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From Rainless Days to Systemic Drought Risk in Indonesia: Climate Drivers, Drought Propagation, Food–Water Vulnerability, and Adaptive Resilience

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ABSTRACT

Prolonged rainless periods are an increasingly important climate-risk signal in Indonesia, but their societal significance cannot be understood from rainfall duration alone. This qualitative literature review synthesizes recent evidence on how meteorological dryness evolves into agricultural, hydrological, and socioeconomic drought and examines the implications for food production, water security, rural livelihoods, and drought governance in Indonesia. The review integrates peer-reviewed literature published mainly during 2020–2026 with the September 2026 episode of exceptionally long consecutive rainless periods as a contemporary interpretive context. The synthesis identifies four principal findings. First, Indonesian drought is strongly shaped by interacting ocean–atmosphere processes, particularly El Niño–Southern Oscillation, the Indian Ocean Dipole, monsoon variability, and local climatic conditions. Second, drought impacts emerge through nonlinear propagation involving soil-moisture depletion, vegetation stress, declining surface and groundwater availability, irrigation constraints, and socioeconomic exposure. Third, no single drought metric adequately captures this cascade; station observations, SPI/SPEI, satellite precipitation, vegetation indices, soil moisture, and data-driven approaches provide complementary information. Fourth, drought resilience depends on converting climate information into anticipatory decisions through irrigation management, farm adaptation, climate services, social protection, insurance, institutional coordination, and long-term water-system transformation. The article proposes an Integrated Drought–Cascade–Resilience Framework that connects climate forcing, hazard, propagation, exposure, impacts, risk intelligence, adaptation, and resilience. The framework implies that Indonesia should move from predominantly hazard-centred drought monitoring toward impact-oriented, multi-indicator and anticipatory drought governance.

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Received: September 19, 2026; **Accepted:** September 24, 2026; **Published:** September 30, 2026

Keywords: Drought, Prolonged Dry Spell, Consecutive Dry Days, Enso, Indian Ocean Dipole, Agricultural Drought, Water Security, Food Security, Climate Adaptation, Indonesia

Jel Classification: Q54, Q25, Q18, Q12, Q56

Introduction

Indonesia is commonly associated with humid tropical conditions, abundant rainfall, and extensive surface-water resources, yet this broad climatic image can conceal substantial seasonal, spatial, and interannual water deficits. The country's location within the Maritime Continent exposes rainfall to interactions among monsoonal circulation, the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), sea-surface-temperature anomalies, intraseasonal variability, and local topographic and land–sea processes. As a consequence, the timing and intensity of the dry season can vary greatly among islands and even among neighbouring districts. Research conducted during the past several years increasingly demonstrates that drought in Indonesia is not merely an episodic absence of rainfall but a multidimensional risk that connects atmospheric processes with agricultural systems, irrigation networks, reservoirs, livelihoods, and food security [1–4].

The prolonged dry conditions observed during 2026 provide a timely illustration. Monitoring by Indonesia's Agency for Meteorology, Climatology and Geophysics (BMKG) showed that, by 10 September 2026, Pajangan in Bantul Regency had recorded 131 consecutive rainless days, while Masaran in Sragen had reached 130 days, Jatisrono in Wonogiri 129 days, and Juwiring in Klaten 117 days. BMKG classifies more than 60 consecutive days without rain within its extreme dryness category. In East Java, monitoring at the same date indicated that much of the province was experiencing more than 60 rainless days, while rainfall during the first ten days of September was generally [5].

These figures are climatically significant, but they require careful interpretation. Consecutive rainless days, known operationally in Indonesia as Hari Tanpa Hujan (HTH), measure one particular dimension of meteorological dryness. They do not directly measure soil-water availability, crop stress, reservoir storage, streamflow, groundwater, food prices, household welfare, or economic loss. A district with 100 rainless days may retain access to reservoir-irrigated irrigation, whereas another with a shorter rainfall deficit may experience severe crop stress because of shallow soils, limited storage, high evaporative demand, or dependence on rainfed farming. Consequently, equating HTH directly with total drought

severity risks obscuring the physical and socioeconomic processes that convert atmospheric dryness into damaging drought [6,7].

This distinction is particularly important for Indonesia because agricultural drought is mediated by irrigation architecture and water-storage systems. In the downstream Citarum watershed, for example, research demonstrates that agricultural drought does not arise simultaneously with meteorological drought. Its timing and severity are influenced by the distance of agricultural land from major irrigation networks and by connectivity to the Jatiluhur reservoir. Meteorological drought can therefore be partly buffered, delayed, or spatially redistributed by infrastructure.

At the same time, infrastructure cannot be treated as a complete substitute for rainfall. Reservoir storage must be accumulated in advance; irrigation systems have finite conveyance capacities; groundwater abstraction can redistribute risks into the future; and competing domestic, industrial, environmental, and agricultural water demands become more difficult to reconcile when dry conditions persist. Drought should therefore be understood as a process of propagation through interconnected systems rather than a single climatic event. Contemporary drought science increasingly emphasizes such propagation from meteorological deficits to soil-moisture, vegetation, hydrological, ecological, and socioeconomic drought, with time lags and thresholds determined by climate, storage, watershed properties, land management, and human intervention [8–11].

The agricultural implications are substantial. Indonesian food production remains highly sensitive to rainfall variability even where irrigation exists because cropping calendars, reservoir releases, canal reliability, farm-level water access, and seasonal planting decisions remain closely tied to hydroclimatic conditions. Dryness affects rice, horticulture, plantation crops, and mixed farming differently. Studies of vegetable farmers, sugarcane smallholders, tea plantations, oil-palm systems and food-crop regions demonstrate that adaptation decisions depend not only on climate signals but also on information access, farmer organizations, credit, training, irrigation technology, land characteristics, and perceived risks [11–14]

The literature nonetheless remains fragmented. Climatological studies frequently focus on ENSO, IOD or rainfall indices; remote-sensing studies focus on vegetation or satellite precipitation; agricultural research examines crop impacts and farm adaptation; hydrological research studies reservoirs and water supply; and disaster-management studies emphasize governance. These literatures often speak to different stages of what is ultimately a single drought-risk pathway. The result is a conceptual gap between knowing that a dry spell is occurring and understanding how, when, where and for whom it becomes consequential.

This article addresses that gap through a qualitative literature review of recent research, principally from 2020–2026. Rather than performing a systematic review or meta-analysis, it develops a theory-oriented synthesis around seven questions: how climatic processes generate prolonged dryness; how meteorological drought propagates into agricultural and hydrological drought; why impacts vary spatially; how drought affects agriculture, water and food systems; how monitoring technologies can be integrated; how households and institutions adapt; and how early warning can be connected to anticipatory action.

The central argument is that Indonesia's drought challenge should be conceptualized as a cascade rather than an event. Climate anomalies create meteorological hazards; those hazards propagate through soils, vegetation and hydrological storage; exposure and sensitivity determine which livelihoods and systems are affected; and institutions, infrastructure and adaptive capacity determine whether the cascade is interrupted, delayed or amplified. This reasoning provides the foundation for the Integrated Drought-Cascade–Resilience Framework developed in this article.

Literature Review

Conceptualising Drought Beyond Rainfall Deficit

Drought is difficult to define precisely because it develops across several interconnected domains. Meteorological drought refers primarily to abnormal precipitation deficiency over a particular period. Agricultural drought concerns insufficient soil moisture or plant-available water relative to crop needs. Hydrological drought involves sustained deficiencies in streamflow, reservoirs, lakes or groundwater, while socioeconomic drought emerges when water scarcity disrupts production, consumption, livelihoods or other social functions. Recent scholarship emphasizes that these categories should not be regarded as isolated phenomena because one form of drought may trigger another through propagation mechanisms [15].

The temporal scale is equally important. A rainfall deficit lasting several weeks can be highly consequential during crop establishment or flowering but relatively unimportant when soils are saturated and reservoirs are full. Conversely, a sequence of moderate rainfall deficits can gradually deplete storage and produce severe hydrological drought even if no single period appears extraordinary. This explains why drought indicators operate at different accumulation windows: shorter windows are more relevant to agricultural and soil-moisture responses, while longer windows may better represent reservoir, river and groundwater conditions.

The concept of flash drought further complicates the conventional slow-onset interpretation. Flash drought develops through unusually rapid intensification, often when rainfall deficits coincide with high temperatures, low humidity, strong radiation or other conditions that increase atmospheric evaporative demand. Such events may produce rapid soil-moisture depletion before conventional seasonal drought alerts fully reflect the emerging threat [16–18].

Climate warming can intensify this problem because drought impacts are not governed by precipitation alone. Soil moisture and evapotranspiration interact with atmospheric conditions, while compound hot–dry extremes can impose considerably greater stress on agriculture and ecosystems than either heat or rainfall deficiency separately. Research on compound extremes increasingly highlights feedbacks among precipitation, temperature, vapour-pressure deficit and soil moisture [19,20,21].

Climatic Drivers of Indonesian Drought

Indonesia's rainfall variability is shaped by several overlapping climate models, but ENSO and the IOD remain especially important. El Niño conditions generally reduce rainfall across substantial parts of Indonesia, whereas La Niña commonly enhances it. Positive IOD events tend to suppress rainfall particularly over western and southern Indonesia, while negative IOD phases can contribute wetter conditions. Crucially, these phenomena may occur simultaneously, producing compound effects that differ regionally.

show that ENSO and IOD have distinguishable geographical signatures in Indonesian rainfall extremes. ENSO exerts stronger independent influence over northern and eastern areas, whereas IOD effects tend to be stronger in western and southern regions. Their influence is strongest during the dry-season months, when rainfall deficits are particularly important for agricultural and water-management decisions.

Satellite-based drought analysis for Java similarly demonstrates that drought severity can be influenced by simultaneous El Niño and positive-IOD conditions. found satellite-derived precipitation products capable of representing meteorological drought patterns over major rice-producing districts and concluded that drought severity was associated with the intensity of overlapping ENSO and IOD conditions.

The national picture is nevertheless heterogeneous. Ferijal, Batelaan and Shanafield (2021) found divergent dry-spell trends among Indonesian rainfall regimes, reinforcing the importance of distinguishing monsoonal, semi-annual and anti-monsoonal climatic regions. More recent assessments similarly reveal strong geographical differences in agricultural-drought frequency, duration and intensity across Indonesia [22].

Evidence from individual drought episodes further illustrates these interactions comparing Karawang in 2019 and 2023, found differences between drought associated primarily with an extreme positive IOD and drought associated with strong El Niño conditions. Importantly, agricultural drought lagged meteorological drought by approximately two to three months, and reservoir-fed irrigation influenced the resulting spatial patterns [54].

At the broader Southeast Asian level, identify ENSO as a leading large-scale drought driver while also finding roles for IOD, Pacific variability and Atlantic sea-surface-temperature patterns. Regional hydro-meteorological studies also show that basin characteristics and decadal background states can modulate drought persistence and severity across Southeast Asia Anthropogenic forcing is also increasingly relevant. Zhang, Chen and Zhou (2021) found that human influence has increased drought risk over the Southeast Asian monsoon region through changes in precipitation and evaporative demand [23,24,25].

Monitoring Drought: Why One Indicator Is Not Enough

Indonesia's drought-monitoring challenge reflects both the complexity of drought itself and uneven observational density across a large archipelago. Traditional meteorological observations provide essential rainfall information but may not reveal conditions between stations. Satellite systems compensate by providing spatially continuous data but introduce uncertainty associated with retrieval algorithms, cloud conditions, spatial resolution and the indirect nature of many drought indicators.

SPI is one of the most widely used meteorological drought metrics because it standardises precipitation relative to a local historical distribution. SPEI incorporates a measure of climatic water demand and is therefore more sensitive to temperature-related drying. HTH or consecutive dry days provide an intuitive measure of rainfall persistence. These metrics answer related but non-identical questions: an area can accumulate many rainless days while retaining substantial stored water, whereas moderate but persistent rainfall deficits combined with unusually high evaporative demand can generate serious agricultural stress.

Research in West Papua demonstrates that CHIRPS precipitation can provide useful information where observational density is limited, although performance relative to stations is imperfect In Java, likewise demonstrate the value of satellite precipitation for drought monitoring in major rice-producing districts [26].

Agricultural drought requires additional variables. Vegetation indices such as NDVI and condition indices derived from vegetation and land-surface temperature are used to identify plant stress. Sentinel-3 observations, for example, have been used to map drought conditions across Java using vegetation and temperature relationships Landsat-based assessments in Bondowoso detected substantial increases in land-surface temperature during the 2023 El Niño and identified emerging vegetation stress in agricultural [27,28].

Remote-sensing literature therefore increasingly advocates multi-sensor approaches. Jiao, Wang and McCabe (2021) argue that combining precipitation, vegetation, temperature, soil-moisture and hydrological signals permits a more complete drought diagnosis than reliance on one sensor family. Reviews of Southeast Asian drought monitoring similarly find that Earth observation has expanded substantially but that validation and cross-sensor integration remain uneven MODIS-based analyses over mainland Southeast Asia further demonstrate the value of vegetation time series for resolving the spatiotemporal evolution of agricultural drought Machine-learning techniques may improve fusion and forecasting, although training-data quality, interpretability, bias and model transferability remain significant concerns [29,30,32].

Drought Propagation as an Analytical Framework

The core theoretical concept guiding this review is drought propagation. Rainfall deficits first reduce direct water inputs. The consequences then depend on antecedent conditions, evapotranspiration, soil properties, vegetation, hydrological storage, water abstraction and management. The same meteorological event may therefore lead to different hydrological or agricultural outcomes in different places.

Hydrological modelling shows that watershed properties influence both the intensity and duration of propagated drought. Apurv and Cai (2020) demonstrated that climate seasonality, recharge processes, catchment storage and baseflow sensitivity shape streamflow drought characteristics. further showed that meteorological-to-hydrological relationships can be nonlinear, making simple contemporaneous correlations insufficient for understanding drought transmission.

Agricultural propagation likewise depends on time of year and environmental conditions. Dai et al. (2022) found seasonal differences in the transition from meteorological to agricultural drought and identified temperature, soil moisture and precipitation as important influences. The wider drought-propagation literature now includes not only hydrological and agricultural transitions but also socioeconomic, ecological and groundwater drought, as summarized by The Indonesian evidence fits this broader theory particularly well demonstrate that reservoir access and irrigation distance alter time lags between meteorological and agricultural drought. This means that infrastructure changes the propagation function itself. Irrigation does not simply reduce drought severity; it can postpone, redistribute or spatially differentiate the agricultural expression of the same rainfall deficit.

Method

This study applies a qualitative literature review, not a systematic literature review. Its purpose is conceptual integration and interpretive synthesis rather than exhaustive enumeration of all publications, statistical meta-analysis, or formal PRISMA-based evidence screening. The approach is therefore problem-centred and theory-oriented: literature is selected and interpreted according to its contribution to understanding climate forcing, drought propagation, agricultural and hydrological impacts, vulnerability, monitoring, adaptation, and governance.

The primary publication window is 2020–2026. This period was selected to capture contemporary advances in satellite monitoring, drought propagation, machine learning, climate-risk research and adaptation while responding to the requirement that the supporting journal literature be recent. The core geographical focus is Indonesia. Research from Southeast Asia and global drought studies is used where it contributes directly to mechanisms relevant to Indonesia, including ENSO teleconnections, compound hot–dry events, remote sensing, drought forecasting, and propagation theory. Literature identification combined thematic searches around terms such as Indonesia drought, agricultural drought Indonesia, meteorological drought Java, ENSO IOD Indonesia rainfall, drought remote sensing Indonesia, drought propagation, agricultural drought Southeast Asia, water scarcity Indonesia, farmer climate adaptation Indonesia, flash drought, and drought early warning. Peer-reviewed articles indexed or published through established journal platforms were prioritized. The synthesis proceeded through three analytical stages. First, studies were coded according to their primary analytical domain: climate drivers, meteorological hazard, agricultural drought, hydrological drought, remote sensing, exposure and vulnerability, socioeconomic consequences, adaptation or governance. Second, relationships among domains were identified, especially evidence describing temporal lags or causal pathways.

Third, recurring themes were integrated into an overarching drought-cascade framework.

The review does not treat all papers as methodologically equivalent. Ground observations, remotely sensed products, crop studies, household surveys, hydrological models and conceptual reviews provide different forms of evidence. This heterogeneity is considered an analytical asset because the objective is to understand a multi-domain process. However, it also precludes interpreting the review as a statistically representative estimate of drought effects.

Particular attention is given to the distinction between **hazard indicators** and **impact indicators**. Rainfall-based indicators represent meteorological conditions; vegetation and soil-moisture indicators represent biophysical responses; hydrological indicators represent storage and flow; and livelihood or production variables reflect socioeconomic consequences. The framework therefore avoids interpreting a single metric as a comprehensive measure of drought. The September 2026 HTH episode is used as a contemporary interpretive case rather than a standalone empirical dataset. BMKG information is used to establish the meteorological context, while journal literature is used to explain the mechanisms through which such conditions can—or may not—develop into

agricultural, hydrological and socioeconomic impacts. BMKG reported 131 HTH in Bantul by 10 September and extreme HTH conditions across substantial areas, providing a useful example of why hazard monitoring must be connected with impact-oriented analysis.

Results

Theme 1: Drought Risk Begins with Climate Forcing but Is Regionally Differentiated

The first major finding is that Indonesian drought is strongly influenced by large-scale climate drivers but cannot be explained by a single climate index. ENSO has broad influence, particularly during the dry season, while IOD provides an additional and partly independent influence. Their geographical signatures vary across the archipelago, and simultaneous ENSO–IOD conditions can considerably strengthen rainfall. Regional differentiation is reinforced by Indonesia's complex topography, monsoon exposure, island geometry and local land–sea circulations. Consequently, national drought alerts must be translated into locally meaningful information rather than treated as uniform national conditions. Evidence from Java, West Papua, Nusa Tenggara and other regions indicates considerable variation in drought timing, duration and vegetation response. Longer-term Southeast Asian evidence adds a climate-change dimension. Drought characteristics across the region show substantial spatial differences, but several studies identify increasing risk under anthropogenic forcing or projected warming. Zhang, Chen and attribute part of the historical rise in Southeast Asian drought risk to human influence, while project increasing drought duration and severity in parts of Vietnam under higher-emissions scenarios. These studies cannot be transferred mechanically to Indonesia, but they demonstrate why historical drought relationships cannot automatically be assumed to remain stationary [33].

Theme 2: Rainless Days Become Damaging Through Propagation

The second and most important finding is that long rainless periods should be treated as an initiating condition rather than a complete diagnosis of drought impacts. The propagation sequence commonly begins with precipitation deficiency. Soil-water reserves then decline as evapotranspiration continues. Vegetation responds according to rooting depth, crop type, phenological stage and access to irrigation. If deficits persist, reservoir levels, streamflow and groundwater availability may become constrained. At still later stages, harvests, income, food availability and household welfare may be affected. This process is nonlinear. Thresholds matter because moderate rainfall deficits can initially be absorbed by storage. Once reserves pass a critical level, however, impacts can accelerate. Conversely, irrigation, rainfall during key growth stages, groundwater access or reservoir releases may temporarily disconnect crop conditions from meteorological drought.

Figure 1 Synthesizes This Logic into the Proposed Integrated Drought-Cascade–Resilience Framework

Rather than representing drought as a single line from low rainfall to economic loss, the framework distinguishes climate forcing, meteorological hazard, biophysical propagation, hydrological stress and socioeconomic consequences while positioning exposure, risk information and adaptation as mechanisms that shape the resulting pathway.

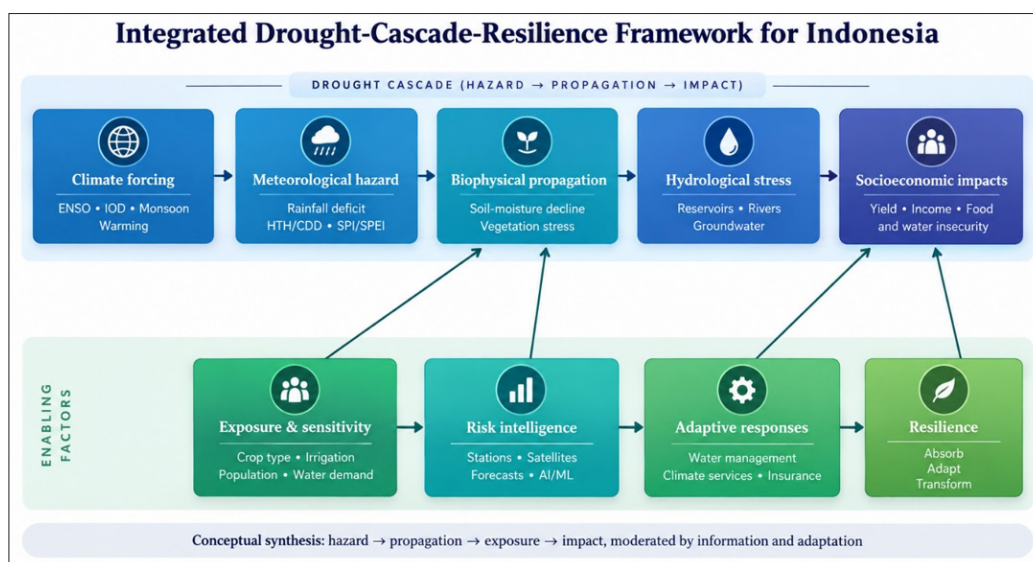


Figure 1: Integrated Drought-Cascade-Resilience Framework for Indonesia

The framework implies that drought severity is jointly produced by hazard and system characteristics. Climate forcing influences rainfall; meteorological dryness modifies soil and vegetation conditions; hydrological storage mediates how quickly scarcity emerges; and socioeconomic consequences depend on who is exposed and what adaptive resources are available. Monitoring systems affect risk through information, while adaptation and infrastructure can interrupt or slow propagation. Thus, drought resilience is not synonymous with receiving more rainfall: it is the capacity to maintain essential functions as rainfall deficits propagate through interconnected systems.

Theme 3: The 2026 Episode Demonstrates the Difference Between Hazard and Impact

The September 2026 episode illustrates why long HTH deserves attention but should not be interpreted in isolation. BMKG's monitoring identified 131 consecutive rainless days in Pajangan, Bantul, while Sragen reached 130 days and Wonogiri 129 days; many locations were classified within extreme HTH conditions.

Figure 2 Visualizes the Locations Reported in the Supplied 2026 Infographic and Demonstrates How Far the Observed Hth Values Exceeded The >60-Day Extreme Threshold Used by Bmkg

The figure should be read as a representation of meteorological persistence rather than a ranking of total socioeconomic drought losses.

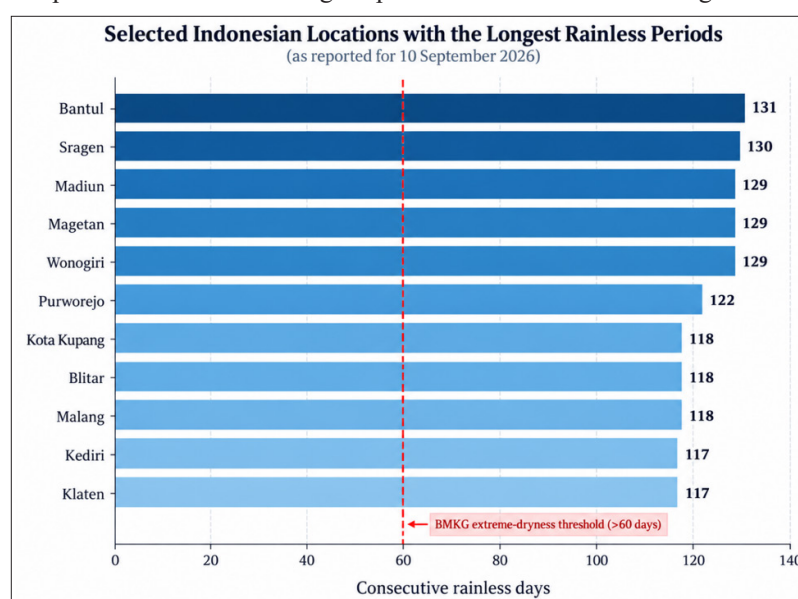


Figure 2: Selected Indonesian locations with prolonged rainless periods reported for 10 September 2026

The visual pattern is striking: all locations in the selected group substantially exceed 60 days. Yet a direct ordering of socioeconomic vulnerability cannot be inferred from these values. Agricultural impacts in Bantul, for example, depend on cropping systems and access to water; the same applies to Sragen, Madiun, Magetan or Kupang. The analytical importance of Figure 2 is therefore not that 131

days is necessarily “one day worse” than 130, but that extended meteorological dryness creates progressively greater probability that buffers such as soil moisture, farm ponds, reservoirs and groundwater will be depleted.

Theme 4: Agriculture Is the Main Transmission Channel to Food-Security Risk

Agriculture frequently represents the first economically visible stage of drought propagation because crops respond to water availability over biologically constrained periods. Water shortage during establishment may reduce plant populations; stress during reproductive stages can sharply reduce yields; prolonged deficits can reduce planted area or cause crop failure. The magnitude of these impacts depends on crop physiology, soil conditions, farm management and irrigation. Evidence from Central Kalimantan oil-palm systems illustrates how impacts can continue long after the initial water deficit. Sukarman et al. (2022) found differing yield responses among soil types and identified delayed effects operating over multiple production stages. This demonstrates that drought impacts can possess “memory”: current climatic conditions may influence production in subsequent seasons or years. Tea systems in West Java likewise demonstrate that both insufficient and excessive rainfall matter. found reduced production under El Niño-associated rainfall shortages and argued for water management, improved human capacity and microclimate adaptation. Meanwhile, satellite-based work in Bondowoso shows how vegetation and thermal indicators can reveal emerging crop stress during El Niño conditions at the national scale, recent evidence that climate shocks affect agricultural output dynamics reinforces the need to interpret drought as both a biophysical and production-system risk. At broader regional scale, estimated substantial crop losses associated with droughts and floods across Southeast Asia and highlighted the high exposure of rainfed agricultural systems. Although their results combine different countries and climates, they reinforce the proposition that dependence on rainfall amplifies sensitivity to drought where water-storage and irrigation buffers are weak. Food-security consequences arise through multiple pathways. Reduced production can lower farm household income and affect local availability; irrigation costs or groundwater pumping may increase; livestock feed can become scarcer; food prices can respond to simultaneous production disturbances; and poor households may have limited ability to absorb income and price shocks. Climate risk to food security therefore involves both production and access rather than crop yield alone [34,35,36].

Theme 5: Irrigation and Reservoirs Buffer Drought but Also Create Spatial Differentiation

Irrigation is among the most powerful drought-buffering mechanisms, yet its benefits depend on storage, conveyance, allocation and farm-level access. The downstream Citarum evidence is particularly instructive: the lag between meteorological and agricultural drought changes according to the position of farmland relative to the irrigation network and Jatiluhur reservoir. This finding has broader implications. Irrigation systems convert physical water storage into resilience only when water can be conveyed to the right fields at the right time. Canal maintenance, sedimentation, leakage, allocation rules and competition among users can therefore influence drought outcomes independently of total reservoir volume. Water infrastructure should thus be understood institutionally as well as physically. Dryland agriculture poses a different challenge emphasize water harvesting, appropriate irrigation and institutional arrangements capable of improving cropping intensity in Indonesian drylands. Evidence from Magelang further illustrates how El Niño-related rainfall deficits can constrain agricultural water availability, underscoring the

value of location-specific water planning. Such strategies become increasingly important where the expansion of conventional irrigation is technically or economically difficult. The critical implication is that two neighbouring farming systems facing identical rainfall deficits may experience very different drought consequences. One may possess storage, irrigation access and institutional coordination; the other may depend almost entirely on rainfall. This helps explain why meteorological maps alone cannot substitute for agricultural-impact monitoring [37,38].

Theme 6: Vulnerability Is Social as Well as Climatic

Drought impacts are also shaped by household assets, poverty, access to credit, information, social networks, extension services and institutional support. Examining agricultural drought vulnerability in East Java, identify climatic conditions alongside irrigation, smallholder characteristics and poverty as important elements of vulnerability. Research in Kalimantan similarly demonstrates that vulnerability varies significantly among districts according to exposure, sensitivity and adaptive capacity. found high or very high food-farming vulnerability in multiple locations and emphasized locally differentiated adaptation measures. Household resilience therefore depends on more than technology. show that smallholder responses to water scarcity are linked to livelihood capitals and household characteristics. Indonesian vegetable-farming research finds that education, experience, credit access, climate information and participation in farmer organizations influence adaptation choices. Climate-risk perception, institutional support and training also affect adaptation among sugarcane farmers and other agricultural groups. These findings imply that drought can exacerbate existing inequality. Farmers who possess pumps, capital, storage, insurance or institutional connections may protect production, while poorer farmers may reduce planted area, incur debt or accept crop losses. Adaptation policy must therefore address both physical water availability and differential capacity to respond [39,40-53].

Theme 7: Multi-Indicator Monitoring Can Support Earlier Intervention

The monitoring literature strongly supports indicator pluralism. Rain gauges and HTH are essential for characterizing rainfall persistence. SPI and SPEI provide standardized anomalies over multiple timescales. Satellite precipitation improves spatial coverage. Vegetation indices reveal biological response. Land-surface temperature can indicate heat and evaporative stress. Soil-moisture products provide more direct information on crop-root-zone conditions, while reservoir and streamflow observations capture hydrological drought. note that remote sensing and GIS have increasingly been applied to drought vulnerability in Indonesia, but different spatial scales entail trade-offs between temporal coverage and local detail. similarly argue that multi-sensor fusion offers opportunities to overcome limitations inherent in individual remote-sensing products. Artificial intelligence and machine learning create further possibilities. They may combine large numbers of predictor variables, model nonlinear relationships, classify vegetation stress or produce probabilistic forecasts. However, they cannot compensate for weak underlying observations. Poor training data, spatial bias, changing climate relationships and limited interpretability can generate deceptively precise outputs. The appropriate objective is therefore not to replace hydrometeorological understanding with algorithms, but to combine process knowledge, observations and data-driven models. Early-warning research also shows that forecasting hazard alone is insufficient. Shukla et al. (2020) demonstrate the potential of operational soil-moisture and hydrological forecasts for drought-related food-security warning. show that impact forecasts can

provide information beyond hazard forecasts; and illustrate the ongoing challenge of extending drought prediction skill to subseasonal timescales. NHESS More recent work shows that precipitation-based forecasts can provide useful hydrological drought information, but forecast skill depends strongly on catchment properties, lag structure and human [41–46–55].

Discussion and Analysis

Reframing the 2026 Dry Spell as a System Stress Test

The 2026 HTH episode should be interpreted less as an isolated meteorological curiosity and more as a stress test for Indonesia's food–water system. A run of more than 100 rainless days challenges multiple buffers sequentially. The first buffer is soil moisture accumulated during previous rainfall. The second may be farm-level storage, groundwater or small reservoirs. Larger irrigation reservoirs provide another layer. Household savings, credit, crop insurance and public assistance create socioeconomic buffers. Drought becomes systemic when several of these layers weaken simultaneously. This interpretation avoids two analytical errors. The first is underestimation: viewing a long dry spell simply as normal seasonality can delay preparedness until crop or water shortages are already visible. The second is overinterpretation: assuming that every location with an extreme HTH value must already be experiencing equivalent agricultural losses. Both errors arise from treating hazard duration as if it were synonymous with impact.

Figure 3 Therefore Separates the Stages of Drought Propagation and Explicitly Introduces Time Lags.

Rainfall deficits may emerge within days, soil moisture can respond over days to weeks, vegetation impacts often emerge over weeks, hydrological storage may deteriorate over weeks to months, and food- or livelihood-related effects may become evident on seasonal timescales.

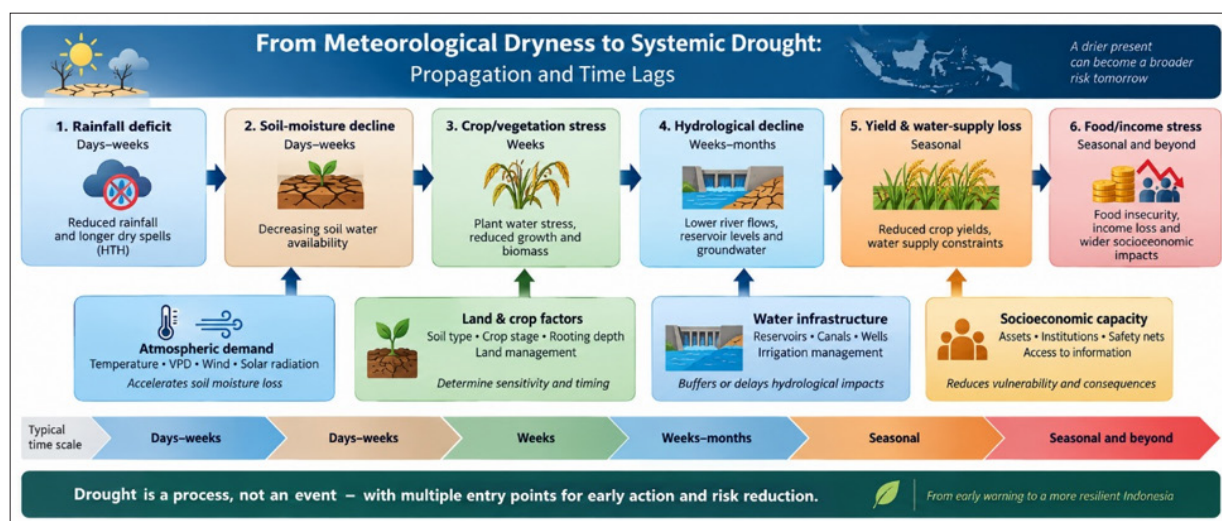


Figure 3: From Meteorological Dryness to Systemic Drought: Propagation Pathways and Time Lags The important message is that these intervals are not fixed. High evaporative demand can accelerate soil-moisture depletion; deep soils can delay it; irrigation can postpone vegetation stress; reservoirs can delay hydrological scarcity; and income diversification can reduce the livelihood effects of production losses. Drought management can therefore intervene at several points rather than waiting for final socioeconomic damage.

From Hazard Monitoring to Impact-Based Drought Intelligence

Indonesia already possesses substantial climate-monitoring capability. BMKG routinely provides HTH, rainfall analysis, forecasts and meteorological drought warnings. The next analytical step is to link these hazard products systematically with soil moisture, vegetation condition, reservoir levels, irrigation operations, crop calendars and socioeconomic exposure.

An impact-oriented system could, for example, distinguish four locations with identical 60-day HTH values. One location might contain irrigated rice supplied from a reservoir at adequate storage levels; the second might be rainfed maize at a sensitive reproductive stage; the third might be urbanized with secure piped water; and the fourth might depend heavily on shallow groundwater. A meteorological indicator would classify all four similarly, while an impact-oriented system would differentiate their risk. The theoretical advantage of such integration is consistent with the drought-propagation literature. Because transmission across drought types is nonlinear and mediated by human intervention, forecasting downstream impacts requires information on more than the upstream rainfall anomaly. Impact-based seasonal forecasting studies similarly show that the decision value of forecasts depends on user-specific action thresholds and the timing of intervention, not simply forecast accuracy in isolation. Operationally, this implies a layered warning architecture. Meteorological information would provide the initial signal. Satellite and land-surface observations would identify emerging agricultural stress. Reservoir and streamflow data would indicate water-system pressures. Agricultural administrative data could track planting, harvest and crop damage. Socioeconomic information could identify households or districts with limited coping capacity. Such integration also reduces the risk of “false reassurance”. A reservoir may buffer farms temporarily even during extreme HTH, but declining storage can create a delayed crisis if dry conditions continue. Conversely, rainfall resumption does not necessarily mean drought impacts are over: reservoir replenishment can take time, crops already damaged may not recover, and household debt can persist [47,48].

Climate Change Alters the Baseline

The historical Indonesian drought record remains essential, but it should not be interpreted as a stationary probability distribution. Human influence on Southeast Asian drought risk is increasingly detectable, and warming raises atmospheric evaporative demand even in situations where rainfall trends remain uncertain Compound hot–dry conditions are particularly relevant because crop stress depends on both water supply and atmospheric demand show that precipitation trends are central to future compound hot–dry occurrence, while Mukherjee et al. (2023) demonstrate feedbacks between drying and heating. Record-breaking climate extremes also become more plausible as warming continues, complicating infrastructure and agricultural planning based solely on historical maxima This does not mean every Indonesian drought can be attributed directly to climate change. ENSO, IOD and other modes generate substantial natural variability, and attribution requires dedicated analysis. It does mean, however, that drought management should increasingly consider the interaction of natural variability with a warmer background climate [49].

Agriculture Requires Trigger-Based Anticipatory Action

The lag between meteorological and agricultural drought creates an important policy opportunity. If rainfall deficits can be identified before crop stress becomes severe, governments and farmers have time to adjust planting calendars, manage irrigation allocation, deploy pumps or emergency storage, modify crop choices, strengthen extension services, or prepare targeted financial assistance. Anticipatory action should be trigger-based rather than dependent entirely on emergency declarations after losses occur. Possible trigger combinations could include HTH duration, SPI/SPEI thresholds, forecast rainfall probability, reservoir storage, soil-moisture anomalies and crop-stage information. Trigger design should differ by agroecological zone because the same rainfall threshold has different implications in irrigated Java,

dryland Nusa Tenggara, plantation systems or humid regions with different soils. International evidence shows that forecast-based triggers are most useful when they are calibrated to user-specific losses, lead times and false-alarm tolerance, and when preparedness and activation thresholds are connected to pre-agreed actions and financing Crop insurance may also benefit from better drought intelligence. demonstrated the potential of UAV multispectral vegetation information for more rapid and objective assessment of drought damage in Indonesian paddy systems. Remote-sensing methods could therefore improve not only early warning but also ex-post verification and financial risk transfer. However, financial mechanisms should not substitute for prevention. Insurance can spread residual losses but cannot replace irrigation maintenance, water governance, agronomic adaptation or reliable forecasts [50,51].

Drought Resilience Requires a Portfolio Rather Than a Single Intervention

The review shows no single adaptation capable of addressing all drought pathways. Water harvesting helps where storage is feasible; efficient irrigation reduces demand but can be limited by water availability; crop diversification reduces production risk; drought-tolerant varieties can reduce sensitivity but cannot eliminate severe water deficits; insurance can transfer part of financial risk; climate services support decisions but only when farmers can act on the information. Adaptation must therefore be conceived as a portfolio operating across time horizons. Short-term measures address an emerging drought. Seasonal measures modify production and water allocation. Structural measures improve the long-term resilience of water, agricultural and social systems. The portfolio is summarized in Figure 4, which organizes these options by governance scale and time horizon and shows how early action connects with seasonal adaptation and longer-term transformation.



Figure 4: Indonesia's Drought-Resilience Portfolio: From Anticipatory Action to Structural Transformation

At household level, early action may include planting-date decisions, emergency watering and input adjustments. Seasonal adaptation may involve drought-tolerant crops, mulching, changes in cropping calendars and livelihood diversification. Structural resilience involves efficient irrigation, farm water storage and improved access to finance.

At irrigation or watershed level, short-term decisions concern reservoir releases and canal prioritisation. Seasonal planning involves water-allocation rules, conjunctive use and maintenance. Structural interventions include storage, groundwater recharge protection and demand management. At government level, early action includes trigger-based warnings, extension mobilisation and targeted assistance. Seasonal actions involve climate services, contingency finance and coordination. Long-term resilience requires institutional

integration, interoperable data systems and explicit food–water risk governance.

Governance Is the Critical Missing Link

The literature indicates that the technical ability to observe drought has expanded faster than the institutional ability to translate information into coordinated action. Indonesia has meteorological monitoring, remote-sensing capabilities, irrigation agencies, agricultural extension, disaster-management institutions and social-protection mechanisms, but these functions do not automatically operate as a unified drought-management system. identify fragmented regulation and overlapping responsibilities among the challenges facing drought management in Indonesia. This finding is especially important because drought crosses administrative sectors: meteorological agencies observe the hazard; water institutions manage reservoirs; agricultural agencies address crops; disaster agencies manage emergencies; local governments face water-supply impacts; and social-protection agencies may address household welfare. A drought-cascade perspective suggests that coordination should occur before impacts reach crisis levels. Climate information should trigger predefined questions: Which reservoirs are approaching critical thresholds? Which crops are at vulnerable stages? Which districts combine long HTH with low irrigation access? Which communities depend on shallow wells? Which households have limited coping capacity? Without such pre-agreed decision rules, increasingly sophisticated forecasts may simply produce more information rather than more resilience. Recent anticipatory-action research demonstrates that operational systems perform best when thresholds, forecast verification, decision responsibilities and financing are designed as a single chain from warning to action.

Adaptation Effectiveness Must Be Evaluated, Not Assumed

Global evidence warns that adaptation is frequently incremental and that documented implementation does not automatically demonstrate actual risk reduction. synthesizing global adaptation evidence, found widespread implementation but relatively limited evidence demonstrating transformational adaptation or measured reduction in climate risk This lesson applies directly to drought programs. Building a water-storage structure does not demonstrate resilience unless storage is available when drought occurs and users can access it. Providing climate information does not guarantee adaptation unless the information arrives at a useful time, is trusted, and is connected to feasible choices. Promoting drought-tolerant seed does not ensure benefit if markets, input access or irrigation constraints make adoption impractical. Indonesian evidence supports this behavioural and institutional interpretation identify education, information, credit and institutional access as factors influencing farmers' choices. similarly emphasize risk perception, extension, training and farmer support systems. Adaptation effectiveness therefore depends on the interaction between technology and the institutional conditions enabling its use [52].

An Integrated Drought-Cascade–Resilience Framework

The synthesis supports a framework comprising eight linked analytical layers. The first four describe the physical cascade: climate forcing includes ENSO, IOD, monsoonal variability, sea-surface-temperature anomalies and background warming; meteorological hazard comprises rainfall deficits, long HTH, SPI/SPEI anomalies and abnormal atmospheric demand; biophysical propagation includes soil-moisture depletion, vegetation stress and changing evapotranspiration; and hydrological propagation encompasses reservoir drawdown, lower streamflow and groundwater stress.

Together, these layers explain how atmospheric anomalies can move through land and water systems rather than producing uniform or instantaneous impacts The remaining four layers describe the human and decision context. Exposure and sensitivity encompass crop types, irrigation dependence, population, water demand and socioeconomic characteristics, while cascading impacts include crop losses, water shortages, income shocks and food insecurity. Risk intelligence brings together monitoring, forecasting, satellite observations, climate services and decision-support systems, whereas adaptive resilience captures capacities to absorb shocks, adjust practices and structurally transform systems. Framing these dimensions together is important because drought losses depend not only on hazard magnitude but also on who is exposed, which buffers are available and whether information reaches actors early enough to support feasible This structure extends drought-propagation theory by incorporating adaptation inside the propagation pathway rather than treating adaptation only as a final response after impacts occur. Irrigation can interrupt transmission from rainfall deficit to crop stress; insurance can interrupt transmission from yield loss to financial crisis; social protection can reduce transmission from income shocks to food insecurity. The framework consequently defines resilience as the capacity to interrupt undesirable propagation before hazard signals become irreversible social and economic losses.

Conclusion and Recommendations

Indonesia's prolonged dry spells, including the extreme HTH conditions observed in September 2026, demonstrate why drought should be interpreted as a multidimensional and cascading risk rather than simply the number of days since the last rainfall. Long HTH provides an important meteorological warning, but the severity of eventual agricultural, hydrological and socioeconomic consequences depends on atmospheric demand, soil moisture, irrigation, reservoir storage, groundwater, crop stage, livelihood exposure and adaptive capacity. The literature shows that ENSO and IOD remain fundamental drivers of Indonesian rainfall variability, with their impacts differentiated spatially and seasonally. Climate change adds a changing background through warming and evaporative demand, increasing the importance of compound hot–dry conditions. At the same time, Indonesian evidence demonstrates that drought propagation contains substantial time lags and that infrastructure can alter those lags. Meteorological drought should therefore be viewed as the beginning of a decision window rather than merely as evidence that losses are inevitable. Drought monitoring should consequently evolve toward a multi-indicator system integrating rainfall observations, HTH, SPI/SPEI, satellite precipitation, vegetation condition, soil moisture, reservoirs, irrigation networks and socioeconomic exposure. Artificial intelligence and machine learning can strengthen this architecture, but they should complement rather than replace high-quality observations and physical understanding. For agriculture, the priority is to connect monitoring to predetermined anticipatory actions. Planting calendars, irrigation allocation, reservoir releases, drought-tolerant crops, extension services, insurance and social protection should increasingly be activated through transparent risk thresholds rather than only after widespread losses are documented. Water management should similarly move from emergency supply toward long-term resilience. This includes maintaining irrigation networks, improving storage and water harvesting, protecting groundwater recharge, strengthening demand management and accounting explicitly for competition among agriculture, domestic users, ecosystems and industry. Institutional integration is equally important. Drought crosses meteorology, agriculture, water resources, disaster management and social protection.

An effective national approach therefore requires interoperable information and clearly allocated responsibility across agencies and levels of government. The central policy implication is that Indonesia does not need to choose between better monitoring and better adaptation. The two must become one decision system. The value of drought information lies not simply in describing dryness but in enabling action before a meteorological anomaly becomes a crop failure, water-supply crisis, income shock or food-security emergency. The Integrated Drought-Cascade–Resilience Framework proposed here therefore shifts the focus from the descriptive question “How long has it not rained?” toward the more consequential question “Where is the drought cascade now, who is at risk, and which intervention can still interrupt it?”

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