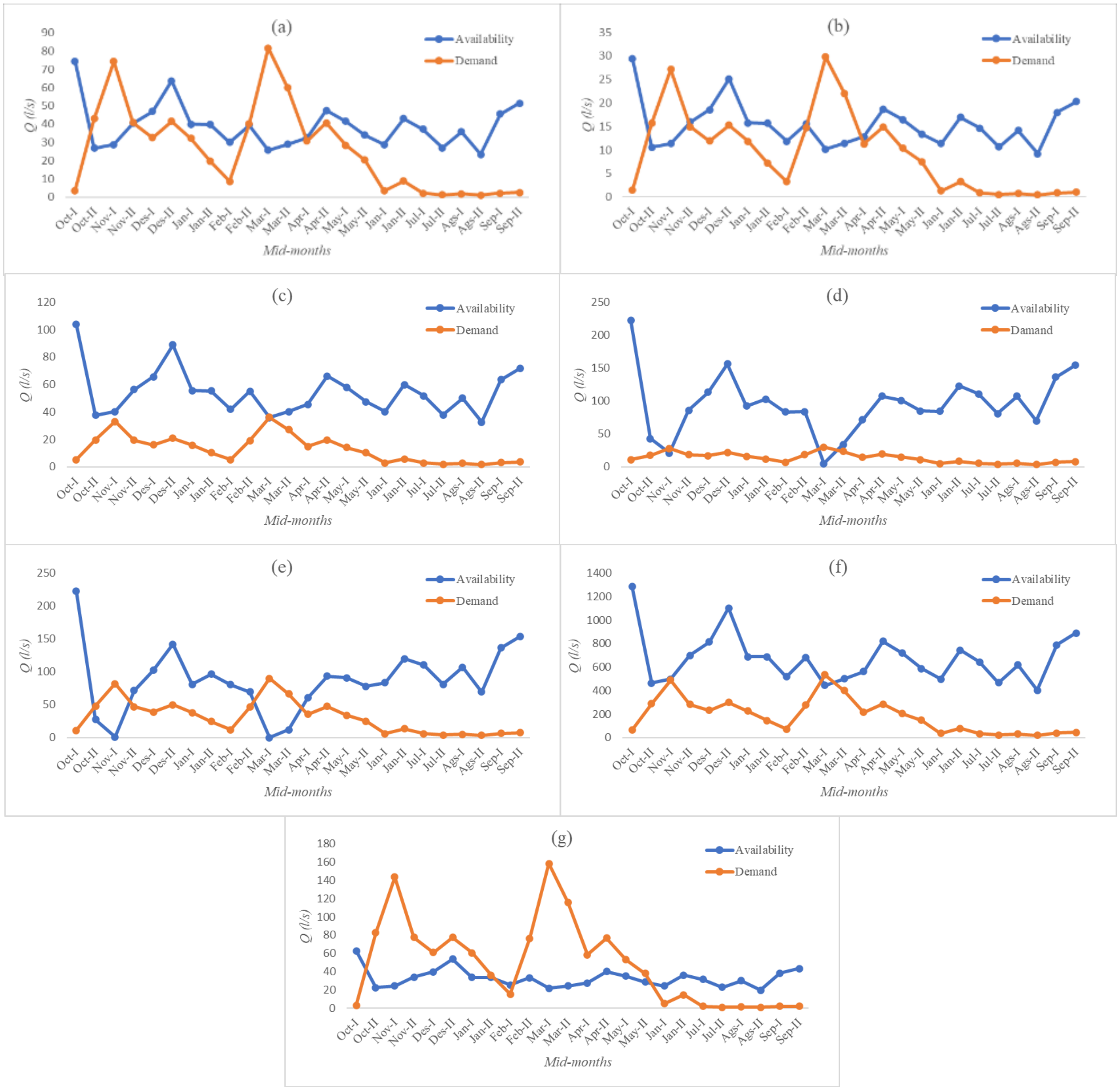

Figure 4. Water balance of (a) Tuindrao; (b) Faohe; (c) Hilimbulawa; (d) Guliho; (e) Laza Gau; (f) Sefa; and (g) Olo-Olo irrigation area.

4. Conclusion

This study shows that irrigation water allocation problems in the Idano Eho watershed are caused not by year-round water scarcity, but by specific periods when irrigation demand increases while dependable discharge becomes limited. Although the watershed generally has surplus water, seven irrigation areas experience deficits during certain semi-monthly periods, indicating that allocation stress is mainly driven by a temporal mismatch between water availability and demand. These findings suggest that irrigation management should apply time-specific and priority-based allocation strategies, including adjustments in scheduling, cropping patterns, and service priorities, to reduce shortages in deficit-prone areas. The study provides a useful basis for watershed-scale irrigation planning in data-limited conditions, although its results are constrained by limited rainfall station data, planning-level hydrological assumptions, and reliance on historical discharge data; therefore, future research should incorporate climate projections, optimization models, and decision-support tools to support more adaptive irrigation management.

4. Acknowledgements

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5. Conflict of Interest

The authors of this work testify the absence of conflicts of interest.

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