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Mesolandform-Driven Variability in Coffee Water Demand and Productivity: A CROPWAT 8.0 Analysis for Sustainable Smallholder Farming in Indonesia

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Abstract

The southern slope of Mount Kawi is a strategic center for coffee production in East Java, yet smallholder plantations face declining productivity due to suboptimal water management. This study aims to estimate Coffee Crop Water Requirements (CWR) across different growth stages and mesolandforms, and to analyze their correlation with coffee productivity. This research supports SDG 2 (Zero Hunger) by enhancing smallholder livelihoods, SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) through climate-adaptive water modeling. Using CROPWAT 8.0, the study integrated climatic, rainfall, soil, and crop data across various mesolandforms (1–10,000 ha) in the Kletek Sub-Watershed. The results indicate significant variations in CWR during the initial, development, mid-season, and late-season phases. A U-shaped distribution of water demand was observed, with the highest requirements occurring during the mid-season phase. Furthermore, the analysis reveals that coffee productivity is significantly influenced by the spatial characteristics of mesolandforms, which dictate water availability. The correlation analysis confirms that precise CWR estimation is a critical factor in optimizing coffee yields. These findings provide a scientific basis for site-specific irrigation scheduling to improve the resilience of smallholder coffee farming systems.

Keywords: coffee productivity, CROPWAT 8.0, mesolandform, SDGs, water requirement

Introduction

Coffee plays a pivotal role in Indonesia's economy as a major contributor to foreign exchange earnings. Between 2014 and 2018, Indonesia ranked fourth globally in coffee exports with a 7% market share, trailing only behind Brazil, which led with 31.5% (Bilen et al., 2022). Notably, approximately 90% of this production is derived from smallholder coffee plantations, highlighting their critical role in the national economy. In East Java, which ranks as the sixth-largest coffee-producing province in Indonesia (Department Agriculture, 2019). Malang Regency stands out as a primary production hub, particularly the regions situated on the southern slopes of Mount Kawi (Irawan et al., 2022).

Despite its economic importance, coffee productivity in East Java experienced a 2.5% decline between 2018 and 2021 (Direktorat Statistik Tanaman Pangan, Hortikultura, dan Perkebunan, 2024). This downward trend is particularly concerning for smallholder farms, which are significantly more vulnerable to climatic fluctuations and suboptimal agricultural practices compared to government-managed plantations (PTPN Bangelan). This productivity is intrinsically linked to the United Nations Sustainable Development Goals (SDGs). Addressing these challenges directly supports SDG 2 (Zero Hunger) by safeguarding the livelihoods of smallholder farmers and SDG 12 (Responsible Consumption and Production) by promoting efficient resource use. Moreover, developing adaptive strategies for coffee cultivation aligns with SDG 13 (Climate Action) in mitigating the impacts of climate change (Sachs et al., 2019).

One of the most critical determinants of coffee productivity is the Crop Water Requirement (CWR). Water is essential for plant development, accounting for 80–90% of a plant's biomass (Seleiman et al., 2021). Coffee plants are exceptionally sensitive to water availability during specific phenological stages, particularly during flower bud formation and fruit development (Ronchi and Miranda, 2020). Insufficient water supply during these stages leads to significant yield losses. To address this, the CROPWAT 8.0 software, developed by the FAO, serves as a robust tool to estimate CWR by integrating climatic, rainfall, soil, and crop data across four distinct growth stages: initial, development, mid-season, and late-season (Tadesse et al., 2020).

In the complex terrain of the Kletek Sub-Watershed, water requirements are not uniform. This study employs a spatial approach using mesolandforms—landforms analyzed at a scale of 1 to 10,000 ha—as a primary variable. Topographic diversity within these mesolandforms, such as variations in elevation and slope, significantly influences microclimates and soil moisture retention (Sholikah et al., 2025). For instance, higher elevations typically experience lower temperatures, while steeper slopes may accelerate water runoff, negatively impacting plant-available water. To date, research exploring the correlation between specific mesolandforms, coffee CWR, and productivity remains scarce. Therefore, this research aims to analyze the variations in CWR across growth stages and mesolandforms, assess coffee productivity levels, and determine the correlation between water requirements and yield performance in the Kletek Sub-Watershed.

Materials and Methods

This research was conducted in the Kletek Sub-Watershed, situated on the southern slope of Mount Kawi, East Java. The study specifically focused on the administrative jurisdiction of Malang Regency, covering four sub-districts: Wonosari, Sumberpucung, Ngajum, and Kromengan. All research activities, ranging from field data collection to analysis, were carried out over a one-year period from August 2023 to July 2024. Soil physical analysis, particularly the determination of soil texture, was performed at the Physics Laboratory, Department of Soil Science, Faculty of Agriculture, Brawijaya University. The research design employed a spatial-analytical approach using mesolandforms (spatial scale of 1–10,000 ha) as the primary variable to account for the topographic diversity within the study area. Mesolandform classification is carried out by integrating several spatial datasets, including the Normal Difference Vegetation Index (NDVI), Topographic Position Index (TPI), curvature, slope, and geological data, using semi-automatic classification to determine representative observation points (Sholikah et al., 2025).

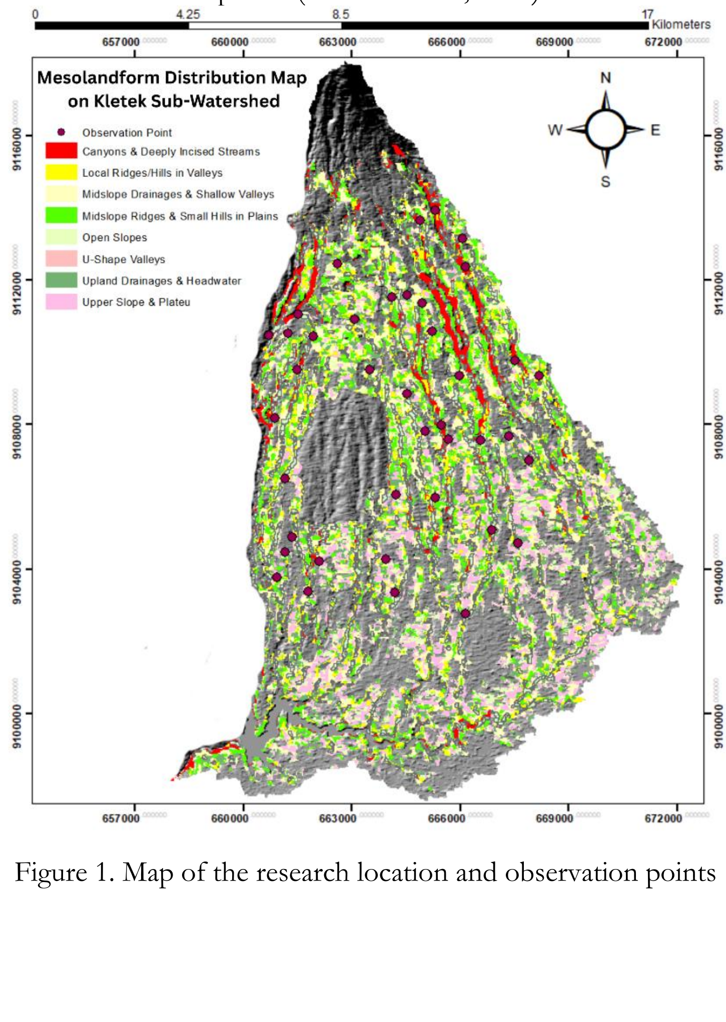

Figure 1. Map of the research location and observation points

The data collection procedures were divided into three main phases: pre-survey, field survey, and post-survey analysis. During the pre-survey phase, an extensive literature review was conducted, and research permits were obtained from the relevant regional authorities in Malang Regency. Subsequently, the field survey was carried out by establishing 10 m x 10 m observation plots at each validated point. Disturbed soil samples were collected from mini-pits at depths of 0–30 cm and 30–60 cm, while a soil auger was utilized for depths reaching up to 175 cm. Simultaneously, coffee productivity was measured by selecting five representative sample plants per plot; coffee cherries were weighed using an analytical scale and subsequently converted into tons per hectare (tons/ha).

The estimation of Coffee Crop Water Requirement (CWR) was calculated using CROPWAT 8.0 software by integrating four primary data categories (Haq and Khan, 2022). Climatic data spanning the last ten years (2014–2023), including maximum/minimum temperature, humidity, wind speed, and sunshine duration, were retrieved from the AgERA5 database to calculate Reference Evapotranspiration (ETo). Monthly rainfall data for the same period were obtained from the CHIRPS database to determine effective rainfall. Crop data, covering the initial, development, mid-season, and late-season stages, were derived from FAO secondary data and adjusted to local field conditions. Lastly, soil data from laboratory results were used to define the total available water capacity. All processed data were statistically verified using Rstudio, involving T-tests to identify significant differences in CWR and productivity across various mesolandforms, as well as correlation and regression analyses to determine the relationship between water requirements and coffee yield performance.

Result and Discussion

Dynamics of Coffee Crop Water Requirements (CWR) Across Phenological Stages on Initial Phase

Water balance resulted by CropWat 8.0 consists of water deficit that was produced by the difference between input and output data. Input and output data according to CropWat 8.0 consecutively are effective rainfall (mm) and ETo (mm/day). This software only shows water deficit, whereas water surplus indicates with a value of 0.

Water balance that was shown on the software was divided according to each crop development stages, which are initial or flower formation phase, development or flowering development to pollination phase, mid or fruit development, and late or harvest period. Each date of crop development stages was determined by using actual condition and secondary data. Initial stage was started on Oktober until mid-November (50 days), development stage started from the end of November until January (65 days), mid stage started on the end of January until the end of April (100 days), and late stage that started from Mei until July (90 days).

Both phases/stages exhibit a deficit, which was caused by the effective rainfall being lower than the crop water requirements or ETo. This is due to the results of the average of 10-year rainfall analysis which show that these two stages have low rainfall, specifically from July to September. Low rainfall can be considered as dry months, which could be defined as months that has rainfall < 100 mm. According to the software, there are two stages that resulted a water deficit condition on each mesolandform, which are initial and late stages. These stages could be shown in Table 1 and Table 2.

Table 1. Coffee Crop Water Balance in the Initial Phase for each Mesolandform

Mesolandform	Observation Point	Input (mm/day)	Output (mm/day)	Deficit (mm/day)
Canyons and Deeply Incised Streams	6	2.13	4.88	2.75
	7	2.77	5.06	2.29
	13	2.72	5.04	2.32
	21	2.72	5.04	2.32
	36	2.73	5.22	2.49
Midslope Drainage and Shallow Valley	3	2.79	5.05	2.25
	10	2.72	4.88	2.16
	14	2.71	5.04	2.33
	15	2.72	5.23	2.51
	20	2.70	5.04	2.34
Upland Drainage and Headwater	1	2.78	5.24	2.47
	16	2.73	5.41	2.67
	18	2.70	4.88	2.17
	25	2.72	5.22	2.50
	38	2.72	5.03	2.31

Table 1. (Continuation)

Mesolandform	Observation Point	Input (mm/day)	Output (mm/day)	Deficit (mm/day)
U-Shape Valley	2	2.77	4.89	2.11
	11	2.72	4.88	2.16
	22	2.70	4.87	2.17
	33	2.76	4.88	2.13
	37	2.70	4.88	2.17
Open Slope	8	2.79	5.06	2.27
	17	2.70	4.89	2.19
	30	2.79	5.06	2.27
	34	2.72	5.53	2.81
	35	2.70	4.88	2.18
Upper Slope and Plateu	4	2.74	5.40	2.66
	5	2.77	4.89	2.12
	23	2.70	5.04	2.33
	32	2.72	5.53	2.81
	39	2.70	4.88	2.18
Local Ridges/Hills in Valley	9	2.79	5.06	2.27
	27	2.79	5.36	2.57
	28	2.77	5.05	2.28
	29	2.83	5.26	2.43
	31	2.73	5.23	2.50
Midslope Ridge and Small Hill in Plain	12	2.72	4.71	1.99
	19	2.71	5.22	2.52
	24	2.72	5.04	2.32
	26	2.80	5.44	2.65
	40	2.79	5.06	2.26

Table 2. Coffee Crop Water Balance in the Late Phase for each Mesolandform

Mesolandform	Observation Point	Input (mm/day)	Output (mm/day)	Deficit (mm/day)
Canyons and Deeply Incised Streams	6	3.39	3.53	0.14
	7	3.37	3.69	0.32
	13	3.33	3.73	0.40
	21	3.28	3.73	0.45
	36	3.31	3.87	0.57
Midslope Drainage and Shallow Valley	3	3.40	3.66	0.26
	10	3.29	3.59	0.30
	14	3.34	3.70	0.37
	15	3.37	3.84	0.48
	20	3.40	3.73	0.34
Upland Drainage and Headwater	1	3.37	3.80	0.43
	16	3.38	3.96	0.58
	18	3.37	3.55	0.18
	25	3.35	3.82	0.47
	38	3.25	3.71	0.46
U-Shape Valley	2	3.39	3.53	0.14
	11	3.30	3.59	0.29
	22	3.40	3.60	0.19
	33	3.37	3.53	0.16
	37	3.40	3.68	0.28

Table 2. (Continuation)

Mesolandform	Observation Point	Input (mm/day)	Output (mm/day)	Deficit (mm/day)
Open Slope	8	3.40	3.66	0.27
	17	3.37	3.54	0.16
	30	3.39	3.64	0.26
	34	3.26	4.13	0.87
	35	3.40	3.57	0.17
Upper Slope and Plateu	4	3.39	3.99	0.60
	5	3.39	3.52	0.13
	23	3.37	3.69	0.32
	32	3.26	4.13	0.87
	39	3.40	3.60	0.21
Local Ridges/Hills in Valley	9	3.40	3.66	0.27
	27	3.38	3.82	0.44
	28	3.38	3.67	0.29
	29	3.41	3.80	0.40
	31	3.33	3.87	0.54
Midslope Ridge and Small Hill in Plain	12	3.31	3.45	0.14
	19	3.39	3.82	0.43
	24	3.32	3.72	0.40
	26	3.39	3.97	0.58
	40	3.39	3.63	0.24

The water balance shown in the software was divided into the following crop development stages: the initial or flower-formation phase; the development or flowering-to-pollination phase; the mid or fruit-development phase; and the late or harvest period. Coffee phase stages were determined by using actual conditions and secondary data. The initial stage started in October until mid-November (50 days), the development stage started from the end of November until January (65 days), the mid-stage started at the end of January until the end of April (100 days), and the late stage started from May until July (90 days).

The CROPWAT 8.0 simulation revealed that coffee water requirements in the Kletek Sub-Watershed follow a distinct temporal pattern. The CWR values exhibited a "U-shaped" curve: starting relatively high in the initial stage, slightly dipping during the development stage, and reaching the maximum peak during the mid-season stage, before declining in the late-season.

This peak in the mid-season stage (flowering and fruit development) is scientifically critical. During this phase, physiological processes such as cell division and carbohydrate accumulation in coffee cherries require optimal turgor pressure. A water deficit during this window leads to stomatal closure, which inhibits photosynthesis and causes abortion of flowers or fruits. These findings align with Tilahun et al. (2021), emphasizing that mid-season water management is the most decisive factor for yield. In the context of SDG 12 (Responsible Consumption and Production), identifying this peak enables farmers to apply precision irrigation, ensuring water is used efficiently and precisely when plants need it most.

Relationship between Mesolandforms and Coffee Water Demand

The analysis conducted using CROPWAT 8.0, supported by a t-test, revealed significant spatial variation in Coffee Crop Water Requirements (CWR) across different mesolandform units. Notably, the U-Shape Valley exhibited a water requirement profile that differed significantly from other landforms, such as Canyon and Deeply Incised Stream, Midslope Drainage, Upland Drainage, and Local Ridges. The T-test yielded a P-value (two-tailed) of less than 0.05, confirming that the topographic positioning of a plantation inherently dictates its hydrometeorological characteristics, which subsequently determine the volume of water required by the crops in that specific location.

The variation in CWR across these mesolandforms is primarily driven by fluctuations in microclimatic variables, specifically sunlight duration and solar radiation. Prolonged sunlight duration extends the period of stomatal opening. The difference was caused by several factors relating to climate, which are sunlight duration and solar radiation that contributes to the increase of crop water requirement or ETo (Bernado et al., 2021). While this is essential for CO_2 diffusion during photosynthesis, it also facilitates higher transpiration rates. This process occurs due to a concentration gradient, in which water vapor diffuses from the leaf's saturated interior (high concentration) to the drier atmosphere (low concentration). Furthermore, solar radiation serves as the primary energy source for evaporation. Increased solar energy enhances the kinetic energy of water molecules on both the soil surface and plant tissues, accelerating the transition of water from a liquid phase to vapor (Smirnov et al., 2022). In the CROPWAT model framework, which utilizes the Penman-Monteith formula, high radiation levels directly amplify the Reference Evapotranspiration (ETo) values; thus, mesolandforms with high solar exposure require a greater CWR to maintain physiological turgor and optimal plant development.

Research data further demonstrates that CWR is not uniform across the Kletek Sub-Watershed due to the significant influence of elevation and slope gradient. Mesolandforms at higher elevations, such as Upper Slopes and Plateaus, recorded lower ETo values compared to lower-lying areas. This phenomenon is attributed to the adiabatic lapse rate, where higher altitudes experience lower temperatures and higher relative humidity. These conditions reduce the Vapor Pressure Deficit (VPD), effectively lowering the atmospheric demand for moisture and reducing the plant's transpiration rate (Juárez-López et al., 2017). Conversely, mesolandforms with steeper gradients, such as Canyons and Midslope Ridges, face substantial challenges regarding effective rainfall retention. Despite abundant precipitation, the steep topography facilitates rapid surface runoff, which in turn diminishes the "Effective Rainfall" component within the CROPWAT model, potentially leading to localized water stress.

The findings regarding these spatial variations provide a crucial technical foundation for achieving SDG 13 (Climate Action) through "site-specific adaptation" strategies. The fact that topography dictates water availability implies that a uniform irrigation strategy is insufficient for the Kletek Sub-Watershed (Sholikah et al., 2025). Farmers managing plantations on steep mesolandforms or in high-radiation zones must implement robust soil conservation techniques, such as terracing or mulching, to compensate for low water retention and high ETo values (Bali et al., 2023; Sholikah et al., 2024). By aligning CWR modeling with mesolandform mapping, this research offers a strategic guide for smallholder farmers to enhance their resilience and productivity amidst local climate variability, ultimately supporting the economic sustainability of the smallholder plantation sector.

Conclusion

This study concludes that coffee crop water requirements (CWR) in the Kletek Sub-Watershed follow a temporal "U-shaped" demand curve, peaking during the critical mid-season fruit development stage. Spatially, CWR is significantly dictated by mesolandform characteristics; high-elevation units benefit from lower evapotranspiration due to the adiabatic lapse rate, while steep gradients suffer from reduced effective rainfall caused by rapid surface runoff. These findings imply that the observed decline in smallholder productivity is linked to localized water stress during phenological peaks. Consequently, this research suggests a shift from uniform management to "site-specific adaptation" strategies. To achieve SDG 2 (Zero Hunger) and SDG 13 (Climate Action), farmers should implement targeted interventions, such as terracing and mulching on steep slopes, to optimize water retention and stabilize yields against climatic variability. While the study is limited by its reliance on secondary climatic datasets and the modeled assumption of optimal management, it provides a critical scientific foundation for transitioning from uniform practices to site-specific adaptation. Future research should integrate real-time soil moisture monitoring and economic feasibility studies of conservation techniques to refine irrigation scheduling, ultimately supporting the resilience and productivity of smallholder coffee farming in alignment with SDG 2, 12, and 13.

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